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TIME-STRESS EQUIVALENCE APPLIED TO NONLINEAR CREEP OF BIBOLO: DIBETOU (Lovoa trichilioides)

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ABSTRACT

Bibolo (*Lova trichilioides*) wood is marketed locally under a commercial name of Dibetou and in what follows it shall be referred to as Bibolo. Stress induced changes in intrinsic timescale were investigated by nonlinear short period (3 h) creep tests on Bibolo at room temperature and atmospheric pressure, for stresses ranging from 9.19 MPa to 27.56 MPa. The creep strain and creep compliance curves versus time at four different stress levels were determined. The resultant creep compliance curves depart from each other, indicating nonlinear viscoelastic behaviour. The creep strain curves were shifted along the logarithmic time axis to get a master creep curve at a given reference stress level according to the principle of time-stress superposition. It is shown that the time-stress superposition principle provides an accelerated test method for evaluating the long-term mechanical performance this wood.

Keywords: Bibolo, time-stress superposition, shift factor, master curve, nonlinear creep.

INTRODUCTION

Wood is widely used in many structural engineering applications. Wood is used as a constructional material for small bridges, houses, etc as structural carrying members. It remains a common and cheap constructional material when compared with iron, steel etc[1]. However, wood is facing a stiff challenge from plastics and polymers composites. Wood also suffers serviceability problems due to exposure to alternate moisture and dry conditions, and due to other defects[1].

Synthetic polymers in the form of plastics, rubbers and fibres, offer such obvious advantages in certain applications that synthetic polymers have permanently replaced conventional material such as metal, wood in these particular fields. These advantages include lower density, resistance to corrosion and chemicals, and ease of processing into fairly intricate shapes [2].

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 [2].

If wood has to retain its role as a leading structural engineering material then a thorough knowledge of its mechanical properties is crucial.

Required structural life times vary and can be as high as 120 years [3, 4] and the prediction of long term behaviour becomes an issue of concern.

The mechanical behaviour of wood can be thought of as being somewhere between that of elastic solids and liquids. Wood is termed viscoelastic as it displays both viscous and elastic types of behaviour.

Woods like most polymers exhibit time-dependent mechanical behaviour, usually referred to as viscoelasticity[5].

There are two time scales in the study of viscoelasticity [5]. The first is the observation time measured by the ordinary clock or watch. The second is the material's intrinsic time that is revealed by viscoelastic relaxation or retardation time.

This material's intrinsic time (and viscoelasticity in general) can be influenced by many factors such as temperature [6], physical aging [7] and R.D. Bradshaw [8, 9], pressure, solvent concentration [10, 11], strain [12, 4], stress level [4, 13, 14, 15], moisture (humidity) [4]. Among them, temperature and stress are the two most important factors for load-bearing polymeric materials [4].

A complete study of individual and combined effect of these service (or environmental) factors is necessary to characterize creep of wood. Most of the published studies in this area have, however, focused on the effect of one or more of these factors but not on all. [2].

With regard to the temperature effect on this intrinsic time, 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 stress (creep) behaviour of polymers [3, 4,16, 17, 18,19]. By virtue of its structure wood is basically a polymeric material.

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 [11]. 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*. [11] have proposed a modification to Boltzmann superposition principle to account for the effects of elevated stresses.

Based on the fact that higher stresses quicken creep or relaxation of viscoelastic materials, which is similar to the effect of higher temperatures, several time-temperature-stress superposition principles (TTSSP) have been proposed [15, 20, 21,22].

Later, Griffith [23] proposed a Time-Temperature-Stress-Superposition Principle (TTSSP) combining TTSP and TSSP together (detailed discussion in [24, 25].

According to the TTSSP, time-dependent mechanical properties of viscoelastic materials at different temperatures and stress levels can be shifted along the time scale to construct a master curve at a reference temperature and stress level.

By taking into account the combined effect of temperature and stress on the creep of viscoelastic materials, other researchers [26, 27] have tested different specimens at various temperatures and stress levels.

First, the time-temperature principle is applied to produce master curves at various stress levels at a selected reference temperature. Then, the time-stress principle is applied on the obtained master curves to get the final master curves at a reference stress and temperature level.

In the present research the objectives are to investigate: (1) the non-linear deformation behaviour of Bibolo wood, characterizing such a property as creep, (2) the stress effect on the creep behaviour of Bibolo wood, and to obtain a master creep curve using a TSSP.

EFFECT OF STRESS ON CREEP

An increase in stress at constant temperature accelerates the creep rate of wood resulting in increase in creep compliance.

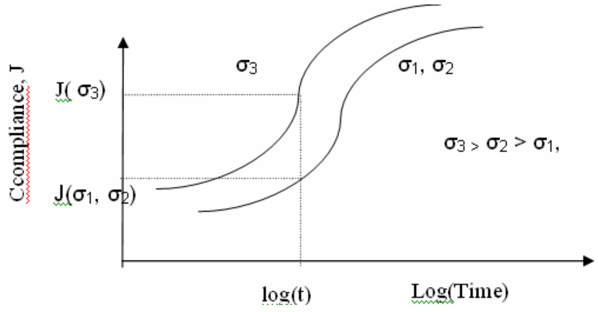


Figure-1. Compliance-time relation for linear and non-linear creep.

