Temperature Effects on Creep Behaviour of Bovine Cortical Bones

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Abstract. A widely acknowledged fact is that viscoelastic behavior exhibited in cortical bone that influences the biomechanical reaction when an external load applied to an implant. Moreover, the successful operation of an implement can be easily affected by long term load, i.e., relaxation, creep, and remodelling. In the current study, the design and manufacture of creep equipment is complied with ASTM D2990, and an apparatus is specially designed for creep tests and test samples were taken from femur bovine cortical bones of animals with 24 month age. The current work states the viscoelastic behavior of bone which is simulated theoretically, using Burgers rheological model. The behavior of bone is demonstrated by the model and its parameters when it is subjected to longitudinal loading. Additionally, the simulations with the model excellent show agreement among all experimental and theoretical results reaching up to \((99.11\% - 100\%)\). The results and their diagrams for each stress were recorded and drawn separately. The influence of different temperature has been studied on the behavior of creep for bovine femur samples, the samples were examined for 1800 seconds under the influence of three degrees of stress (25, 50, and 65) MPa respectively. Each stress was examined with different temperatures of (29, 35, 40, and 50 °C), due to the fact that such degrees are the average climate temperatures. The results shows that the temperature effects on creep behavior of bovine cortical bones, with the increase of temperature the initial strain was increase (from 0.032\% to 0.11\%), the duration of the first stage of creep curve is decrease and the creep strain rate was increased (from 1.88 \(\mu\varepsilon/\text{sec}\) to 8.05 \(\mu\varepsilon/\text{sec}\)).

Keywords: cortical bone, Burgers model, viscoelasticity and creep

1. Introduction

One of the critical challenges that may face orthopaedic surgeons is fixation of fracture that patients experience with their bones. The challenge lies in the difficulty of achieving fracture fixation stability that is enough, allowing patients to mobilize freely. In cortical bone, the measurement of the quantity of stability is used as the quantification of rigidity of fracture fixation that is further used as devices in the treatment of fracture. Since it is well proven that creep and relaxation take place during normal activity every day, the investigation of the time-dependent performance and under loading (creep) is as an important and vital process.

Creep may be seen as one of the fundamental criterions that describe time dependent behavior of viscoelastic materials. It is the increase in strain under loading. Biological materials usually experience creep at low repeated loading in daily life [1]. Bone is responsible for carrying load, mainly the body load. Hence any extra load, applied to bones may stimulate strain of various significance and magnitudes, according to the circumstances, geometry and the behavior of the material in the bone [2].
Examining the bone behavior, particularly under loading, has been the subject of a good number of scientific experiences and research (See [3] [4]). Generally speaking, cortical bone shows viscoelastic-viscoelastic behavior, affecting the biomechanical reaction. This is particularly true, when the implant undergoes any external pressure or load. Moreover, the influences of long term, i.e. creep, may well affect the favorable outcome of the implant throughout time [5]. The stimulation of the bone viscoelastic behavior is achieved in the current work theoretically, then analysed, via rheological model of Burgers of the cortical bone. This was done with the incorporation of long term pressure and load, intending to predict stress-strain at different stress, as well as, various levels of temperature; that is, in addition to the vivo effect over time on cortical bone behavior. The parameters of the rheological model, used in this process, illustrate the bone behavior, when subjected to longitudinal axial loading. Due to the use of such model parameters for a cortical bone, the current model is also usable in the process of bone behavior predicting, under particular load circumstances. The experimental results of creep for cortical bones under uniaxial loading were reported.

2. Methodology
The experimental aspect of this study involved the investigation of the design and manufacture of creep equipment, using a device specially designed for creep tests.

2.1. Creep Rig
The creep equipment was designed and manufactured according to ASTM D 2990 [10] to handle a full range of creep tests for different materials. The creep rig consisted of the following parts:

- Base plate
- Support column
- Transmission lever (load beam)
- Dial gage
- Grips
- Balance weight
- Hanger and load weights, As show in the figure(1)

2.2. Electric furnaces
Additionally, an electric furnace was designed and manufactured for testing, featuring

- Aluminium frame with dimensions 50 x 50 x 50 cm
- Aluminium sheets
- Thermal insulator (Rock wool)
- Electrical fan
- Electrical heater
- Temperature control (measurement probe located close to bone specimen as shown in figure 3).
2.3. Samples
The bone specimens were chosen from a bovine femur bone of nearly 24 months age, taken while the bone was still fresh. Figure 5 shows the process of the samples were being cleaned to remove any soft tissues found on the femur bone; this was followed by cutting the samples into several pieces in rectangular shapes along the axial direction, following the long axis of the bone. This process was followed by the reshaping of the samples using a grinding stone to create the final dimensions as stated in ASTM D638 [11], and as shown in figure (4).

3. Testing
3.1. Creep test
The design and manufacture of creep equipment is complied with ASTM D2990 [7]. At the creep test a sample is tightened between the grips of the creep rig. The distance between grips was (25.4) mm. Creep test begin when a load applying on the specimen and the displacement ($\Delta l$) will be recorded continuously throughout the test.

