The Effect of Temperature on Stress Relaxation Behaviours in Bovine Cortical Bones

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Abstract: Stress relaxation is defined as the decay resulting from stress placed upon a material exposed to constant strain. Stress relaxation equipment designed and manufactured according to ASTM E328-86 was thus created to test this type of decay. Samples were extracted from animal femurs, in particular cortical bones from bovine around 24 months in age. The effect of various temperature on the stress relaxation behaviours of bovine femur samples was thus studied. The samples were examined for 1,800 seconds under the influence of three degrees of stress (25, 50, and 65 MPa respectively), with different temperatures of 29, 35, 40, and 50 °C used for each stress level; the stress results and diagrams for the effects of each stress were recorded and drawn separately.

Keywords: stress relaxation, cortical bone, viscoelasticity, creep

1. Introduction

Viscoelasticity characterises the time-dependent mechanical properties of materials. Bone is considered to be a viscoelastic material, referring to its ability exhibit both elastic and viscous behaviours. Viscoelastic material measurements are thus essential in the process of quantifying bone mechanical properties, and one of its important behaviours is stress relaxation. The information obtained about bone material properties from studying this may be useful for creating individualized surgical treatment, for instance by adapting implant design preoperatively to enhance the interface between the bone and implant [1].

Fixation of fractures that may occur in patients' cortical bones can present a significant challenge to orthopaedic surgeons, as creating sufficient fracture fixation stability to allow patient mobilization may prove difficult. Where stability can be quantified, it can then be used as a measure for the rigidity of fracture fixation equipment used for the treatment of fractures in cortical bones. Bones creep and relax during daily activity, and thus examination of time-dependent performance under stress is particularly important [2].

The number of knee replacement surgeries in the US has reached up to 600,000 per year, making it one of the most common, though costly, surgical operations. Among the significant presentations for the failure of the mechanism is implant loosening as a result of loss of fixation of the bone and implant interface. The most likely reasons for such loosening is creep deformation and stress relaxation of the bone [3].

Creep and stress relaxation are two fundamental criteria that describe time dependent behaviours of viscoelastic materials. Creep refers to increase in strain under loading, while stress relaxation refers to decrease in stress when the displacement is held constant. Biological materials usually experience creep or stress relaxation due to low repeated loading in daily life. Synthetic composite bones are often used and tested to simulate the mechanical behaviour of human bones. However, Papini et al. [4] showed that osteoporotic synthetic specimens more closely resembled normal healthy human bones than osteoporotic ones [4]. Salas [5] showed that synthetic osteoporotic bones do not display the same failure patterns as human cadaveric specimens, suggesting a real need to produce composite bones that have similar behaviours to both normal and osteoporotic bones. In order to develop such synthetic bones, the viscoelastic properties of bones must be more thoroughly understood and quantified, and previous studies have shown that viscoelastic behaviour represents a fundamental component of both tissue and bone behaviour [6-9]

This work thus reports experimental observations of relaxation experiments of cortical bones under loading and the effects of different temperature on the stress relaxation behaviours. This further illustrates bone's behaviours under such testing, with or without temperature changes.

2. Experimental Procedures

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

2.1. Stress Relaxation Rig

The stress relaxation equipment was designed and manufactured according to ASTM E 328-86 [10] to handle a full range of stress relaxation tests for different materials. The stress relaxation rig consisted of the following parts:

1. Frame
2. Clamps
3. Load cell (Temperature range -30 /+70 °C) and load indicator.
4. Load applying device
5. Dial gage holder
6. Dial gage (allowable temperature < 100 ˚C), as show in the figures 1 and 2.