The creep behaviour of wood and its composites may be independent of the applied stress, and this is known as linear creep. Alternately, the creep may be a strong function of the applied stress and this is known as non-linear creep. The creep behaviour may similarly be dependent or independent of creep time at constant stress and temperature.

The difference in creep behaviour can be easily differentiated by plotting the creep compliance as a function of creep time (log (time)) at different stress levels [2]. Since the compliance is defined as the ratio of creep strain to the applied constant stress (J(t) = $\frac{\varepsilon(t)}{\sigma}$), the creep compliance would not increase with increase in stress, and the compliance curves would superimpose at those stress levels for which the material is "linearly viscoelastic". In the diagram above creep curves at σ_2 and σ_3 do not superpose as the material's creep becomes nonlinear at stresses above σ_2. A previous study by [28] shows that for this material nonlinear creep behaviour starts at stress level 9.2 Mpa (245N).

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 the extrapolated for lower stress levels. The extrapolation introduces many uncertainties [3, 4].

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 determine 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.

In general, service life of wood at service stress would range from a few years to a few decades. However, it is not possible to characterize the complete creep (or creep failure) behaviour of wood material for its entire service life experimentally. Normally, allowable experimental test time would range from a few hours to a few days. The data beyond this experimental time window is generated using an accelerated characterization and superposition principle, known as Time-Stress - Superposition Principle (TSSP).

According to this principle, creeps compliance at a service stress ($\sigma_{service}$) for a time beyond the experimental time window (e.g. creep for periods 5-10 years in Figure-2) can be generated within the experimental time window by testing at stresses higher than $\sigma_{service}$ [29,30,31]. These experimental creep data at σ_1 to σ_4 are then shifted horizontally along the time axis to superpose to yield the creep compliance curve at $\sigma_{service}$ beyond the experimental time window.

The shifting procedure assumes that the shape of the creep compliance curve (i.e., creep mechanism) does not change in the range of $\sigma_{service}$ to σ_4 [2,32,33].

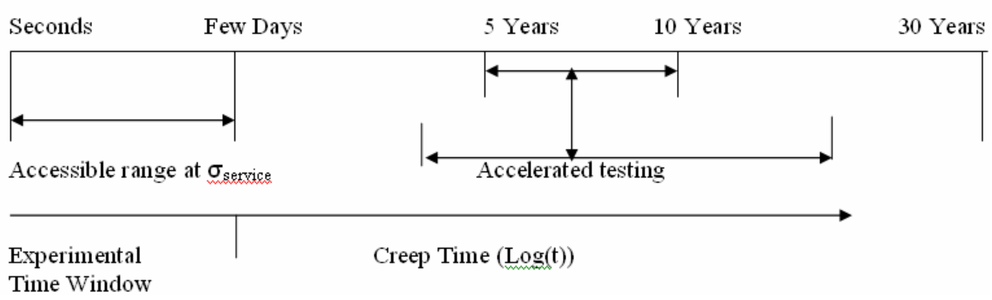


Figure-2. Time-stress superposition principle for long-term creep characterization.

Time-temperature-stress superposition principle (TTSSP)

The TTSSP proposed by W. Luo *et al*. [15] could be deduced within the framework of the free volume theory.

Free volume is the empty or void space that is available for unit or segmental motions in materials such as wood and other polymers. An alteration in free volume has a bearing on the mobility of the material and has a direct impact on the time-dependent mechanical properties of the material [5]. The larger the free volume, the greater the mobility of the molecular response to external loading.

According to the free volume theory, the viscosity of the material, η, which reflects the material's intrinsic time, can be related to the free volume fraction, *f*, via the Doolittle equation [6] in the form,

$$\eta = A\exp\left[\mathrm{B}\left(\frac{1}{f}-1\right)\right] \tag{1}$$

where A and B are material constants.

The change in free volume fraction that results from a change in temperature is linearly dependent on the temperature change. We assume that the stress has a similar effect, so that, the change in free volume fraction resulting from a change in stress is linearly dependent on the stress change.

When the combined effect of temperature and stress on the free volume fraction of viscoelastic materials is considered, then the free volume fraction can be expressed as [4].

$$f = f_0 + \beta_T (T-T_0) + \beta_\sigma (\sigma - \sigma_0) \tag{2}$$

where β_T is the thermal expansion coefficient of the free volume fraction, β_σ refers the stress-induced expansion coefficient of the free volume fraction, and f_0 is the free volume fraction at the reference state.

Suppose that there exists a temperature-stress shift factor $a_{T\sigma}$, which satisfies the relation

$$\eta\,(T, \sigma) = \eta\,(T_0, \sigma_0)\, a_{T\sigma} \tag{3}$$

then, from Equations (1) and (2), we have

$$\log a_{T\sigma} = -C_1\left[\frac{c_2(T-T_0)+C_3(\sigma-\sigma_0)}{C_2C_3+C_2(T-T_0)+C_3(\sigma-\sigma_0)}\right] \tag{4}$$

Where $C_2 = f_0/\beta_\sigma$

Equation (4) reduces to the WLF equation at a single stress level so that there is no stress difference.