With the use of the simple equation:

$$\varepsilon(t) = \frac{\Delta l(t)}{l_0} \hspace{1cm} \cdots (1)$$

We calculate the strain in certain time and then we draw the creep curve between strain and time as in figure (4), we use the short term test which represents the first stage of creep curve. We use three levels of stresses (25, 50 and 65) Mpa; which are the degrees below the yield stress (Yield stress is 94MPa)[8] and each stress tested with four degrees of temperature (29, 35, 40 and 50) °C [9].

![Figure 4. Creep strain at various constant stresses.](image)

### 3.2. Creep model

The creep behaviour of viscoelastic material usually modelled using models consists of springs and dashpots that replicate the elastic and viscous components of the materials behaviour. In the current work Burgers model were used, they are also known as four-element model which consist of two springs and two dashpots as in figure (5). This model is able to describe the viscoelastic behaviour of cortical bones with good accuracy, so we chose it.

![Figure 5. Parameter or Burgers model](image)

Four parameter burger equations were used as:

$$E(t) = \frac{\sigma}{E_1} + \frac{\sigma}{\eta_1} t + \frac{\sigma}{E_2} \left(1 - e^{-\frac{E_2}{\eta_2} t}\right) \hspace{1cm} \cdots (2)$$
Where:

\( \varepsilon(t) \)  equals the strain evaluated at a certain time \( t \)

\( \sigma^0 \)  is stress applied on specimen

\( E_1 \) and \( E_2 \) are the elastic modulus of the springs (springs parameter)

\( \eta_1 \) and \( \eta_2 \) are viscosity of dashpots (dashpots parameter)

The material parameters were determined by fitting experimental result of creep test as described in (Creep) [10].

The parameters identification of the tested material are determined using the creeping curve when normalized (figure 6)

From the instant elongation at \( t = 0 \) times (\( \varepsilon_0 \)), the determination of \( E_1 \) (parameter of the spring) value can be done easily.

\[
E_1 = \frac{\sigma^0}{\varepsilon^0} \tag{3} \quad [10]
\]

Where:

\[
\sigma = \frac{F}{A} \tag{4} \quad [11]
\]

Draw a tangent line towards the \( \varepsilon(t) \) curve at \( t=T \) time (when the test ends), now, construct a parallel line to the previous one at the \( (0, \varepsilon_0) \) point. At this point draw a parallel line again with the x axis. The \( \varepsilon(t) \) curve is divided into the three deformations components (\( \varepsilon_e(t) \), \( \varepsilon_d(t) \), \( \varepsilon_p(t) \)) by the line drawn earlier as shown in Figure (7). Hence, \( \varepsilon_p(t=T) \) and \( \varepsilon_d(t=T) \) can be measured. Thus, \( E_2 \) and \( \eta_1 \) values are determined as:

\[
E_2 \approx \frac{\sigma^0}{\varepsilon_d(t=T)} \tag{5} \quad [10]
\]
\[ \eta_1 \approx \frac{\sigma_0}{\varepsilon_p(t=T)} \cdot T \]  

\[ \eta_2 = E_2 \cdot \tau_2 \]  

\( \eta_2 \) can be described from the equation below

\[ \eta_2 = \frac{E_2}{\varepsilon_0} \cdot \tau_2 \]  

In order to calculate \( \tau_2 \), a distance of \( 0.63 \varepsilon_{\text{rel}}(t=T) \) is measured towards the y axis at \( t = 0 \) time from \( \varepsilon_0 \), firstly. Then, a parallel line is to be drawn with the tangent line of the \( \varepsilon(t) \) curve at \( t = T \) time.

The value of \( \tau_2 \) is found by drawing a vertical line at the intersection point between \( \varepsilon(t) \) curve and the parallel line drawn earlier.

Now the can be described, First step is to measure distance to the, then draw a parallel in this point with \( \varepsilon(t) \) curve’s asymptote \( (t = T \text{ time}) \). In order to get \( \tau_2 \) project, the section of this line and creeping curve to axis x. the value of

4. Results and Discussion

Figure (7) shows the clear creep tests results, indicating that the creep curves for twelve exactly similar cortical bone specimens when subjected to three different stress levels (25, 50 and 65) Mpa each stress tested in four different temperature (29, 35, 40 and 50°C) and to show the effect of difference temperatures on the creep behaviour of bovine cortical bones we draw each stress level at all temperatures that test with it. The increase of stress between zero and the already specified value can take between 3-5 seconds, when the strain may also increase in an elastically. The values of the initial strain for each specimen are showed in table (1).
Figure 7. Temperature effect on creep behaviour (A) at 25 MPa (B) at 50 MPa, (C) at 65 MPa.

