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STEPPED-ISO-STRESS APPROACH FOR BIBOLO: Dibetou (*Lovoa Trichilioides*)

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***Abstract*— Wood based structures are required to have long life spans which can be as high as 12 decades. Conventional creep testing to obtain performance data for such long periods is cumbersome and difficult. An accelerated technique, the Stepped Iso-Stress Approach (SISA), which allows accelerated testing of materials to determine their creep response in a few hours, is presented. Creep strain is recorded as a function of time and the stress is increased step-wise after 3 hours creep periods.**

The creep curves at different stress levels can be shifted along the time axis to generate a single curve known as a master curve, from which long term performance data can be obtained. The technique, needed to obtain a smooth master curve is explained. The procedure in SISA is similar to the more familiar Stepped Iso-Thermal Method (SISTM) but the acceleration is now obtained by increasing the stress in steps rather than stepping the temperature. An additional stress provides energy to the system in an analogue of the effect of heat in SISTM.

SISA relies on the time-stress superposition principle concept. Various theories, assumptions and the different steps of the method are described. This method is advantageous over SISTM because there is no need to use elevated temperatures, which may affect the chemical properties of the tested materials. The applicability of the method is investigated.

The activation volume is determined and found to vary with stress level.

This paper presents testing on Bibolo, Dibetou (Lovoa trichilioides) using (SISA). The resulting creep curves are similar to those obtained from conventional creep testing.

The ability to carry out reliable creep tests in a reasonable time at low stress levels allows the designer to have much more confidence in the performance data and allows confident prediction of structural lifetimes.

***Index Terms*—** Dibetou (Lovoa trichilioides), Stepped Iso-Stress Approach, accelerated testing, activation volume

I. INTRODUCTION

The economic potential of the forests in countries of the south where profitable conifers are hardly available has been poorly evaluated. A scientific study and transformation of local wood species is therefore important in order to enhance the sustainable exploitation of the forests, resulting in the maintenance of the natural resources of the countries concerned [1]. Apart from the protected rainforests, there are huge warm regions which yield exploitable useful timber like the Bibolo, Sapelli, Beté, eucalyptus and so on [1].

Timber and forestry exploitation make a substantial contribution to the economy of those countries possessing large forest reserves, but these forests remain largely unexploited.

Wood is a fascinating material in terms of both its structure and mechanical performance. Wood is a low-density cellular polymeric composite and consequently does not fall into any one category of material [2].

Wood is of vital importance as a structural engineering material; during the last few years, wood-based panel products have been more and more frequently used as structural components, not only as shield materials but also as load carrying elements of composite beams [3, 4].

Poor durability can have serious consequences on the safety, serviceability, utility and virtual performance of structures. Timber structures are particularly vulnerable to damage from moisture, ultra violet light, insects and fungi [5].

Traditional design and construction practices are being replaced by reliability based design, so that it becomes necessary to establish a long term performance for wood to account for its time-dependent behaviour.

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The wood market is facing strong competition from other materials like wood-plastic composites because of its poor utility performance, which results from the fact that the mechanical and physical properties are not well mastered. These properties are thought to be dependent on load bearing and duration of loading among others.

The design of composite structural elements requires knowledge of elastic and strength properties, and of the creep behavior of used materials [3].

A study of the mechanical performance of wood will add value to this material in building constructions and increase its feasibility in facing the competition with materials like PVC, PP composites in a race to be the preferred structural material [1,3,4].

For timber to resist the challenge from new materials like WPCs, a proper evaluation of mechanical and performance properties of wood must be made, to determine its future in increasingly demanding applications.

During the design and development of any material product it is necessary to ensure efficient material utilization, in order to avoid an intolerable degree of deformation or premature failure. This requires a good understanding of the mechanical behaviour of the materials involved [6].

Required structural life times of wood structures vary and can be as high as 12 decades [7] and the prediction of long term behaviour becomes an issue of concern.

If wood has to retain its role as a leading structural engineering material then a thorough knowledge of its time-dependent mechanical behaviour, and especially its long-term performance are crucial for structural designers [8].

Wood is termed viscoelastic as it displays both viscous and elastic types of behaviour. As a result, stress is proportional strain, strain rate, and possibly higher time derivatives of strain [9].

Viscoelasticity in general can be influenced by many factors such as temperature[10], physical aging[11] and R.D. Bradshaw[12,13] pressure, damage[8], solvent concentration[14,15], strain [8,16], stress level[8, 17-19], moisture(humidity)[8]. Among them, temperature and stress are the two most important factors for load-bearing polymeric materials [8]. Early studies on the mechanical behaviour of wood were mainly based on the linear viscoelastic theory, which has been elegantly developed [20].

If the material is linear viscoelastic, the Boltzmann superposition principle can be used to predict the deformation of polymeric solids subjected to arbitrary time-dependent loads [21]. This is generally true for cases in which the applied stresses are sufficiently small to have a negligible effect on the material's properties. However, at higher stresses, most polymers exhibit nonlinear viscoelastic behaviour due to the fact that stresses change the distribution of relaxation times to shorter times; that is stresses change the material's intrinsic timescale. W.N Finley et al.[21] have proposed a modification to Boltzmann superposition principle to account for the effects of elevated stresses. Bibolo wood has been shown (in a separate article of ours) to exhibit nonlinear viscoelasticity at 9.19 MPa and above.

With regard to the temperature effect on viscoelasticity, the well-known Time-Temperature-Superposition Principle (TTSP) states that the mechanical behaviour of viscoelastic materials at different time scales can be made equivalent by changing their service temperatures. TTS concept has been extensively used in the past to predict creep behaviour of polymers [22-24].

Acceleration by changing the temperature works because energy is supplied to overcome the resistance to creep, but that energy can also be applied by increase in stress.

The stress effect has also received much attention in recent years, and the Time Stress Superposition concept (TSS) has been proposed and used to predict the creep behaviour of various polymeric materials.

Various researchers [21, 25] have performed creep tests at various stress levels and at ambient temperature conditions, and have constructed a master curve at a reference stress level using the Time-Stress Superposition Principle (TSSP).

Lai and Bakwer[19] performed creep tests on polyethylene specimens at various stress levels and at ambient temperature, and constructed a master curve at a reference stress using a time-stress superposition principle (TSSP).

Hadid et al [25] carried out creep tests on fiber glass reinforced polyamide specimens at various stress levels; the duration of each test was 30 minutes and by combing the results they constructed a smooth master curve at reference stress. Jazouli et al [21] studied the creep behaviour of polycarbonate by testing various specimens at room temperature under various sustained loads for only 1 h. They then used these to construct a smooth master curve for 1 year.

The effect of stress on creep was also modelled by Yeow et al [26] using a superposition methodology known as Time-Stress-Superposition Principle(TSSP), that is similar to TTSP.

Creep curves obtained at different stress levels and at constant temperature are shifted horizontally to a reference stress value with respect to time. Here, a shift factor(a_σ) is defined as the ratio of the time(t) to reach a particular value of creep compliance /modulus/creep at some higher stress level to the time(t_R) to reach the same compliance value at a reference stress level.

By analogy with the activation energy, where heat provides the energy needed for creep to occur, TSS assumes that stress can supply energy. This leads to the concept of an activated volume. When the stress changes in the course of creep, this is called stepped loading.

Based on the methods described above a different accelerated method, called the Stepped Iso-Stress Method (SISA) [8,7] has been suggested to predict long-term creep behaviour of Bibolo, Dibetou. This method involves loading a single specimen, instead of many specimens required in TSSP.

This single specimen is subjected to a series of timed isostress exposures at elevated stress levels in a stepped fashion under constant temperature (the ambient temperature of the lab). At each stress step a creep curve(strain versus time) is obtained; these can be adjusted to compensate for the different stress levels and a creep master curve at a reference stress level is produced.

A stress-rupture point can be determined as the very last point of each master curve [7].

A number of adjustments may be needed for each SISA test to produce a single creep master curve [8]. The actual number will depend on the creep test machine and procedure. Ioannis et al. [6] used four different adjustments (initial vertical adjustment, vertical shifting, rescaling and horizontal shifting). These adjustments are described in more detail elsewhere [27].

In this work three adjustments were made: vertical shifting, rescaling and horizontal shifting.

The Boltzmann superposition principle and Eyring equation provide justification for rescaling and horizontal shifting of the creep curves obtained at each isostress exposure in order to produce a creep master curve at a reference stress [8]. The use of a single specimen minimises concerns about specimen variability and handling effects. TSSP needs more specimens and more handling. SISA can be automated and takes less time than TSSP, so offers several advantages.