Moreover, we may define the stress shift factor at constant temperature, a_σ^T, and the temperature shift factor at constant stress, a_T^σ, in such a way that

$$\eta(T,\sigma)=\eta(T,\sigma_0)a_\sigma^T=\eta(T_0,\sigma_0)a_T^{\sigma_0}a_\sigma^T=\eta(T_0,\sigma)a_T^\sigma=\eta(T_0,\sigma_0)a_\sigma^{T_0}a_T^\sigma \tag{5}$$

then we have

$$a_{T\sigma} = a_T^{\sigma_0}a_\sigma^T = a_\sigma^{T_0}a_T^\sigma \tag{6}$$

It is shown from Equation (6) that the time-dependent mechanical properties of viscoelastic materials at different temperatures and stress levels for some convenient time scales can be shifted along the time scale to construct a master curve of a wider time scale at a reference temperature, T_0, and reference stress level, σ_0, in one step via the temperature-stress shift factor, $a_{T\sigma}$, or in two steps via a combination of the shift factor at a constant temperature, a_σ^T, and the temperature shift factor at constant stress level a_T^σ.

Where the service temperature is chosen as the reference temperature, T_0, as it was in our case, Equation (4) reduces to

$$\mathrm{Log}\ a_\sigma = -\frac{B}{2.303f_0}\left(\frac{\sigma-\sigma_0}{f_0/\beta_\sigma+(\sigma-\sigma_0)}\right) = -\frac{C_1(\sigma-\sigma_0)}{C_2+(\sigma-\sigma_0)} \tag{7}$$

where a_σ denotes the stress shift. With this shift factor, the nonlinear creep behaviour can described via the stress-induced reduced time, t/a_σ:

$$\varepsilon(\sigma, t) = \varepsilon(\sigma_0, t/a_\sigma) \tag{8}$$

$$J(\sigma, t) = J(\sigma_0, t/a_\sigma)$$

MATERIALS AND METHOD

Figure-3. Bending creep testing device.

Material samples and specimen preparation

Test specimens were cut from seasoned Bibolo 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 27 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. The wood had an average density of 0.5 gcm^{-3} and relative moisture content (RMC) of 7%. This value is acceptable because the value of 12% has been the commonly used one[34].

Test set up

The test setup is shown in Figure-3. 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 cylindrical shape is preferred for the load application points and support in order to avoid excessive shear stress. The vertical metal rod ends at its lowest point on a flat rectangular plate such that the combined system can carry masses by placement or by slotting.

The top part of the 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 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 (i.e., 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 centre point of the specimen. Therefore, the deflection of the specimen was measured at the midpoint of the load span at the bottom face of the specimen [35].

Accelerated flexural creep tests (3-14 h)

Creep tests were conducted on 27 Bibolo specimens for durations ranging from 3 h to 14 h, at different stress levels. Specimens BIB1 to BIB 6 and BIB 27 were used for accelerated creep tests in 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.

The other specimens were used to generate constitutive models and for aspects of the research.

Figures 5(a) to (f) show strain-time curves for the material tested; Figures 6(a) to (f) show the corresponding compliance- time curves.

Compliance is defined as the ratio of strain and stress at a specific time. A comparison of compliance-time curves at different stress levels indicates the stress influence on the creep behaviour.

It is seen in Figure-1(a) to (f) that the compliance-time curves at different stresses diverge from one another for this material. Creep behaviour cannot be described by a single compliance curve (the compliance curves do not superimpose), which means that the material exhibits nonlinear viscous behaviour; creep compliance for Bibolo depends on both time and stress.

At high stress levels, creep strain does not grow very fast during the testing and large deformations do not occur.

The maximum stress level tested during this study was restrained by instrumental limitations (height of the load bearing rod, strain gauge capacity and the dimensions of the loads).

Short term creep behaviour

To study the creep behaviour of Bibolo within different time windows, strain-time curves for 3 h creep tests are shown in Figure-5

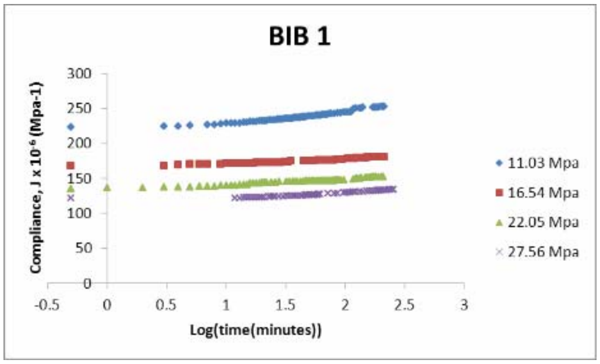
Creep test with step loading

Creep tests at several stress levels on a specimen can be done in two different ways. On the one hand, in a conventional creep test (CCT), the specimen is allowed to creep under a constant stress for a period of time, then the stress is removed and the specimen is allowed to recover from the strain for a sufficiently long period of time. This procedure is repeated at another stress level for the same creep time period.