Figure 1. the Stress Relaxation Rig

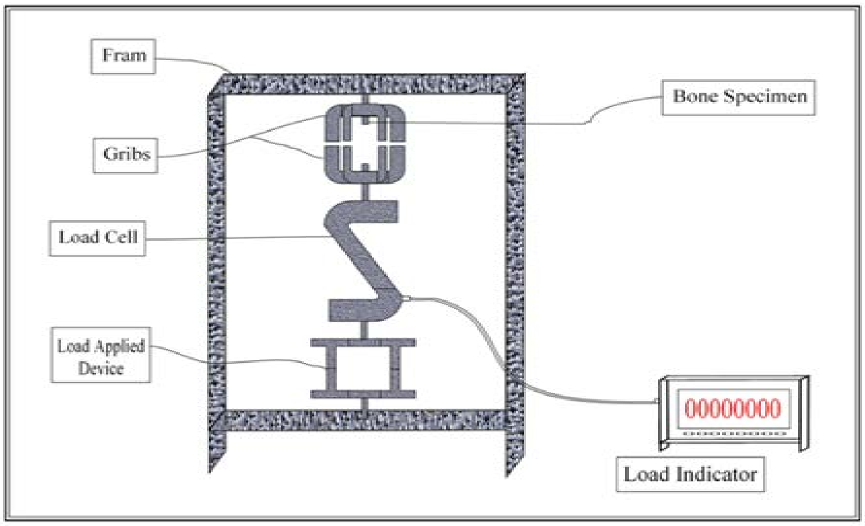


Figure 2. Sketch showing Stress Relaxation Rig

2.2. Electric furnaces

Additionally, an electric furnace was designed and manufactured for testing, featuring
1. Aluminium frame with dimensions 50 x 50 x 50 cm
2. Aluminium sheets
3. Thermal insulator (Rock wool)
4. Electrical fan
5. Electrical heater
6. Temperature control (measurement probe located close to bone specimen as shown in figure(3).

Figure 3. Electric furnaces

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).

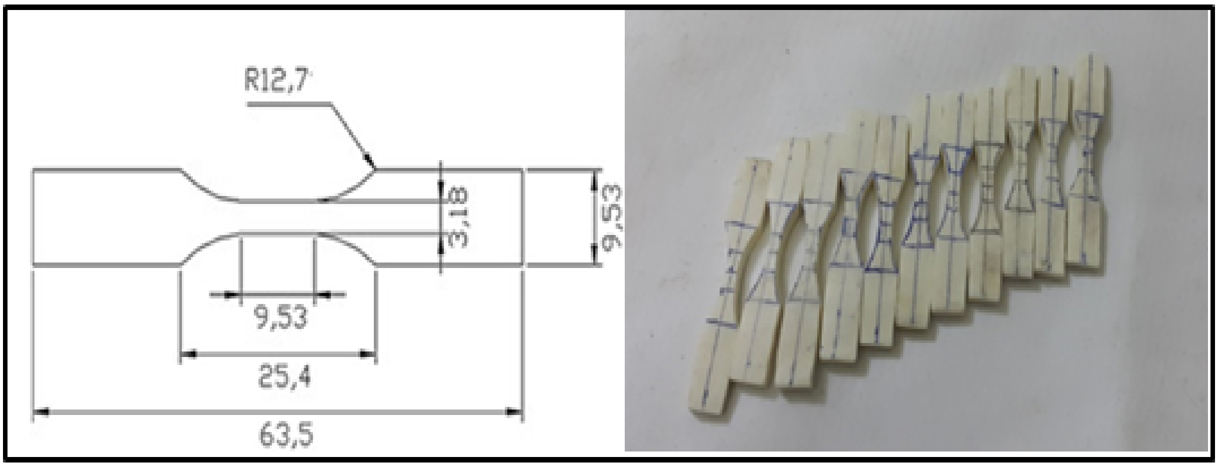


Figure 4. The dimensions of the stress relaxation specimens in millimetres based on ASTM D638 [9].

Figure 5. Cleaning the soft tissues from the femur bone and cutting rectangular specimens along the bone axis.