Ioannis et al. [7] used this method to predict very well, long-term behaviour and creep failure of aramid fibres. In their case the last stress level was maintained until creep failure. In our case the loading machine did not allow very high stress levels. Though all specimens had the same dimensions and the specimens were held in the same grip, differences could arise due to wood anisotropy.

A similar method has been applied in the past by Farquhar et al.[28] to develop creep-rupture properties of single IM6 carbon fibres, though without focusing creep itself, and using a power law(Weibull stress vs. lifetime) framework.

Long term creep behaviour of material can be determined in two ways. Tests can be carried out at very high stress levels (> 60 % of breaking load) in short time periods and then extrapolated for lower stress levels [29-39]. The extrapolation introduces many uncertainties [7].

Alternatively, accelerated creep testing can be carried out at low stress levels in such a way that the long-term creep and creep-rupture properties can be determined within shorter time scales.

The creep rate is accelerated, thus reducing the time needed for a given amount of creep to occur; failure of the specimen can then take place in practical timescales.

Two accelerated methods make use of the effect of temperature to creep rate [7]. Using the time temperature superposition principle(TTSP), which usually assumes that creep is a thermally activated process, multiple specimens are tested under a constant load at different temperatures resulting in separate plots of creep strain versus log(time) at different temperatures. A reference temperature is then selected, usually close to ambient, and all individual curves are shifted along the log (time) axis to compensate for the different temperatures. By applying the principle of superposition a creep master curve is produced.

The second temperature-accelerated method is the stepped isothermal method (SITM) which was first used by Thornton et al [24] to predict the long-term creep behaviour of geogrids in soil reinforcement applications. Later, Alwis and Burgoyne [22] applied this method to high modulus yarns.

SITM involves loading a single specimen under a constant load. The temperature is then increased in a step-wise fashion, either until sufficient creep has occurred or the specimen fails. By applying a series of corrections, which account for the stepping of the temperature and the different degrees of creep at each stage, a single response curve known as the master curve is obtained which predicts the long term behaviour.

SITM testing relies on the knowledge of an activation energy which has to be constant at all temperatures to show that the same creep mechanism is occurring.

This research is intended to:

- Assess the short term creep behaviour of Bibolo wood material in a pure loading mode (i.e. bending in a 4-points loading).
- Investigate the stress effect on the creep behaviour of Bibolo wood in a stepped stress fashion.
- To predict the long-term creep behaviour of Bibolo wood using an accelerated technique called the Stepped Iso-Stress Approach (SISA).
- To obtain master curves from short term creep tests.

The work is important because SISA offers several advantages when compared to the other existing methods. In addition the master curves developed can be used to predict the long term behaviour of solid Bibolo lumber for various stresses. This can be useful:

- To compare the long behaviour of different woods and of different structural lumber products.
- As a tool in the development and evaluation of new wood products like composites

II. THE STEPPED ISO STRESS APPROACH (SISA)

This method involves loading a single specimen, instead of the many specimens required by TSSP.

In the SISA, a specimen is allowed to creep under a constant stress, σ_1, for a period of time, t_1. Without unloading or retracting any part of the stress the specimen is allowed to continue to creep under a higher constant stress, σ_2 for a period of time, t_2. The procedure is repeated for other higher stress levels as the need may be. This similar to the stepped isothemal approach, in which a specimen is subjected to a step-wise increase in temperature. During the creep at each stress level the time-dependent strain is recorded as a function of time and a creep curve (strain vs. time) is obtained; these can be adjusted to compensate for the different stress levels and a creep master curve at a reference stress level is produced. The *reference stress* is the stress level at which it is desired to construct the creep master curve. The other stress levels are referred to as *accelerating stresses*. In this work the lowest stress was taken as the reference stress, but it is not a rule. A creep-rupture point could be determined as the very last point of the creep master curve[7].

A number of adjustments may be made on the data to obtain a master curve. The number depends on the loading machine and the test material. Some of these are explained in detail elsewhere and include vertical shifting, rescaling and horizontal shift [7, 27]. They are summarised below.

The use of a single specimen minimises concerns about specimen variability and handling effects. Furthermore, this method can be automated and takes less time than TSSP, so offers several advantages [7].

Vertical shifting

At each stress jump ($\sigma_{1(tj)}$ to $\sigma_{2(tj)}$) there occurs an immediate increase strain from $\varepsilon_{(\sigma1(tj))}$ to $\varepsilon_{(\sigma2(tj))}$ due to the elasticity of the material (Fig.3). Since the jump is almost instantaneous, there is no additional creep strain during the jump. The creep curve at stress σ_2 after the jump must be shifter vertically to remove the elastic strain, so that the final master curve is a purely creep curve. The vertical shift can be determined graphically, so that the last point before the jump coincides with the first point after the jump. This method deals with the real elastic strain of each test. The elastic strain is, $\varepsilon_{elastic} = \varepsilon_{(\sigma2(tj))} - \varepsilon_{(\sigma1(tj))}$

Rescaling

After the vertical shifts the creep curves from the various stress levels are shifted to the left so that it starts from a point where it would have started if it had not been previously loaded. This process is known as rescaling and takes the form of a horizontal shift along the linear time axis of each creep curve at higher stress levels. The breaking down of the SISA curve into a set of rescaled creep curves, each of which would have been obtained from TSSP tests, is valid according to the Boltzmann's superposition principle. The point for each stress level can be obtained graphically.

Horizontal shift

Rescaling results in a series of curves, each of which represents part of a conventional creep curve that would have been obtained from different specimens at different stresses. They are thus the same as those that could have been obtained in separate TSSP tests. They must be shifted along the logarithmic time axis to obtain a creep master curve at a reference stress σ_R. The magnitude of this horizontal shift is a function of the stress and is similar in principle to the shift in TTSP testing where tests are carried out at different temperatures and the shift is a function of temperature.

III. ACTIVATION VOLUME, V*

Two relationships have been developed to determine the effect of stress on the rate of creep, and hence on the required shift; these are based on (a) the Eyring equation and (b) the modified WLF (Williamson-Landel-Ferry) equation. The choice between these two approaches depends on whether the temperature applied is below or above the glass transition temperature, Tg [37]. Since Bibolo and wood in general are solid (crystalline) polymers which display no glass transition temperature [40], it is expected to follow the Eyring equation, whose general form is:

$$k = \frac{RT}{h} e^{-\frac{\Delta G}{RT}} \qquad (1)$$

ΔG is the Gibbs free energy of activation, h is Planck's constant, R is the universal molar gas constant and T is the absolute temperature.

This leads to the following strain rate relationship [37]:

$$\dot{\varepsilon} = \dot{\varepsilon}_0 e^{-\frac{U}{RT}} . e^{\frac{N_A V_\sigma^*}{RT}} \qquad (2)$$

where, V_σ^* is the stress coefficient and is referred to as the activation volume since it has the dimensions L^3, U is the activation energy, N_A is the Avogadro constant and T is the absolute temperature. This derivation assumes that the activation energy remains constant. Equation 2 can be rearranged by comparing the ratio of the strain rate $\dot{\varepsilon}_1$ at stress level σ_1 to strain rate $\dot{\varepsilon}_2$ at stress level σ_2, both measured at the same temperature T, as follows:

$$\mathrm{Ln}\left(\frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2}\right) = \frac{V^* N_A}{RT}\left(\sigma_1 - \sigma_{2)}\right) \quad \Rightarrow \quad \log(\alpha_\sigma) = \frac{V^* N_A}{2.03\,RT}(\sigma - \sigma_R) = \frac{V^*}{2.30\,kT}(\sigma - \sigma_R) \qquad (3)$$

The shifting factor α_σ is the ratio between the time for a viscoelastic process to proceed at an arbitrary stress level and the time for the same process to proceed at a reference stress level:

$$\varepsilon_R(\sigma_R, t) = \varepsilon\left(\sigma, \frac{t}{\alpha_\sigma}\right) \qquad (4)$$

where ε_R is the strain at the reference stress σ_R, t is the time, ε is the strain at the elevated stress level σ.

Both the rescaling and the logarithmic shifting can be done graphically or use a numerical procedure at each stress step so that a sufficiently smooth creep master curve is produced.