On the other hand, in a step loading method, the specimen first creeps for a period of time under a constant stress and creeps for another period of time under another (increased or decreased) constant stress level. For increased stress test, progressive strain growth can be observed; for decreased stress test strain reduction under sustained loading can be observed. In this study it is the former approach that was adopted for the Time-Stress Superposition concept.

In this approach, all creep tests were carried out at room temperature and pressure, for 3 h by single step loading in a four point loading mode. The resulting creep strain as a function of time was recorded and the corresponding creep compliance determined as the ratio of the time-dependent strain to the constant applied stress. The variation of compliance with time enables the linearity of the creep behaviour of the tested wood to be checked.

RESULTS AND DISCUSSIONS



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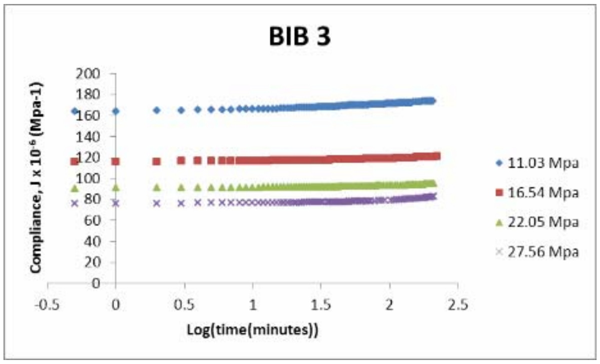

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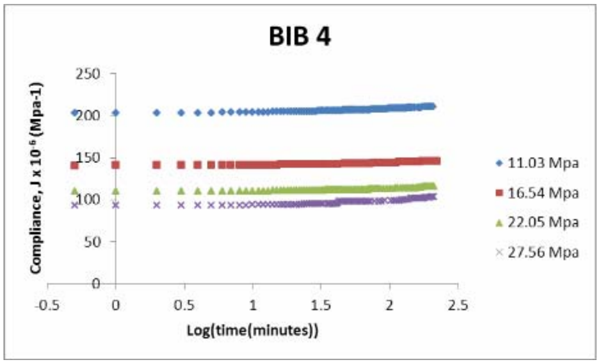

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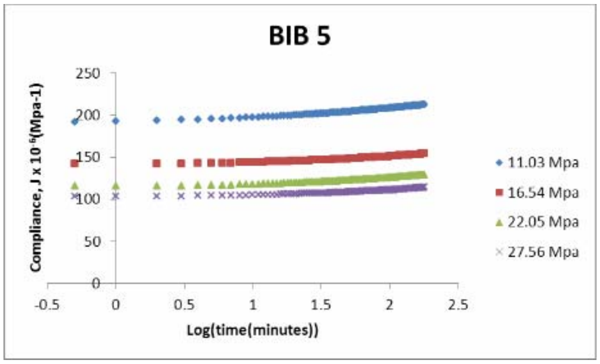

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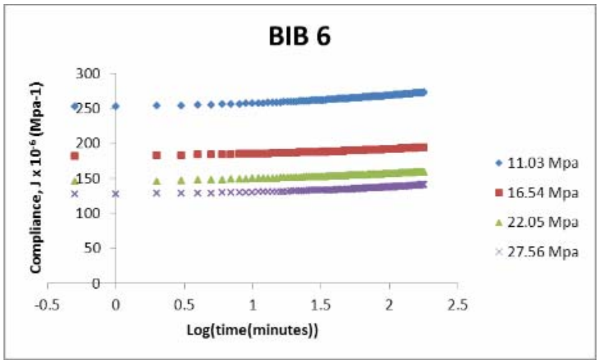

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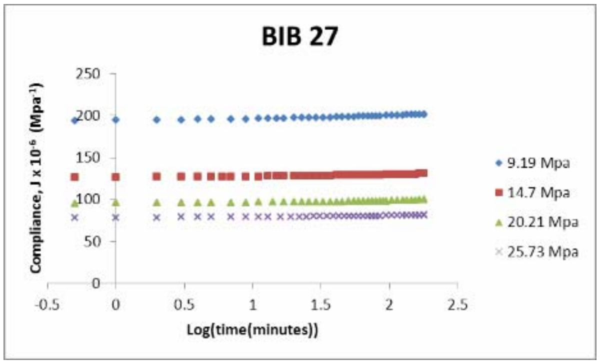
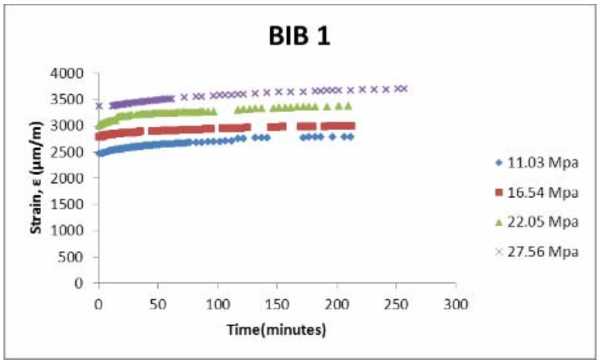


(f)

Figure-4(a)-(f). Show curves of creep compliance versus time in logarithmic scale.