3. Testing
3.1. Stress relaxation test

A sample was placed inside the manufactured examination device using the grips, and the oven was turned on until it reached the required temperature; it was then left to settle to temperature for a few minutes. After that, the sample was subjected to load gradually until the required load level was reached; the readings of the load indicator were documented throughout using a digital camera.
A simple equation

$\sigma(t) = (F(t))/A$ …………… (1)

was used in this work to calculate the stress at a particular time by dividing by the load (based on the load indicator reading) on the cross-section area of the narrow section of the specimen, then drawing the relaxation curves between stress and time, as seen in figure 6. Stress levels below the yield stress, namely 25, 50, and 65 MPa were used, where yield stress was 92 MPa [12], and each stress was tested at four temperatures (29, 35, 40, and 50 °C) as in [13].

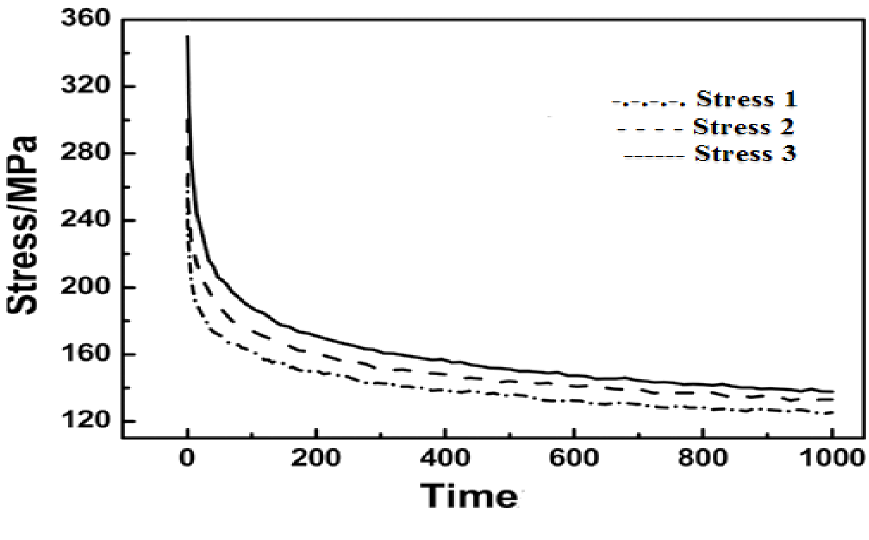


Figure 6. The typical stress relaxation curves [14]

4. Results and Discussion

Figures 7, 8, and 9 show the clear stress relaxation test results with relaxation curves for the twelve similar cortical bone specimens subjected to three different stress levels (25, 50, and 65 MPa), with each stress tested at four different levels of temperature (29, 35, 40, and 50 °C). The values of the percentage of remaining stress after relaxation for 500 seconds ranged from 91.9% to 98.92% of the applied stress. Table (1) shows the values of the percentage of remaining stress for all relaxation tests.