The horizontal shifting along the logarithmic time axis will allow the stress shift factors to be determined from the test results, and the corresponding activation volume to be determined. The master curve should be independent of the sequence of steps used in its determination. Thus, another check on the validity of the method would be to compare the master curves produced using different stress steps [7]. Here, we used the same stress steps due to the limitations of the testing machine.

IV. MATERIALS AND METHOD

4.1 MATERIAL SAMPLES AND SPECIMEN PREPARATION

Test specimens were cut from seasoned Bibolo(Lovoa trichilioides) wood with the length along the fibre axis(trunk grain axis) and with the width and thickness dimensions in the radial and tangential directions of the trunk.

Each of the specimens was sawn to the dimensions 34 cm x 2 cm x 2 cm. The specimens were ensured to be straight, smooth, and free from external defects like twists, cracks, splits, knots, fungi and insect effects. The absence of deep internal micro defects could not however, be guaranteed. The straightness and smoothness were achieved using a planer machine. A specimen's length, width and thickness were measured at five different locations on the sample to account for dimensional variations along the length or thickness of the specimen. The averages of these measurements were taken and verified to be extremely close to the specified required dimensions. The smaller dimensions were measured using a micro meter screw gauge and the length measured using a graduated rule.

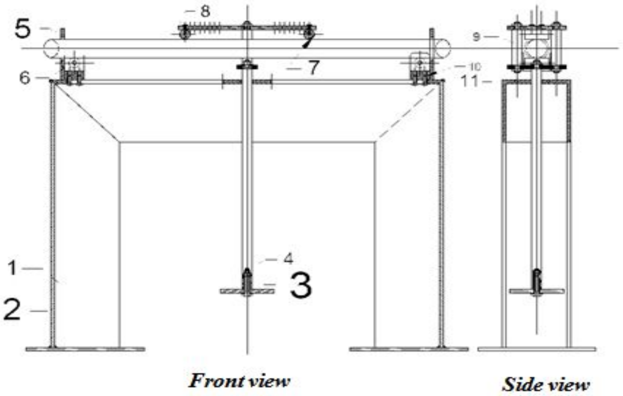


Figure 1. Bending creep testing device

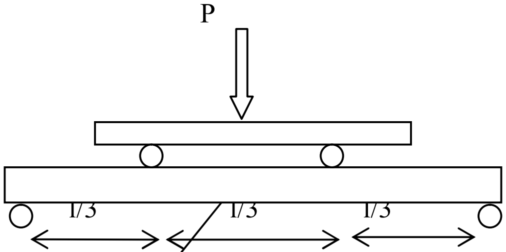


Figure 2. A typical four-point bending setup

Maximum stress and strain creep value

4.2 TEST SET UP

The test setup is shown in fig.1. The creep test machine was constructed in the engineering school, IUT-FV, of the University of Dschang. It was conceived and supervised by the director of the school.

The test equipment is an inverted rectangular U-shaped steel frame, with each of its arms having a heavy flat metal base that ensures stability and support. There is a metal rod-dipper device going vertically along the centre axis, and attached to a flat metal plate bearing two steel cylindrical pipes, each of radius 2.11 cm, which serve as the load application points, spaced at a convenient chosen span length, l. The vertical metal rod ends at its bottom point on a flat rectangular plate such that the combined system can carry masses by placement or by slotting.

The top part of the inverted rectangular U-shaped frame contains devices including another pair of fixed cylindrical steel bars which serve as supports on which the specimen is placed.

The static load is provided by mounting dead weights (or slotted masses) on the base of the vertical rod and along the rod. The system comprising the vertical rod bearing the dead weights and the two load application cylindrical steel bars converts the gravitational load into a tensile force pulling downward.

The loading force is converted into loading stress in MPa (or Pa).

The test specimen is maintained in place to allow no longitudinal and lateral movement. This is assured by the weights applied, the vertical support on the specimen and the screwed metal pieces at the horizontal ends of the apparatus.

Two strain gauges are glued fixed at the middle centre length of the specimen, one on the upper surface and the other on the lower surface of the material such that each is longitudinal to the fibre axis of the specimen. The strain gauges were of the type CF-350-20AA-C(II)-20, with a GF: 2.4(ie gauge factor 2400), impedance: 350 Ω, length: 20 mm and made from metal foil.

These sensors are then connected to a digital strain bridge interface, DELTALAB EI 616 which has a possibility of six entry channels. The strain is read from the strain bridge and recorded manually in units of µm/m, at various time instants. The time instants are read from a digital time piece, KADIO KD-617 while the environmental humidity is read from a digital electronic Thermo-hygrometer (with indoor-outdoor display), an Oregon Scientific instrument, model ETHG 913 R.

All loadings were in a four-point loading mode. In this mode, the maximum strain occurs at the bottom surface mid-span of the specimen.

4.3 ACCELERATED CREEP TESTS (3 h).

Creep tests were conducted on Bibolo specimens for durations of 3h at different stress levels. Specimens BIB1 to BIB 6 and 27 were used for accelerated creep tests in step loading at constant creep time of 3 h and at four different stress levels: 11.03 MPa, 16.54 MPa, 22.05 MPa, 27.56 MPa, and BIB 27: 9.19 MPa, 14.70 MPa, 20.21MPa, 25.73 MPa.

4.4 METHODOLOGY

In order to obtain a relationship between the creep deformation and the different stress levels, we tested a number of specimens, and the stress level was increased in steps.

Creep tests were carried out in the flexural mode. A flexural creep testing rack (Fig.1) was designed based on ASTM D 6112[41]. ASTM uses the four-point loading configuration (Figure 2). The span length for the test was 300 mm. The noses of both the support and loading beams were configured with cylindrical surfaces with a radius of 1.27 mm in order to avoid excessive indentation and shear stress on the specimen. In order to allow for overhanging, 20 mm were maintained at each test specimen ends.

The deflection of the specimen was measured at the midpoint of the load span at the bottom surface of the specimen because when a beam is loaded in a four-point bending mode, maximum tensile stress occurs at the bottom surface of the beam, whereas compressive stress occurs at the top[42].

Step loading was carried out by adding an extra load during the process.

A transducer was placed at the bottom of the specimen (Figure 2) to note the voltage of the transducer with respect to the creep level. The whole setup was housed in a laboratory room where the temperature and humidity alterations were negligible.

The bending creep tests were carried out using specimens of 340 mm, (2x2x34 cm).

A starting reference stress was applied to each specimen and three or four increasing load steps were followed. Each load step was chosen to last 3 h. The steady state of creep is reached in less than an hour and therefore 3 h of testing at each load step is satisfactory. The load jump from one load level to the next was carried out in the shortest time possible, so that the creep that takes place during the loading step can be ignored. The above procedure was followed in each test. Two different sets of initial stress (reference stress) and stress levels (accelerating stresses) were used. For BIBs 1 to 6, the initial load was 11.03 MPa and the load steps were 16.54 MPa, 22.05 MPa and 27.56 MPa while for BIB 27 the initial stress (reference stress) was 9.19 MPa and the stress steps(accelerating stresses) were 14.7MPa, 20.21MPa and 25.73 MPa.

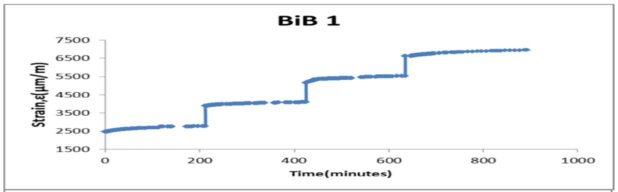
During each test the creep strain is recorded at time intervals and a curve of strain versus time (in minutes) is plotted.

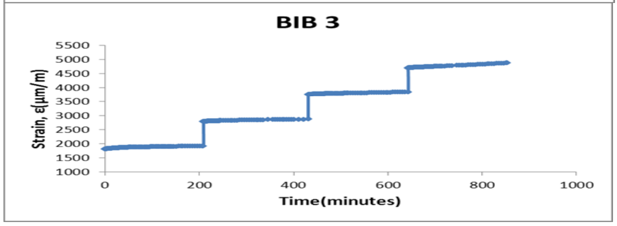
The bending tests, revealed a difficulty in obtaining smooth data, as the data were much scattered, showing perhaps micro defects or inhomogeneity common in woods [1].

The creep curves were subjected to vertical shifts (removing elastic creep), rescaling (correcting creep history) and then shifted horizontally along the logarithmic time axis to determine stress shift factors and construct a creep master curve. The resulting master curve was modelled with a third degree polynomial to make it smoother.