Table 1. the values of the initial strain for each spaceman

| Temp. C° | Load 25 MPa | Load 50 MPa | Load 65 MPa |
|----------|-------------|-------------|-------------|
| 29 °C    | 0.032 %     | 0.064 %     | 0.089 %     |
| 35°C     | 0.04 %      | 0.08 %      | 0.1 %       |
| 40°C     | 0.043 %     | 0.083 %     | 0.104 %     |
| 50°C     | 0.046 %     | 0.089 %     | 0.11 %      |

It is noted that for all stresses and temperatures applied on specimens all exhibited the classical stages of creep curve which is primary, secondary, and tertiary in our work, the primary stage of creep curve is used to describe the behavior of bovine cortical bone. It is noted from table (1) that for all stress levels investigated the magnitude of initial strain increases with the increase of temperature as well as the increase of stress level.

Additionally, figure (7) shows that for all stress levels investigated, the duration of the first stage of creep curve is increase with the increase of stress level, but it decreases with the increase of temperature. Also table (2) show the creep strain rate which calculate according to the equation:

\[ \dot{\varepsilon} = \frac{d\varepsilon}{dt} \]  \hspace{1cm} \text{(8) [11].}

Table 2. the creep strain rate (\(\mu\varepsilon/\text{sec}\)) for all tests.

| Stress (Mpa) | Temp. (29°C) | Temp. (35°C) | Temp. (40°C) | Temp. (50°C) |
|--------------|--------------|--------------|--------------|--------------|
| 25 MPa       | 1.88         | 3.46         | 3.82         | 8.05         |
| 50 MPa       | 1.70         | 5.5          | 6.83         | 7.04         |
| 65 MPa       | 2.69         | 3.78         | 4.33         | 5.12         |

From this table (2) we noted that the creep strain rate was increased with the increase of temperature. From all these results, it is clearly that the high temperature effects on creep behavior of cortical bones
by decreasing the mechanical properties of it due to the decreased ability of the organics phase of the bone material (which responsible for viscoelastic properties of the bone) to carry on the stress, which is comes from a weakening of the linked between collagen fibrils at the higher temperatures [12].

For the Burgers model, the material parameter was determined by fitting experimental result of creep test (see [10]) table (3) show the material parameter for each temperature. This parameter is used to evaluate the strain verses time throw equation (2) and drawing theoretical creep curve. The relation between numerical and experimental strain for each stress level and temperature are presented in figure (8, 9, 10 and 11).

Table 3. Material parameter for each temperature.

| Temp. °C | $E_1$  | $E_2$  | $\eta_1$ | $\eta_2$ |
|----------|--------|--------|-----------|-----------|
| 29 °C    | 1.1607 | 39.39  | 22400     | 1378.65   |
| 35°C     | 1.031  | 28.888 | 68640     | 1386.62   |
| 40 °C    | 1      | 19.696 | 136500    | 878.835   |
| 50 °C    | 0.892  | 13.157 | 24400     | 473.652   |

By examining table (3) it is shows that the values of the parameters $E_1$ and $E_2$ decreases with the increase of the temperature, Also, the relationship between the values of the parameter $\eta_1$ and the temperature level are not clear and the values of $\eta_2$ in high temperature (40 and 50) °C, which is much less than its values in low temperature (29 and 35) °C.
**Figure 8.** Relation between numerical and experimental strain at 29°C (A) stress 25 MPa (B) stress 50 MPa and (C) stress 65 MPa.

**Figure 9.** Relation between numerical and experimental strain at 35 °C (A) stress 25 MPa (B) stress 50 MPa and (C) stress 65 MPa.
Figure 10. Relation between numerical and experimental strain at 40 °C (A) stress 25 MPa (B) stress 50 MPa and (C) stress 65 MPa.
Figure 11. Relation between numerical and experimental strain at 50 °C (A) stress 25 MPa (B) stress 50 MPa and (C) stress 65 MPa.

The Burger creep curves shows strain gradients in first stage of creep curve, thus it is adequate to describe rheological properties of bone.

The error of the fitting of theoretical creep curves to experimental curves does not exceed 8.8%. Figure (10) C considered good agreement between the experimental and theoretical creep curves reaching up to (99.11% - 100%). Figure (10) A can be considered as the lowest form of agreement among all experimental and theoretical results reaching up to (91.2% - 92.6 %).

In general, with the increase of the load applied, the agreement between the experimental and the theoretical results which optioned from Burgers model is increase.

5. Conclusions:
The creep behavior of cortical femur bone was investigated in this paper. A uniaxial tensile creep test was conducted on similar twelve specimens. The results of experimental investigations of the creep strain versus time curve is compared with the theoretical results obtained from using Burger model.

Results showed the Bone exhibited creep behavior at room temperature as well as at high temperature unlike metals that exhibited creep behavior only at high temperature. The four- element model (Burger model) is used for the predicting of the creep behavior of bovine cortical bones with good agreement.

The material parameter was determined by fitting experimental result of creep curve. The temperature effects on creep behavior of bovine cortical bones, in general With the increase of temperature the initial strain was increase , The duration of the first stage of creep curves are decrease and The creep strain rate \( \varepsilon = \frac{d\varepsilon}{dt} \) was increased with the increase of temperature.

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