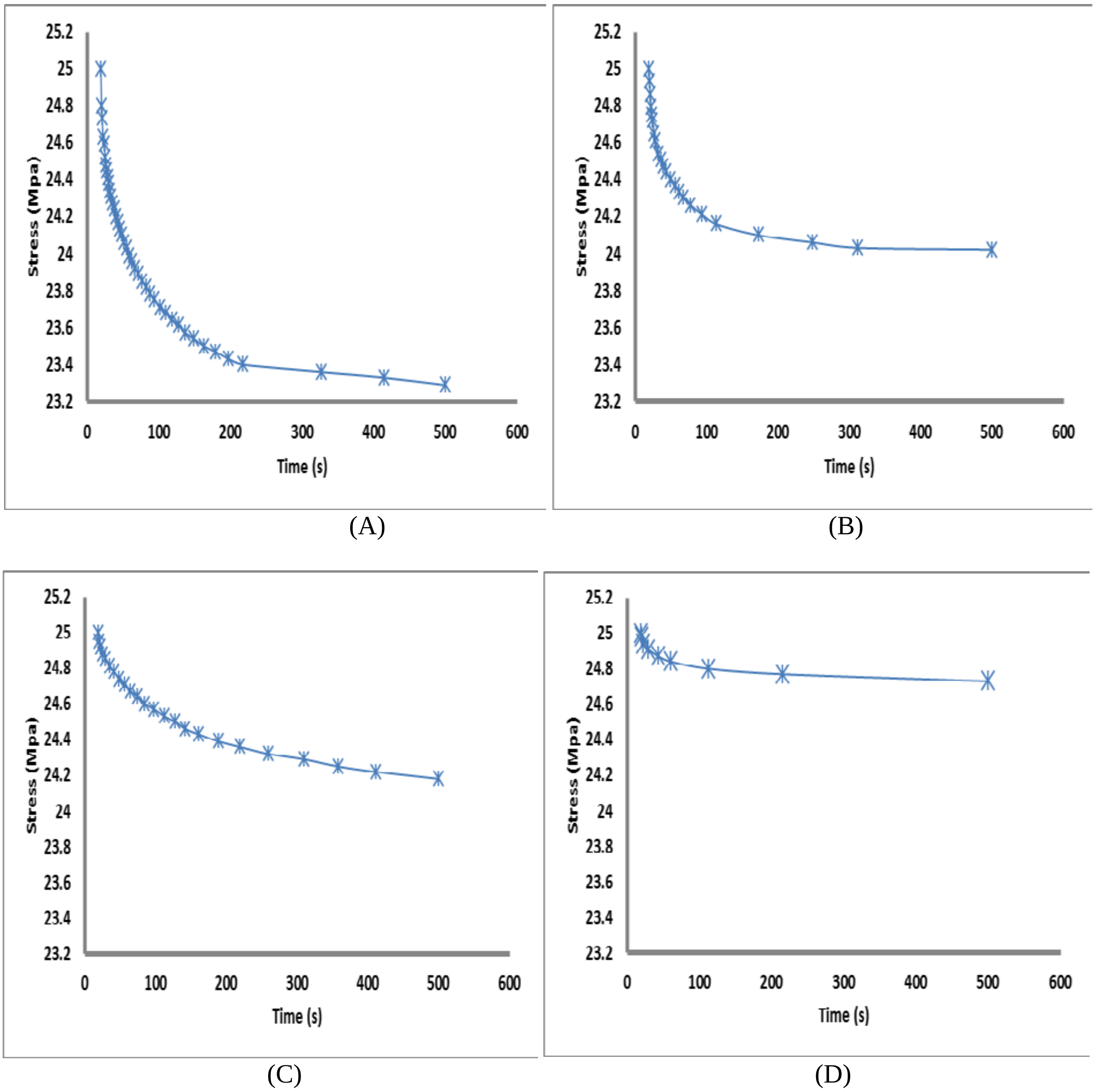
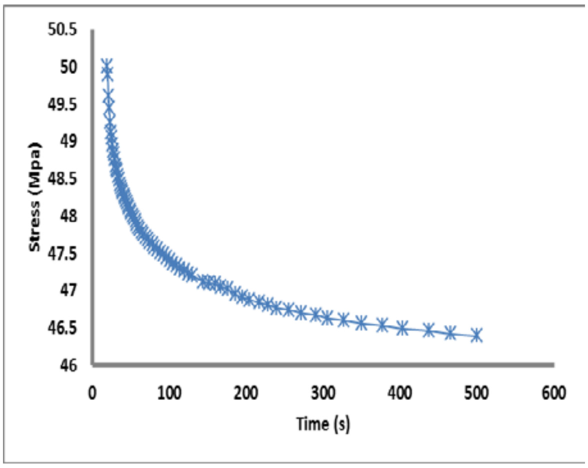
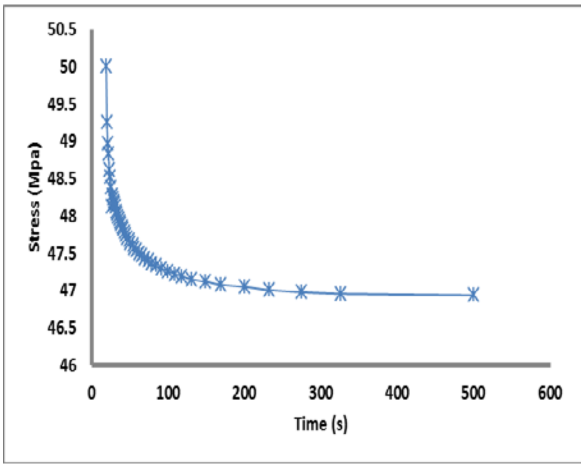