The shift factors are fitted with Eq. 3 to determine the value of the activation volume.

V. RESULTS AND DISCUSSION





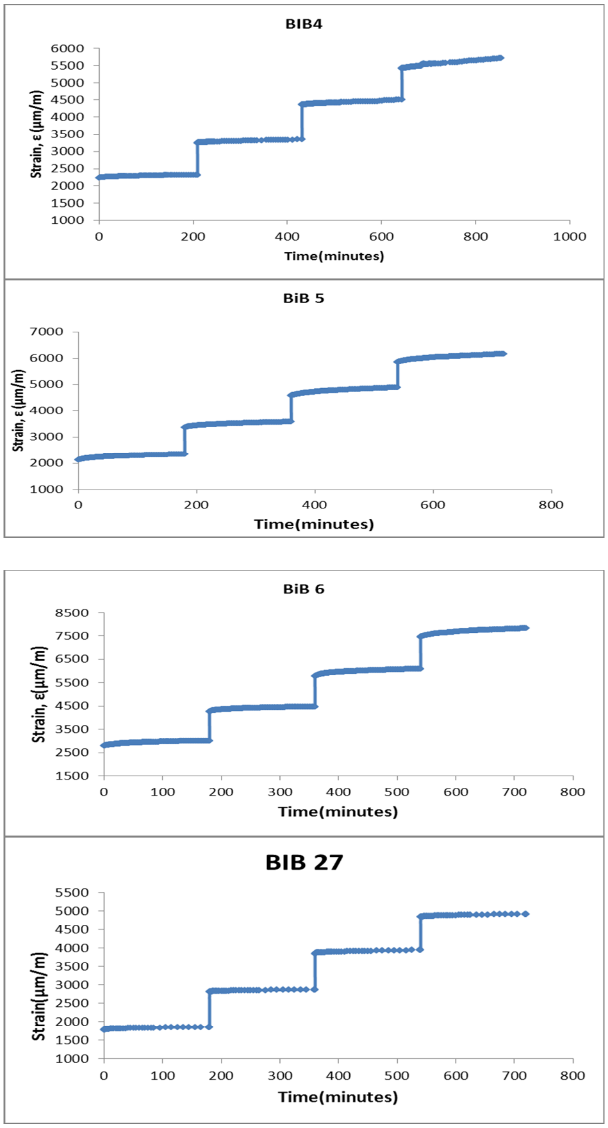


Fig.3. Strain versus time (minutes) curves as measured and shown as continuous strain line.

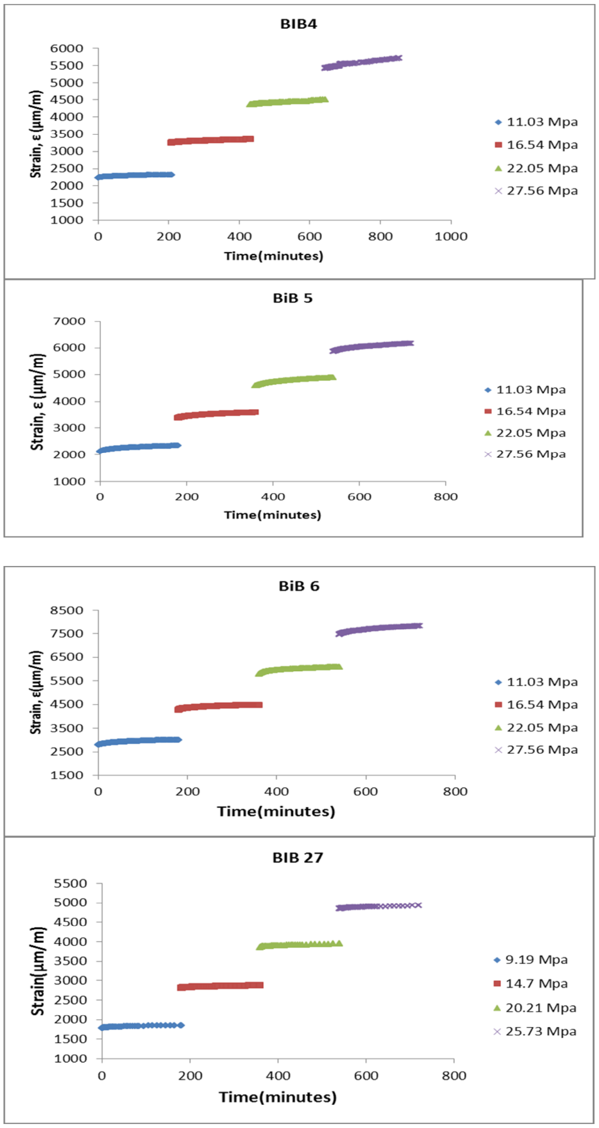
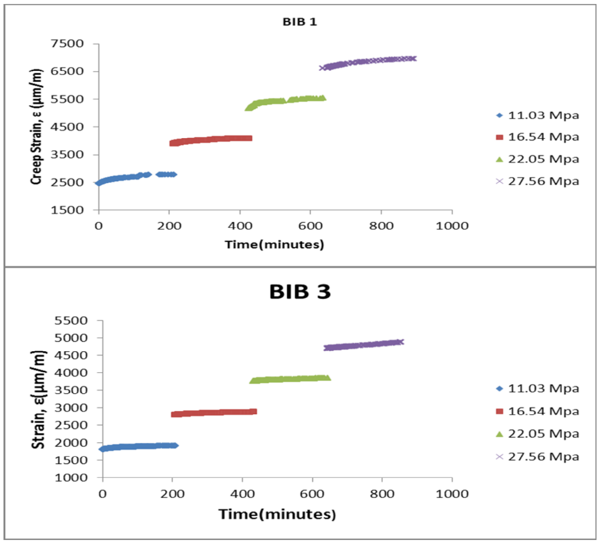
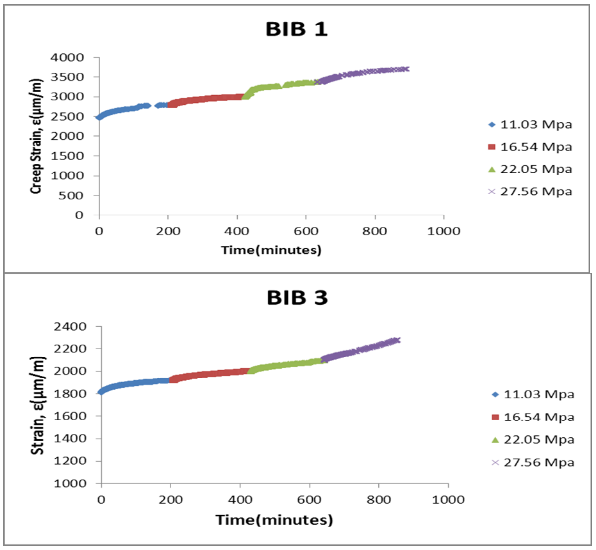


Fig.4. Individual strain versus time (minutes) curves as measured, showing strain jumps.





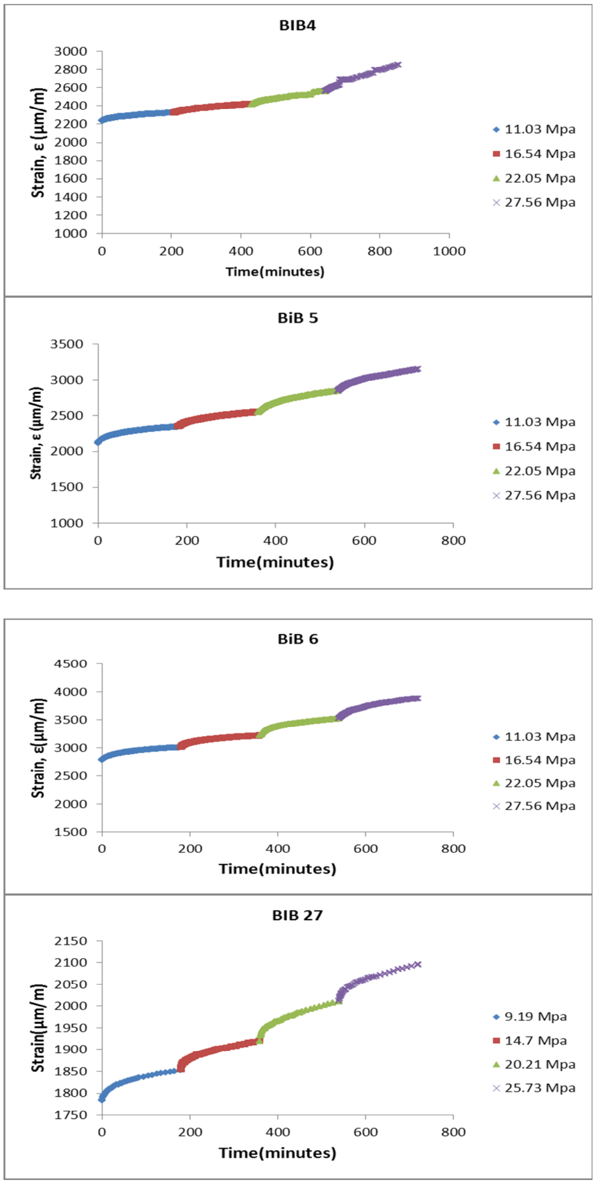


Fig.5. Individual strain versus time (minutes) curves as measured and after vertical shifting