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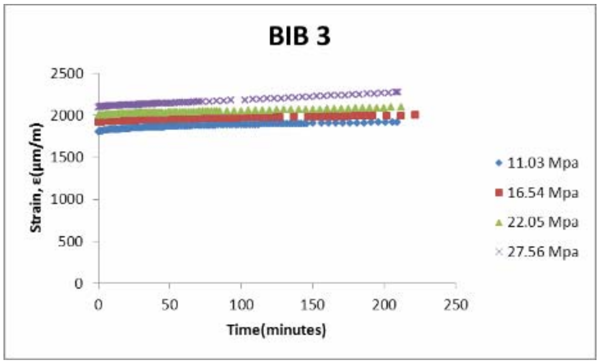

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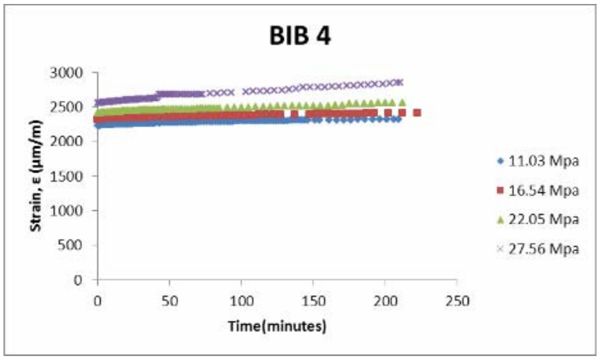

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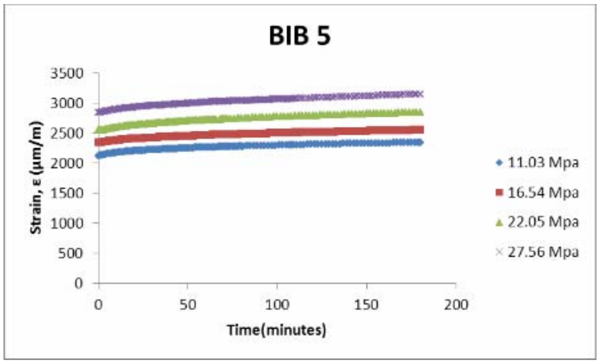

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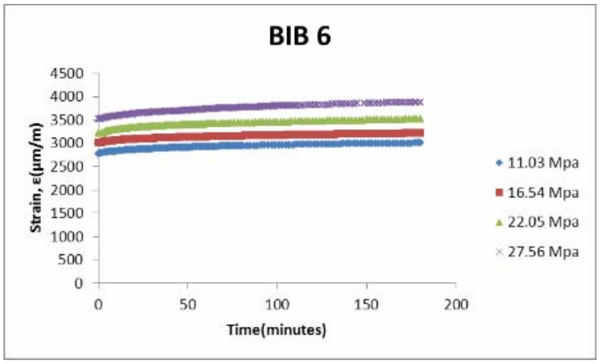

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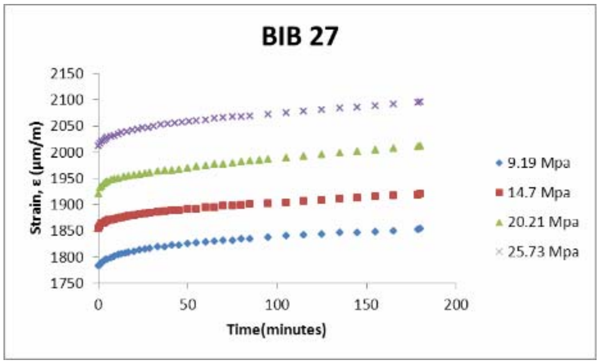

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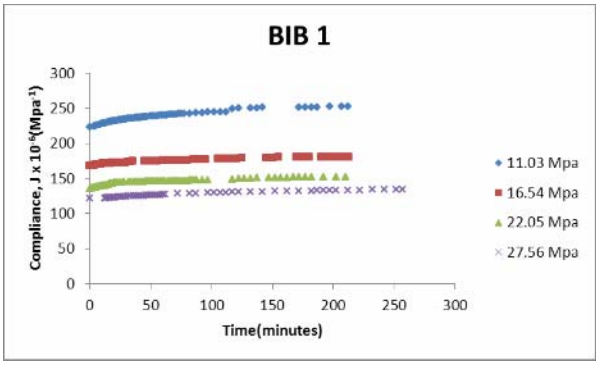
Figure-5(a)-(f). Are curves creep strain against time(minutes).



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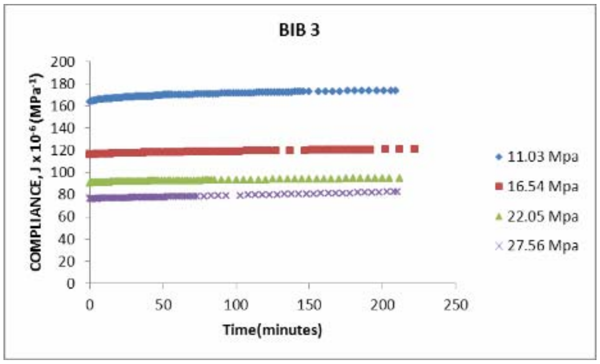