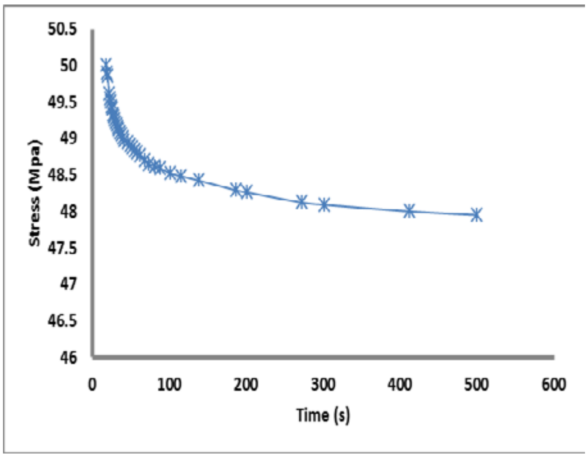
Figure 7. Comparison between stress relaxation in 25 MPa load (A) at room temp. of 29 ºC (B) at 35 ºC, (C) at 40 ºC and (D) at 50 ºC.



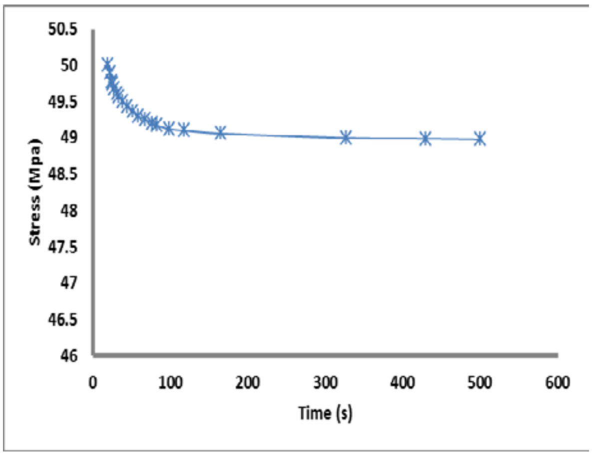
(A)



(B)

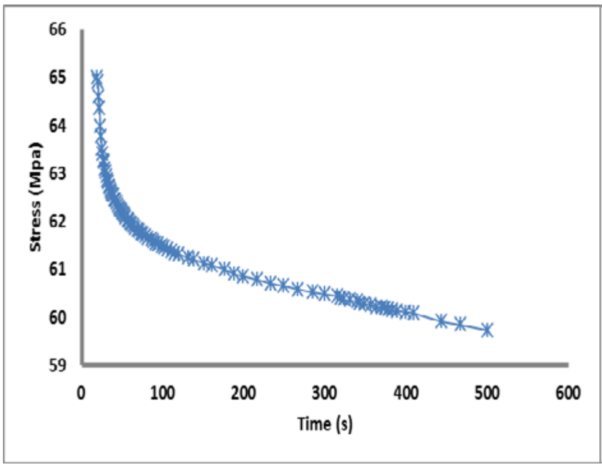


(C)

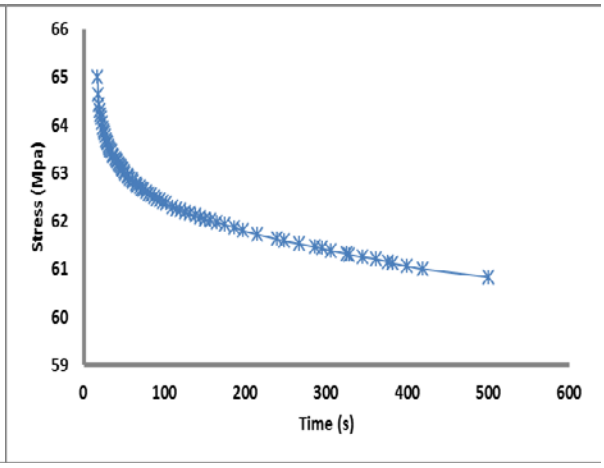


(D)