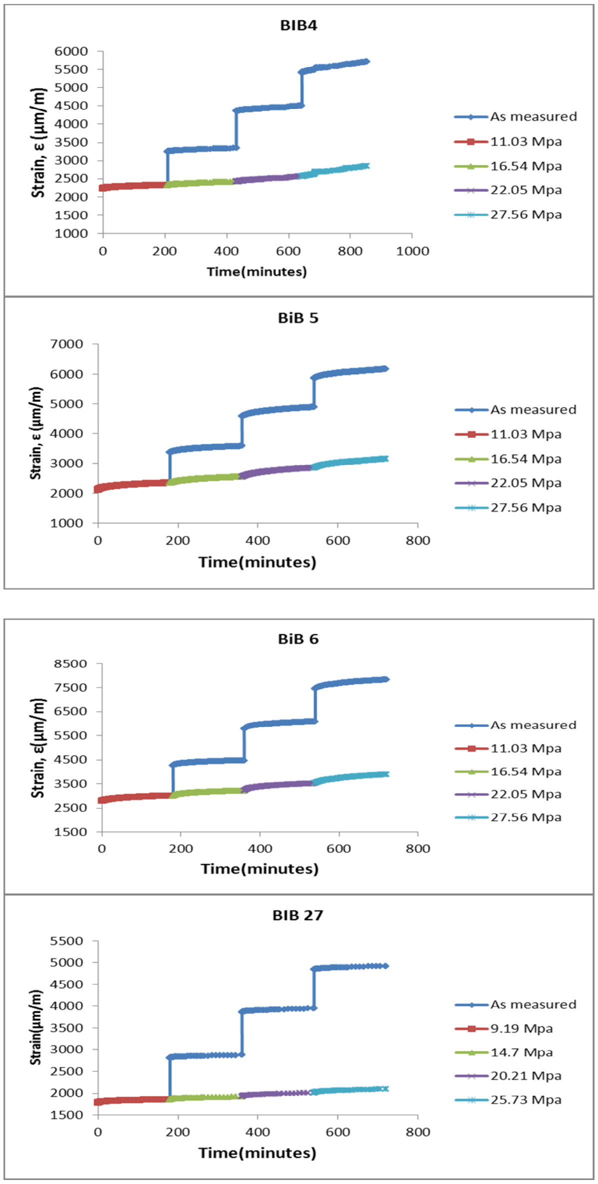
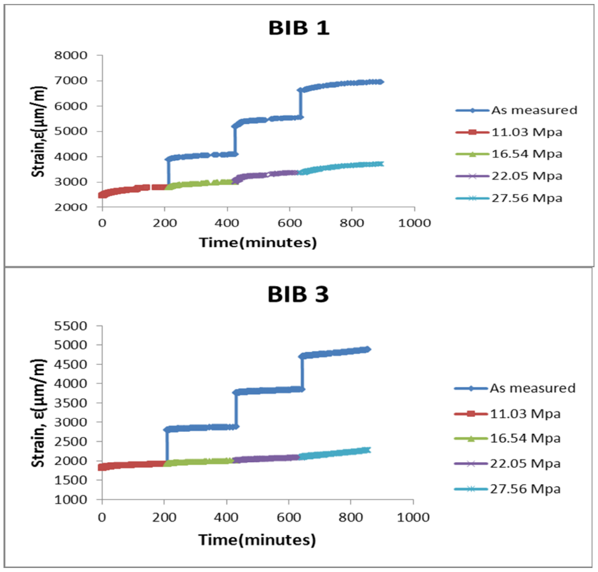
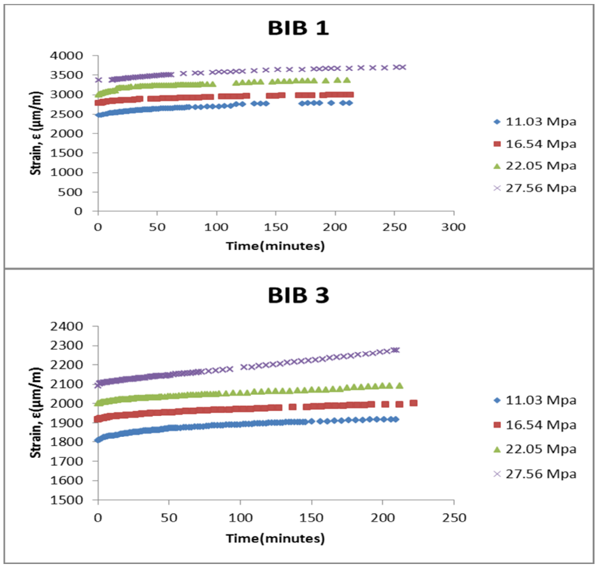


Fig.6. Individual strain versus time (minutes) curves as measured and after vertical shifting(superimposed).





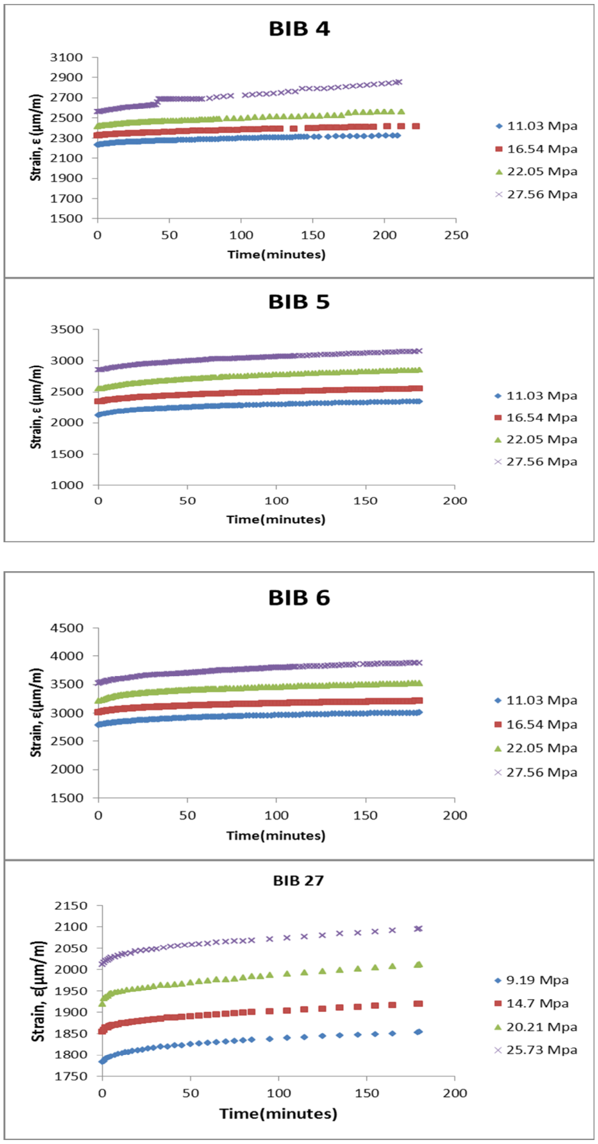


Fig.7. Individual strain versus time (linear time)curves after vertical shifting and rescaling.