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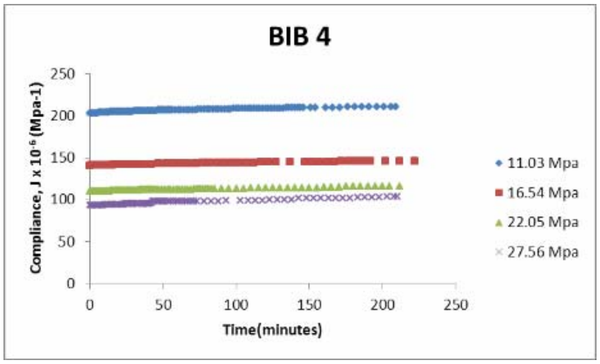

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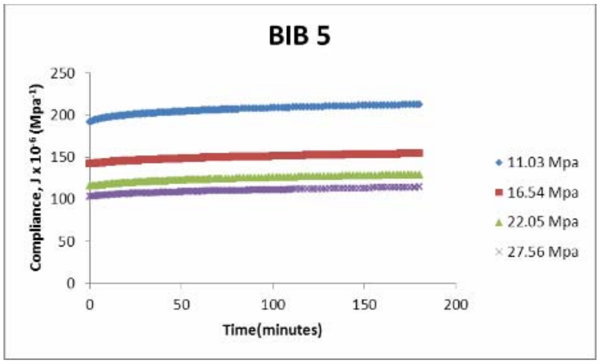

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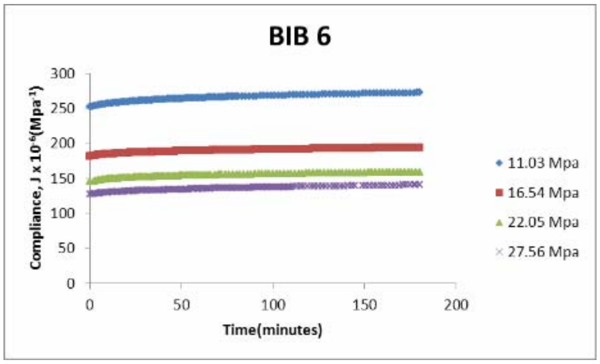

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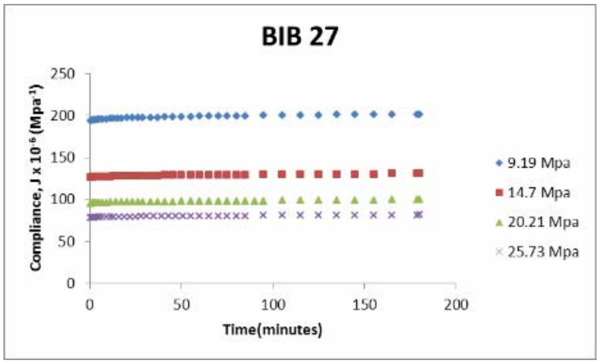

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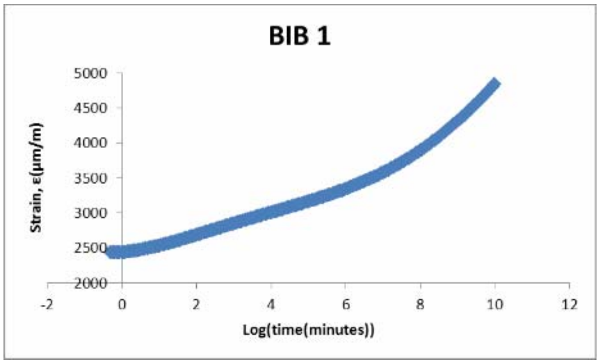
Figure-6(a)-(f). Are creep compliance versus time (minutes) curves.



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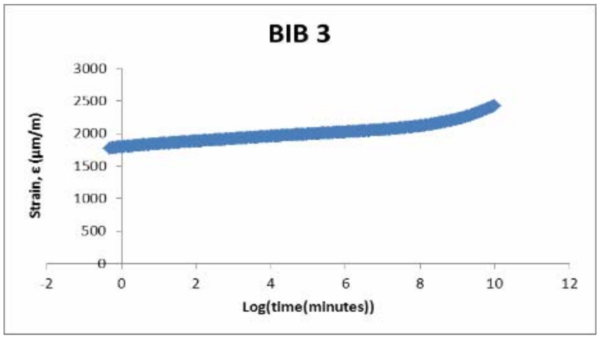

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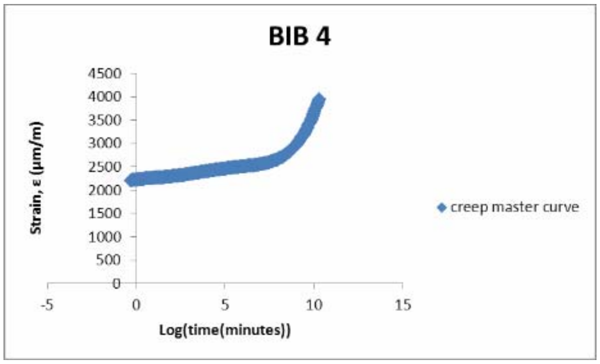

