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Relaxation and creep behaviour of false banana's fibre (*Ensete ventricosum*)

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Abstract. This study was focused on the analysis of viscoelastic behaviour of fibres of false banana (*Ensete ventricosum*). The aim of the experiment was to describe the short term creep and relaxation behaviour under tension loading. The fibers of *Ensete ventricosum*, originally from Ethiopian region Hawasa, were used in this experiment. Moisture content $Mc = 8.40 \pm 0.67\%$ (d. b.) and true density $\rho_t = 668 \pm 44$ kg m^{-3} of the samples were determined. The specimens had initial gauge length of $L_0 = 100 \pm 1$ mm and the average yarn breaking load (YBL) after 20 tests was $\sigma_r = 14.3 \pm 1.7$ N. To determine the relationship between tension force and deformation, tension device (Labortech, MPTest 5.050, Czech Republic) was used to record the course of deformation function. All tests were performed using a constant rate $\alpha = 3.1$ N s^{-1}. The short term creep tests were performed using constant loads of 30%, 60% and 90% of the average YBL. The short term relaxation tests were performed using constant strain of 30%, 60% and 90% of maximal strain. Measured data were analysed by computer software Mathcad 14. Experimental creep and stress relaxation curves at different load levels were determined. Experimental creep lifetimes t_r for different load levels: 24,311 ± 7,489 s (30% YBL), 1,831 ± 462 s (60% YBL) and 17.6 ± 5.5 s (90% YBL) were determined. Initial modulus of elasticity, finite modulus of elasticity and initial energy of stress relaxation and creep of Ensete fibres were determined.

Key words: agriculture, initial modulus, tensile test.

INTRODUCTION

The design of new materials based on natural reseources is essential for both environmental and economical analyses (Alves et al., 2010). Currently, there has been great attention on the application of natural fibres as a substitute for synthetic fibres. The natural fibres are environmentally friendly, biodegradable and recyclable, and also they can help in the reduction of waste and environmental pollution (Kalia et al., 2013). Natural fibres can be a suitable substitute of synthetic fibres because they are available in a fibre form at low costs (Aseer et al., 2013). Literature indicate that natural fibres such as flax, jute, hemp, sisal and pineapple have significant advantages in comparison with conventional fibres (Rao et al., 2007; Silva et al., 2008; Alves et al., 2010; Faruk et al., 2012). They reach relatively high specific strength and a rigidity owing to their low density. Another suitable plant with great potential for the production of natural fibers is

Ensete (*Ensete ventricosum*) also known as false banana (Tsehaye & Kebebew, 2006; Yemataw et al., 2014). The Ensete plant do not bear edible fruits and it is not categorized as usual banana plants (genera Musa). It is a perennial herbaceous plant that grows in Ethiopia and it is primarily intended for human consumption and animal feeding (Vincent et al., 2013; Herak et al., 2014). Over centuries the Ensete fibres have been extracted from the leaves of this plant as major material for the weaving, ropes and cord production, as well as for baskets production (Diriba et al., 2013; Yirmaga 2013). Ensete fibres as reinforcement in composite materials researched Mizera et al., 2015. One of the most important considerations using natural fibres in engineering applications is the relaxation and creep behaviour. Creep and relaxation measurements are of interest to chemists and engineers in any application where the material must sustain loads for long periods (Sedlachek, 1989). However, currently, in terms of creep and relaxation behaviour the Ensete fiber are not adequately described. Previously published scientific work focused specifically on Ensete plant deal with chemical and physical properties (Nurfeta et al., 2008). The aim of this experiment was to describe creep and relaxation behavior of *Ensete ventricosum* fiber under tension loading and to determine the initial modulus of elasticity, finite modulus of elasticity and initial energy of relaxation and creep behaviour.