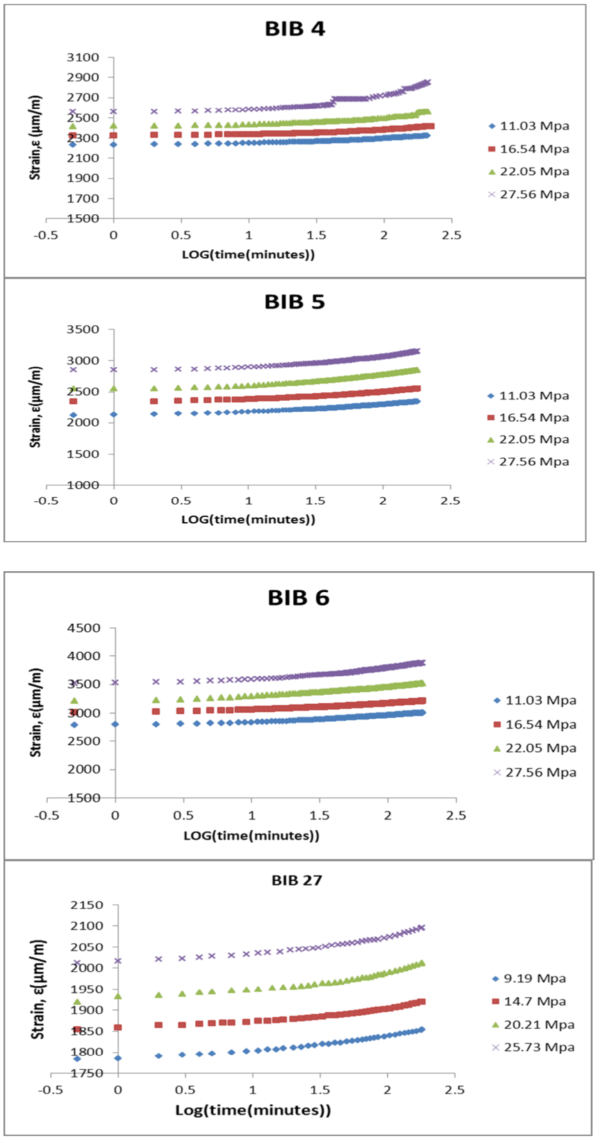
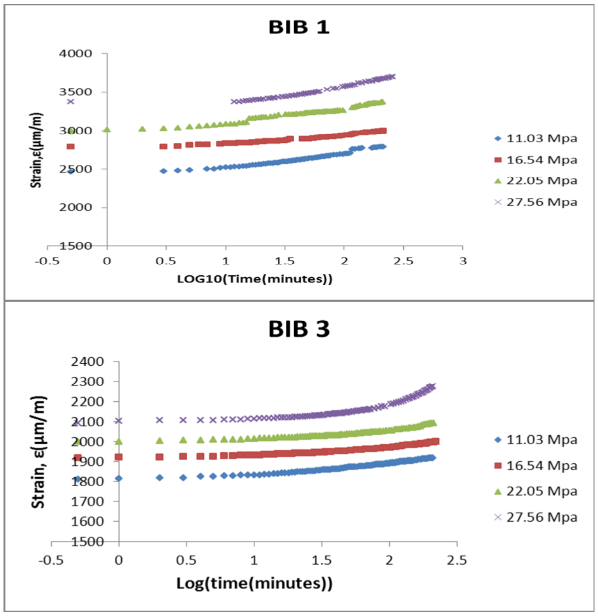
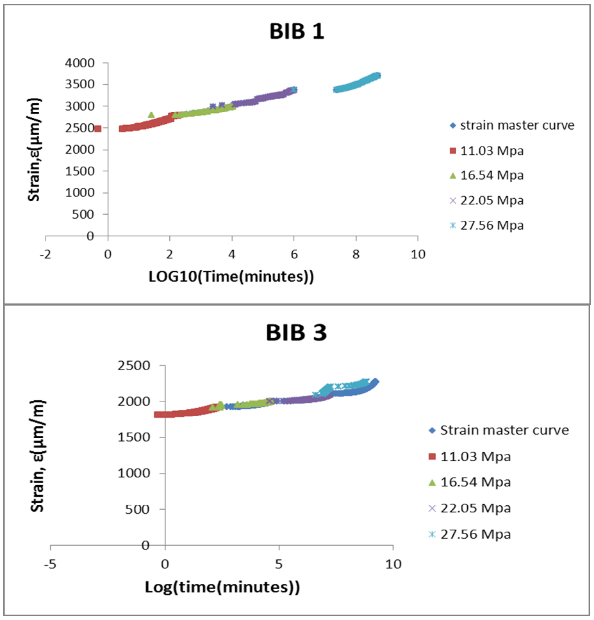


Fig.8. Individual strain versus time (log time)curves after vertical shifting and rescaling.





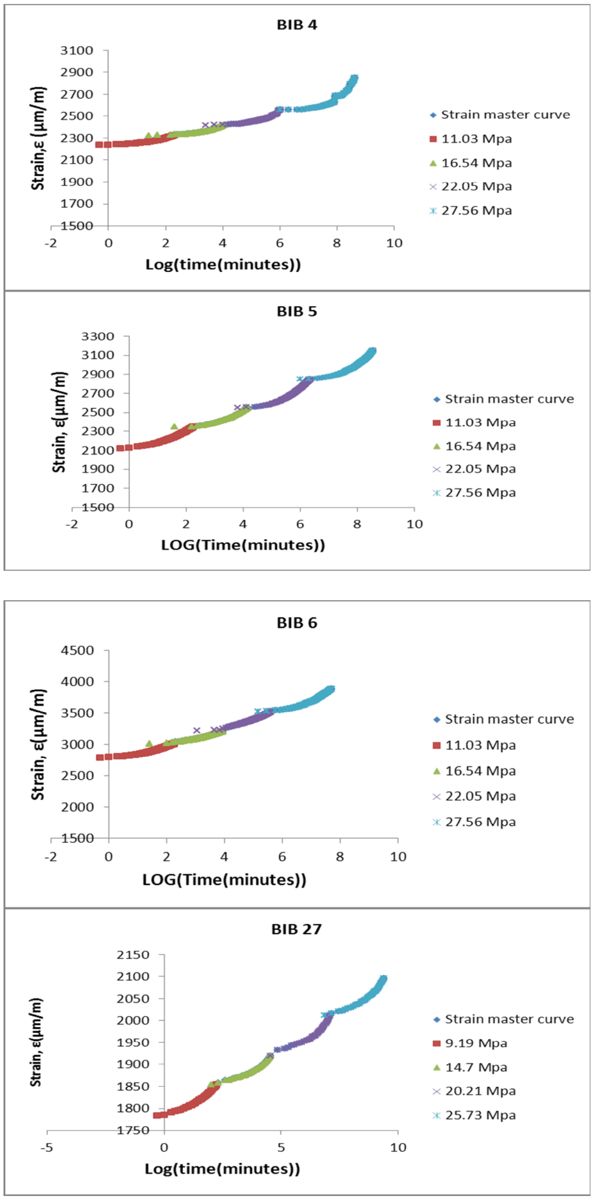


Fig. 9. Individual creep curves after rescaling and master curve after horizontal shifting.