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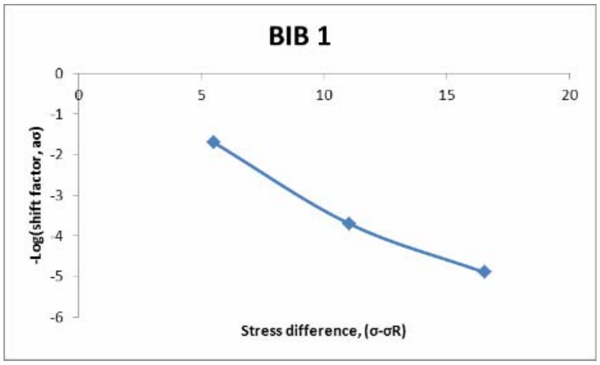

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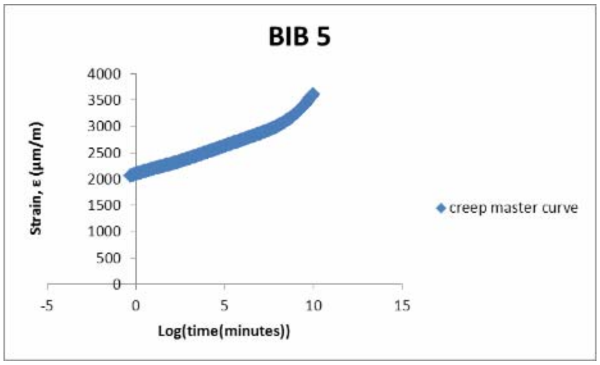

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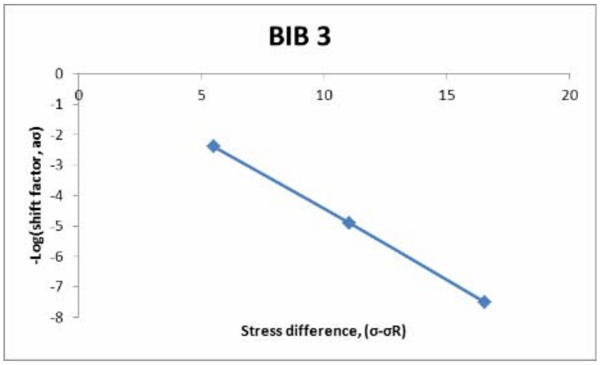

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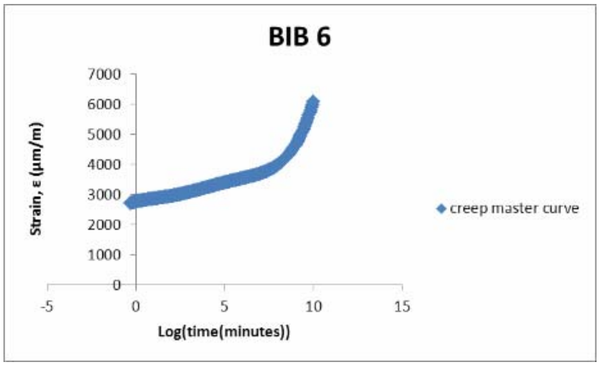

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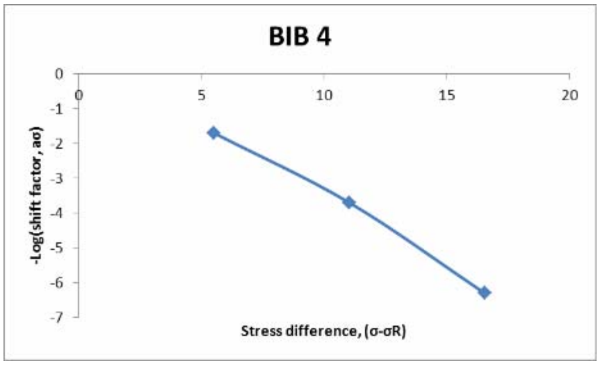

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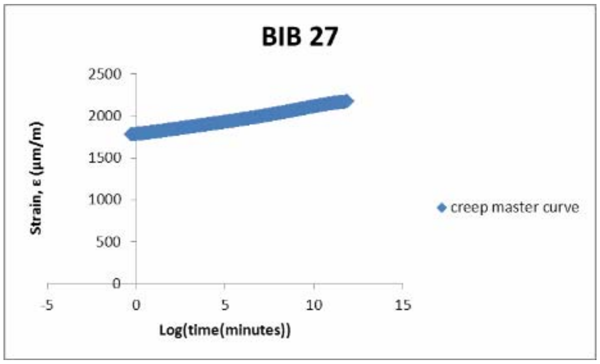