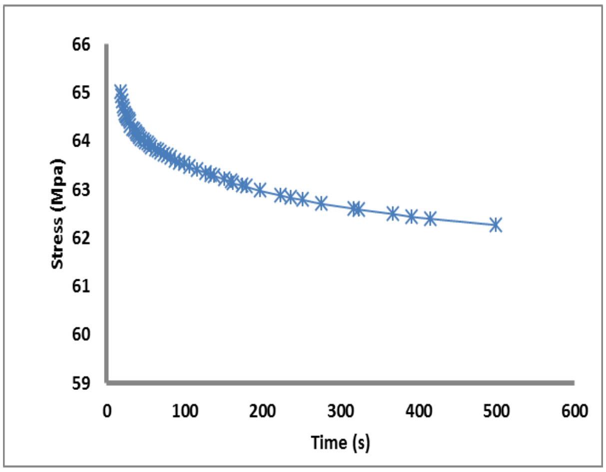
Figure 8. Comparison between the Stress relaxations in 50 MPa load. (A) At room temp. 29ºC (B) at 35ºC, (C) at 40 ºC and (D) at 50 ºC.

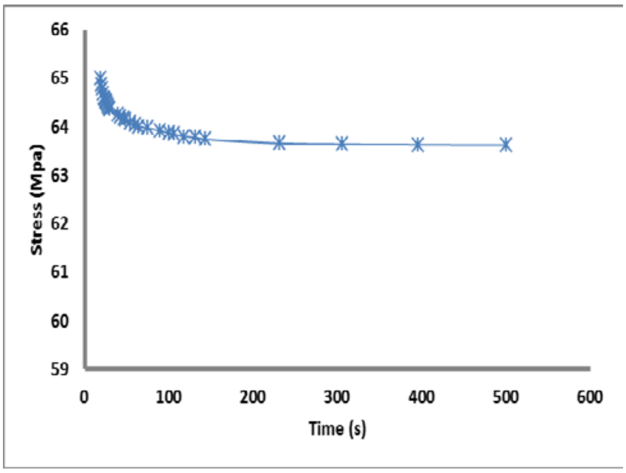


(A)



(B)





(C) (D)

Figure 9. Comparison between stress relaxations in 65 MPa load. (A) At room temp. of 29 ºC (B) at 35 ºC, (C) at 40 ºC and (D) at 50 ºC.

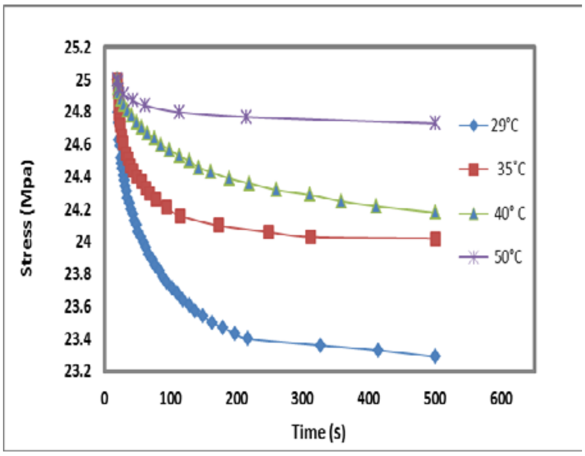
Table 1. The percentage value of remaining stress for all relaxation tests

Stress (MPa)	Temp. °C	Percentage of remaining Stress after (500 sec.)
25	29	93.16%
	35	96.08%
	45	96.72%
	50	98.92%
50	29	92.78%
	35	93.88%
	45	95.9%
	50	97.96%
65	29	91.9%
	35	93.59%
	45	95.79%
	50	97.88%