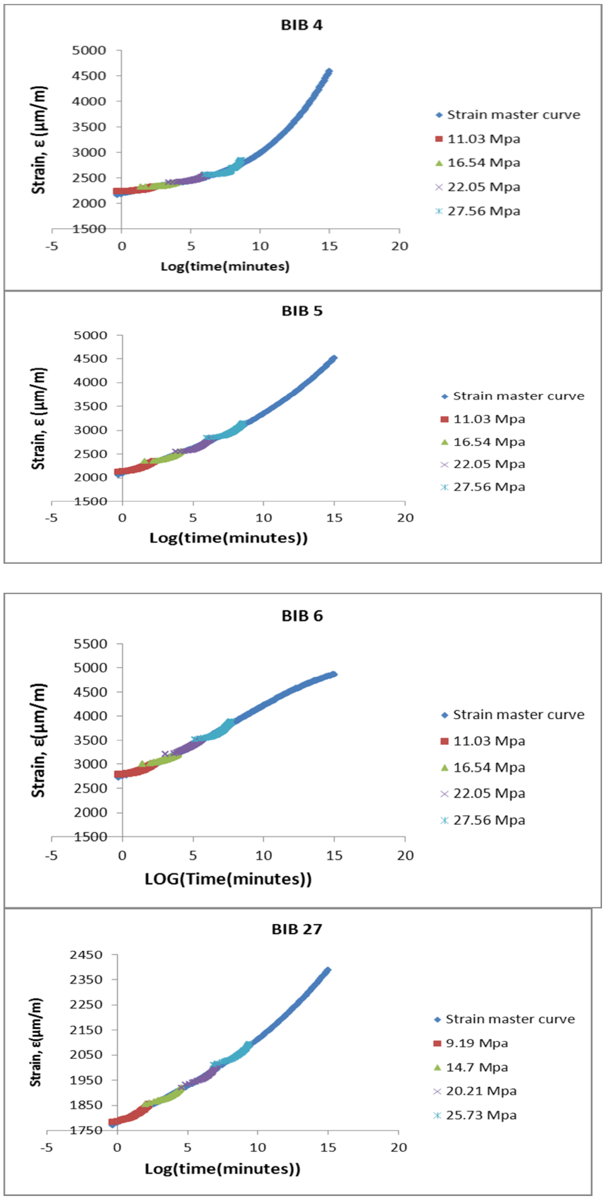
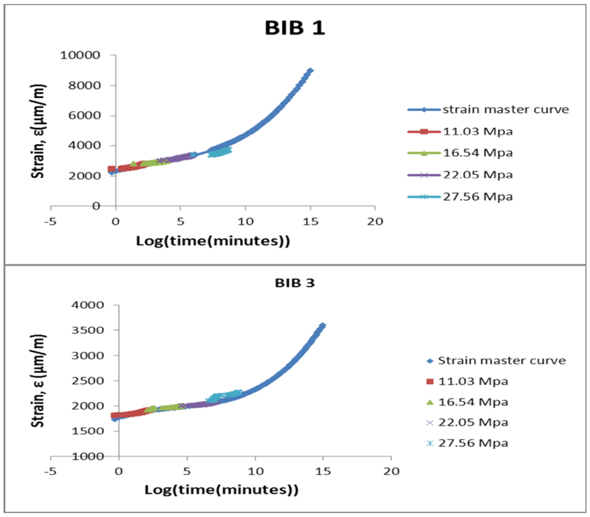
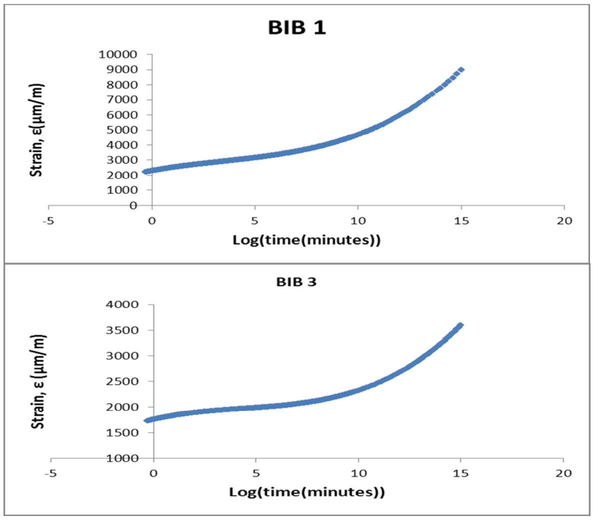


Fig.10. Individual creep curves and smooth master curve after horizontal shifting.





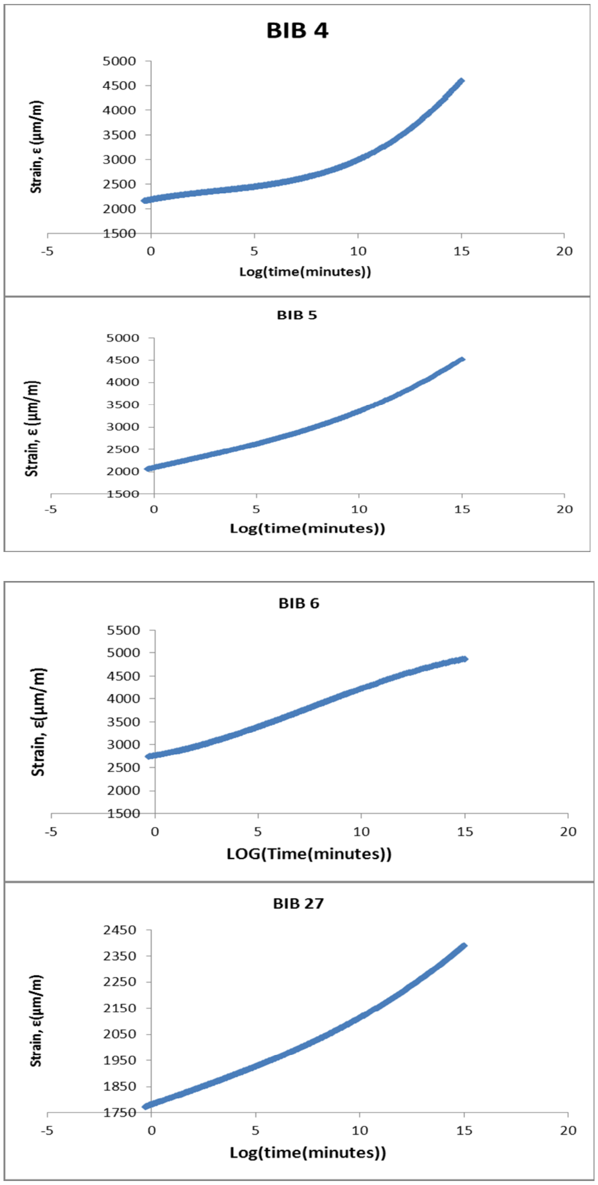
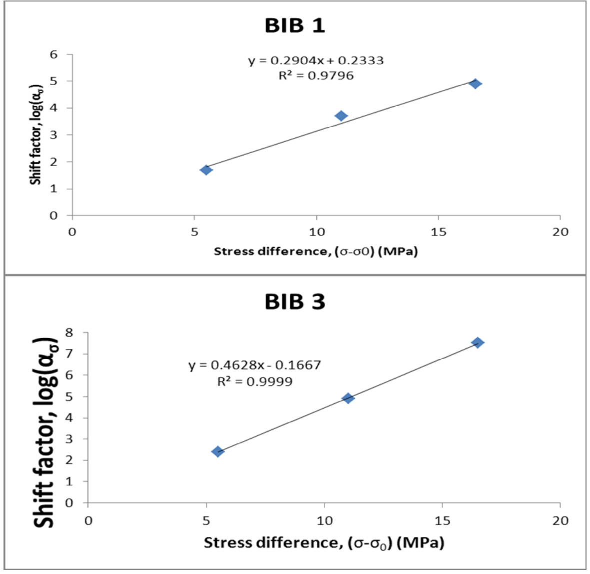


Fig.11. Creep Strain smooth master curves after horizontal shifting



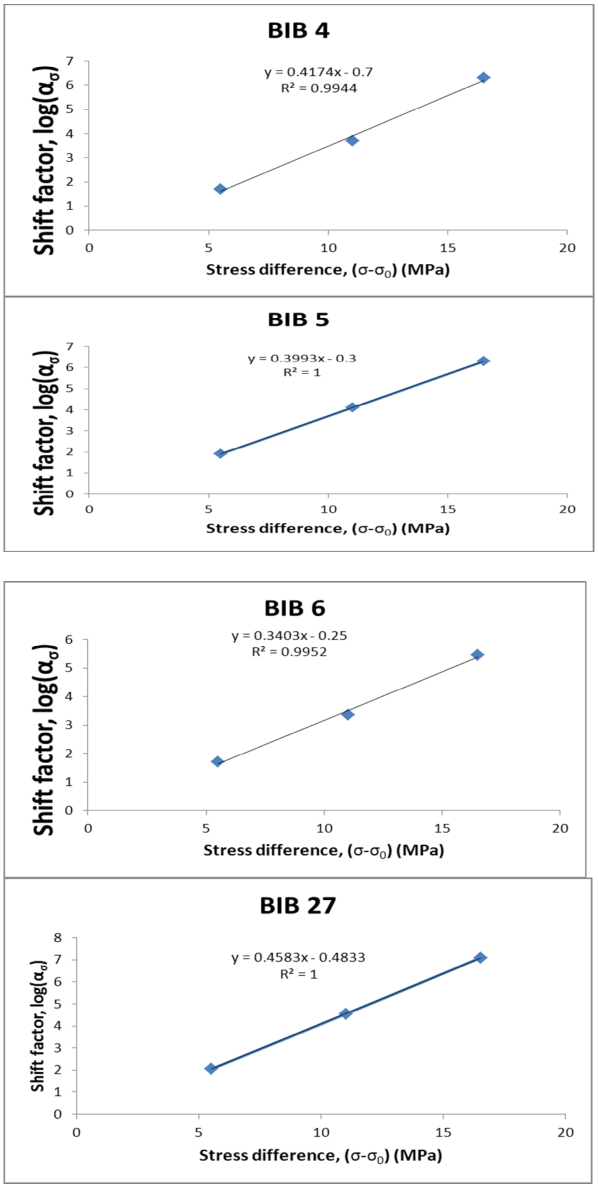


Fig.12. Eyring plots of SISA curves at starting reference stress level, 11.03 MPa (BIB 1-6) and 9.19 MPa (BIB 27).