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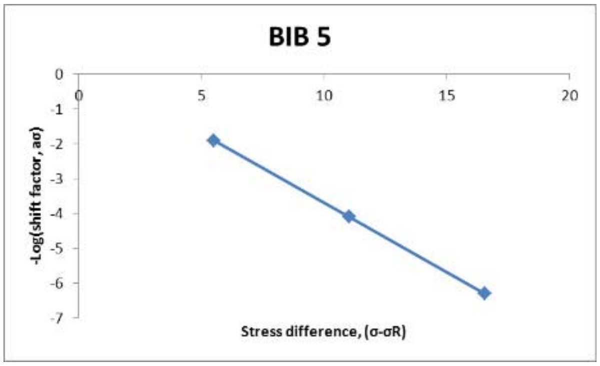
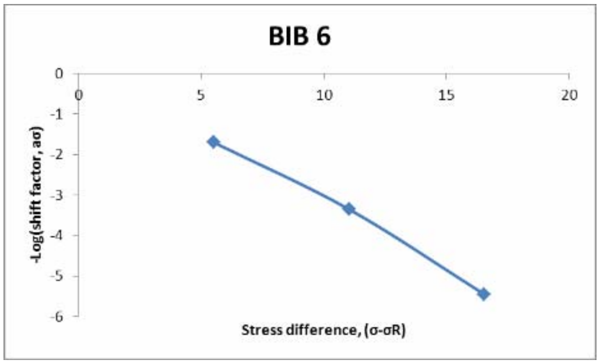
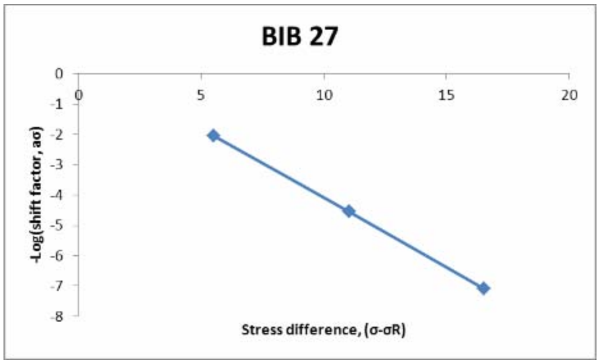


(d)

Figure-7(a)-(f). Are the creep masters curves.



(e)



(f)

Figure-8(a)-(f). Show the variation of the stress horizontal shift factors with stress difference.

Figures 5(a) to (f) show the creep behaviour of Bibolo at four different stress levels, for specimens BIBs 1, 3-6 and 27. At constant stress the stain increases with time. Moreover, the higher the applied stress, the higher the strain rate at any given time.

The compliance versus log (time) curves are shown in Figure-4. The compliance curves do not coincide. This means that the applied stresses are in the nonlinear domain. The lowest stress used was 9.19 MPa, which represents about 9.19% of the average breaking load (ABL). Stresses below this value of 19.19 MPa were not tested. Therefore, there exists the possibility that the stress nonlinear onset could even be lower than 9.19 MPa.

The creep strain curves at various stress levels, plotted in the logarithmic time scale were superposed through a horizontal shift to obtain a master curve, in accordance to TSSP. To obtain the master creep curve, the reference stress chosen was 11.03 MPa for specimens BIB 1- 6, and 9.19 MPa for specimen BIB 27.

The shift factors were calculated manually. The resulting creep master curves and the variation of the horizontal stress shift factor as a function of stress difference, (σ-σ_R), are shown in Figures 7 and 8, respectively.

The master curves represent accelerated creeps of between 8 decades and 13 decades outside the experimental window depending on the specimen. Therefore, to predict the creep performance of Bibolo over a period of 10 decades to 15 decades, it is only required to carry out tests of three hours duration at stress levels from 9.19 MPa to about 27.5 MPa.

Fitting the data of stress horizontal shift factors and stress differences in equation (7) the corresponding values of the constants, C_1 and C_2 were determined. These are shown in the Table-1, below.

Table-1. Values of the constants C1 and C2.

	BIB 1	BIB 3	BIB 4	BIB 5	BIB 6	BIB 27
C1	20.96	23.6	21.67	39.5	22.7	20.72
C2	-73.33	-55.2	-75.6	-120	-84.3	-112.45

Tissaoui J. [34] observed that the values of the constants C1 and C2 depend on the type of polymer material. However, the values of 17.4 and 51.6 for C1 and C2, respectively have been commonly used for temperature shift [6]. Other values in literature are: 8.07 and 29.845 for polycarbonate with reference stress 30.97 MPa [5], 15.016 and -28.406, 8.86 and 101.6.

Therefore, the values of C1 and C2 obtained in this study are generally in agreement with existing data despite the dispersion observed.

CONCLUSIONS

The effect of stress on short-term creep behaviour of viscoelastic Bibolo has been experimentally investigated in this study. An increase in stress will increase the free volume in materials to allow more active motion of the material units, resulting shorter relaxation or retardation times. The creep compliance of Bibolo was found to be a function of stress. The TSSP was used to construct the master creep curve at a selected stress based on the short-term tests in the region of nonlinear viscoelasticity.

The time-stress shift factor is dependent on stress difference between the reference stress and the other accelerating stress levels.

The variation of creep compliance with time shows that Bibolo wood shows nonlinear creep behaviour for stresses of 9.2 MPa and above, which is about 10 % of the ultimate stress.

The accelerated procedure, time-stress superposition (TSSP) applied to Bibolo predicted creep for about 10 decades beyond the test window at room conditions of temperature and pressure at a service stress of 9.2 MPa for specimen BIB 27 and 11.0 MPa for the other specimens.

Potentially the material behaviour can be extrapolated to considerably longer time periods using this technique, thus increasing the efficiency with which creep data can be generated.

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