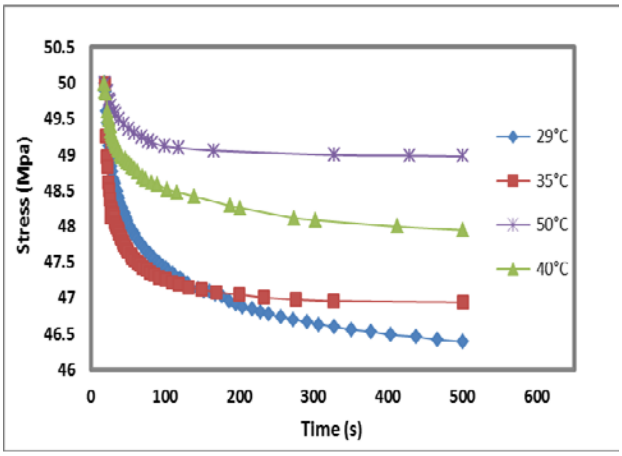
In this work, testing was done for 1,800 seconds, but to describe the behaviour of bovine cortical bone only 500 seconds are used due to the nature of the relaxation phenomena for cortical bone, which occurs very slowly after this point.

From table 1, it is clear that for all stress levels investigated, the magnitude of stress absorption by the bone material was increased with the increase in applied stress level but decreased with the increase of temperature. It can also be noted that the stress relaxation rate decreases with the increase of stress level and temperature applied.

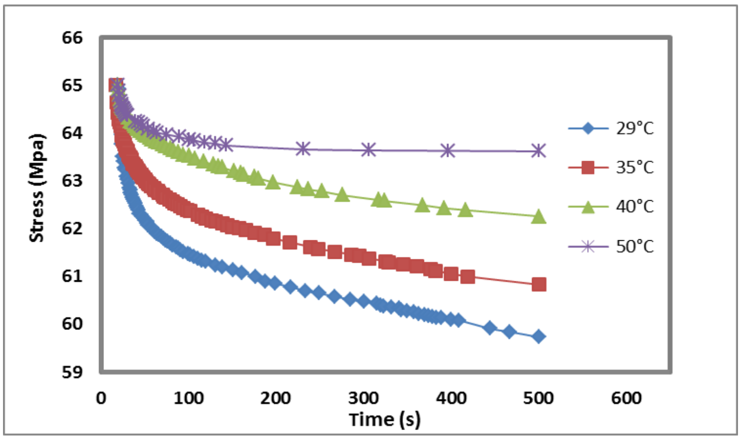
Figure 10 shows a comparison between the relaxation behaviours in different temperatures for all stress levels.



(A)



(B)



(C)

Figure 10. Influence of temperature difference on relaxation curves at (A) 25 MPa (B) 50 MPa, and (C) 65 MPa.

For the 25 MPa load, with the increase of the temperature, the percentage of stress absorption from the applied stress by the bone material was decreased from 6.84% at 29 ˚C to 1.08 at 50 ˚C; for the 50 MPa load, with the increase of temperature, the percentage of stress absorption by the bone material was decreased from 7.22% at 29 ˚C to 2.04% at 50 ˚C; and for the 65 MPa load, with the increase in temperature, the percentage of stress absorption by the material of the bone was decreased from 8.1% at 29 ˚C to 2.12% at 50 ˚C.

5. Conclusions

Based on the experimental tests, several major conclusions can be drawn:

1- Temperature has an influence over the stress relaxation behaviours of femur bovine cortical bone.
2- Increase of temperature leads to a reduction in the bone's ability to absorb part of the load applied to it, resulting in a reduction in stress in general.
3- Whenever the heat increases, the stress relaxation rate decreases; this also decreases with any increase of stress level.
4- Although the variation in human body temperature is very low, the results suggest that increasing the temperature will decrease the percentage of lost implants due to a decrease in the stress relaxation ability of the bone.

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