Table 1. Average values of activation volume ($V^*(nm^3)$) at ambient temperature at reference stress level (11.03 & 9.19 MPa).

SPECIMEN	$V^*(nm^3)$
BIB 1	0.296
BIB 3	0.419
BI3 4	0.322
BIB 5	0.345
BIB 6	0.296
BIB 27	0.382

Table 2. Variation of activation volume ($V^*(nm^3)$) with stress difference, hence with stress level.

Reference stress	11.03 MPa					9.19 MPa
stress difference, $(\sigma-\sigma_0)$	Activation volume, $V^*(nm^3)$					
	BIB 1	BIB 3	BIB 4	BIB 5	BIB 6	BIB 27
5.51	0.291	0.411	0.428	0.325	0.291	0.351
11.02	0.317	0.419	0.317	0.351	0.287	0.389
16.53	0.279	0.428	0.359	0.359	0.311	0.405

Table 3. Summary of coefficients in 3rd degree polynomial for strain master curves

DEGREE	BIB1	BIB 3	BIB 4	BIB 5	BIB 6	BIB 27
3	2.8158	1.12	1.04	0.33	-0.53	0.066
2	-29.135	-14.72	-10.01	-1.09	12.11	-0.179
1	248.29	91.69	76.63	103.97	78.1	28.46
0	2296.2	1755.5	2182	2087	2757.9	1779.7
R-squared	0.9974	0.989	0.9806	0.9951	0.9965	0.9961

The test readings monitored during each SISA test were used to produce the strain (ε) versus time(minutes) curves (Fig.3 & Fig.4). These curves show the creep behaviour of Bibolo at four different stress levels, for all the specimens tested. At constant stress the stain increases with time. Moreover, the higher the applied stress, the higher the strain rate at any given time. However, at high stress levels, creep strain does not grow very fast during the testing and large deformations do not occur.

The curves in Fig.3 show a continuous line at the points of stress (σ) jumps, while those in Fig. 4 reveal the strain discontinuity at the instants of stress level change. A large increase in strain is observed at each stress jump (Fig.3 & Fig.4). The as-measured strain versus time curves presented in Fig. 3 and Fig.4 are adjusted vertically to remove the elastic strain, resulting in the curves presented in Fig.5 in which the curves comprise a purely creep curve. This implies that the final master curve will be solely a creep curve void of any elastic strain. The as measured strain versus time curves are superimposed with the vertically shifted strain-time curves and shown in Fig.6. Each portion of the curves of Fig.5, corresponding to a different stress level is rescaled by applying a horizontal shift in the left direction so as to take into account the stress history of the specimen. This shift takes the strain at a stress level back on the time scale to start as if the specimen had never been loaded before the current loading. The resulting curves are shown in Fig.7. The curves in Fig.7 appear to be parts of the creep curves that could have been obtained from TSSP tests. The rescaled curves are transformed from the linear time scale to logarithmic time scale. The strain versus log(time(minutes)) curves are presented in Fig.8. From these curves it is seen that creep strain values increase almost linearly with logarithmic time scale.

These creep strain curves at various stress levels, plotted in the logarithmic time scale are superposed, one at a time, through a horizontal shift (in the right direction) to obtain a master curve, in accordance to TSSP. The shifting procedure assumes that the shape of the creep compliance curve (ie creep mechanism) does not change in the range of σ_R to σ_4 [19].

To obtain the master creep curve, the reference stress chosen was 11.03 MPa for specimens BIB 1- BIB 6, and 9.19 MPa for specimen BIB 27. Both the horizontal shifting and the calculation of the stress shift factor are done manually. The resulting creep master curves, as well as the individual shifted curves are shown in Fig.9 and it is observed that strain master curves are not yet smooth curves.

In order to obtain smooth strain master curves, a third degree polynomial was fitted to the rescaled and shifted curves to cover the entire test duration. This action is imperative, given that the creep data shows a degree of scatter. The coefficients in the polynomial are shown in Table 2.

The final creep master curves, as well as the individual shifted curves are shown in Fig.10, while the individual master curves are shown in Fig.11.

The master curves represent accelerated creeps of about 15 decades outside the experimental window. Therefore, to predict the creep performance of Bibolo over a period of about 15 decades, it is only required to carry out stress accelerated tests of three hours duration at stress levels from 9.19 MPa to about 27.5 MPa.

If the loading is increased up till specimen rupture, then the very last point of the master curve will correspond to the creep-rupture point of the specimen [7,8]. In our case we did not attain creep rupture because the maximum stress level was imposed by instrumental limitations (height of the load bearing rod and strain gauge capacity).

VI. Activation volume, V*

The Eyring equation(Eq.3) predicts a linear relationship between the activation volume and the shifting factors required to produce master curves. The creep data resulting from the Steeped-Iso-Step Approach tests may be used to verify this prediction for Bibolo. Figure 12 show the plots of shifting factors, calculated manually, against the accelerating stress difference for Bibolo tested with an initial stress(and reference stress) of 11.03 MPa (BIB1-BIB6) and 9.19 MPa(BIB27). For all the speciments the data points lie close to straight lines though a small experimental scatter may exists. This behaviour implies that the creep mechanism remains the same for creep at all stress levels and thus justifies the use of the superposition theory in adding creep curves for different stresses to produce the creep master curve which is the bedrock of the Steeped-Iso-Step Approach. Judging from equation, Eq.3, the slope of each line in Figure 12 is equal to $\frac{V^*}{(2.30kT)}$, where V* is the activation volume, k is the Boltzmann's constant with a value 1.38×10^{-23} JK^{-1} and T is the absolute temperature. The activation volume, V* can thus be calculated by using the slope and gives a sort of average value. Alternately each stress level can be substituted in Eq.3 and the corresponding value of the activation volume calculated by substituting the values of the Boltzmann's constant, k and temperature.T, and an average value may the be computed. The resulting values of the activation volume, V* obtained by using the slopes in Figure 12a-f are presented in Table 2 and reveal a general increase with the increase of the accelerating stress. This implies the type relationship that exists between stress and activation volume. Based on the transition state theory, activation volume, V* for a chemical process is defined as difference between the partial molar volumes of the transition state and the sum of partial molar volumes of the reactants at the same temperature and pressure[43]. It may be interpreted on physical basis that the products of the creep process occupy a larger volume than the original fibre. This may be in agreement with the fact that the molecules are pulled apart during creep.

From the data in Table 2 it is observed that the activation volume, V* varies only very slightly with the reference stress but the direction of variation is not conclusive because only two reference stress levels were used and the specimens did not show the same variation. A larger number of reference stresses is required in order to ascertain a trend in the variation (if any) of the activation volume, V* with reference stress levels. The near constant nature of V* validates the original assumption implicit in the stated theory and explicitly used earlier in the derivation of Eq. 3.

CONCLUSION

The effect of stress on short-term creep behaviour of viscoelastic Bibolo, in a step fashion has been experimentally investigated in this study. The results obtained here indicate that the Steeped-Iso-Step Approach is afeasible method to predict the long-term creep behaviour. The tests in this method are carried out at one temperature and presussure which are the laboratory service conditions. This means that there is no need for an oven or other regulatory material, which is an advantage over other methods like the stepped iso-themal approach and TTSP. The adjustments and shifting to produce a smooth master curve have been done maually which can imply some degree of subjectivity.

It has been shown that the activation volume appears generally to vary with the accelerating stress level.

An increase in stress will increase the free volume in materials to allow more active motion of the material units, resulting in shorter relaxation or retardation times. This dependence of the activation volume on stress contrasts the activation energy which, some works have shown is constant. This difference requires another study.

As wood structures involved in load carrying are expected to last for several decades, the data resulting from Stepped Iso-Stress Approach will be important in practical engineering situations, especially those involving variations in loads.

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