MATERIALS AND METHODS

Sample

Samples of fibres produced from *Ensete ventricosum*, obtained from Hawassa region, Ethiopia were used for the experiment. The moisture content $M_c = 8.40 \pm 0.67\%$ *(d. b.)* of the samples was determined using standard oven method, ASAE method (ASAE S410.1 DEC97, ASAE, 1998). Samples of 100 g mass from a batch of Ensete fibres were randomly selected for the moisture content determination. The mass of each sample m_s (g) was determined using an electronic balance (Kern 440–35, Kern & Sohn GmbH, Balingen, Germany). The true fibre density $\rho_t = 668 \pm 44$ kg m^{-3} was determined gravimetrically (Blahovec, 2008). This means that the mass of individual samples from a batch of fibres, randomly selected and measured using an electronic balance (Kern 440–35, Kern & Sohn GmbH, Balingen, Germany), was divided by the volume of sample. The volume of the individual sample was determined by weighing the sample in toluene and applying the principle of buoyancy (Kim et al., 2012). The results obtained were expressed as mean of three replicates. The morphologies of fibres were studied using a scanning electron microscope (Tescan Mira3, Czech Republic). The samples were covered with a thin layer of gold using a sputter coater (Quorum Q150R ES, United Kingdom) before SEM observation. The observation was prepared in the secondary electron mode with an accelerating voltage of 5 kV.

Tensile rupture test

To determine the relationship between tension force and deformation, tensile device (Labortech, MPTest 5.050, Czech Republic) was used to record the course of deformation function. All tests were performed using a constant rate of $\alpha = 3.1$ N s^{-1} under following conditions: 23 ± 2 °C of temperature and 51 ± 2% of humidity. The specimens had initial gauge length of $L_0 = 100 \pm 1$ mm. The average yarn breaking load (YBL) after 20 tests was 14.3 ± 1.7 N.

The stress σ at a given instant t can be defined as the rate between the applied tensile force $F(t)$ and the average yarn fibre area A_0 (Eqn. 1).

$$\sigma(t) = \frac{F(t)}{S_0}; S_0 = \frac{\rho_l}{\rho} \Rightarrow \sigma(t) = F(t) \cdot \left(\frac{\rho}{\rho_l} \right) \tag{1}$$

where: ρ_l – mass of fibre per unit length, tex, ρ – mass density of fibre material, mg m^{-3}. The rupture stress of fibre σ_r can be defined after that as:

$$\sigma_r(t) = \frac{\sigma(t)}{\rho} = \frac{F_r}{\rho_l} \tag{2}$$

where: σ_r – rupture stress of fibre, N tex^{-1}; F_r – rupture force, N; ρ_l – mass of fibre per unit length, tex.

The natural fibres have different average diameters, it was necessary to normalise the load data to obtain comparable values. In the textile industry, normalisation is generally done using the linear mass of the material, in tex (1 tex = 1g km). Ensete fibres applied in this study have linear weight ρ_l = 118.4 dtex (where 1dtex = 1g 10,000 m^{-1}). Hence the average rupture stress σ_r for fibres is given by (F_r/ρ_l) = 14.3/118.4 ≈ 0.12 N $dtex^{-1}$.

Short term creep test

Each sample with initial length L_0 = 100 ± 1 mm was initially loaded at a rate of α = 3.1 N s^{-1} until a limit constant load F_0. The tests were performed using constant loads of 30%, 60% and 90% of the average YBL (15 times per load levels). Fig. 1 shows the typical loading history the samples in a creep test.

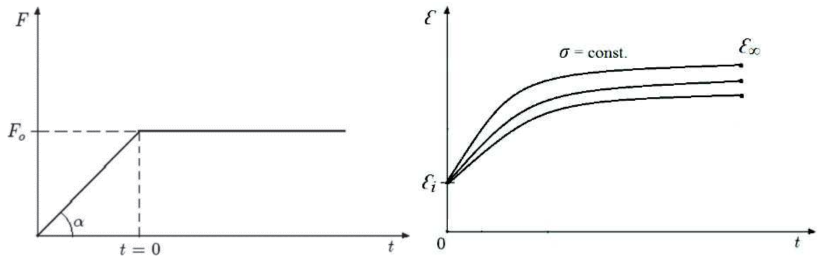

Figure 1. Typical loading history (left) and measured curves (right) in a creep test.

The tests were conducted until the fibre failure. The initial modulus of elasticity for creep E_{Ci} and finite modulus of elasticity $E_{C\infty}$ were calculated using Eqn. 3 and Eqn. 4:

$$E_{Ci} = \frac{\sigma}{\varepsilon_i} \tag{3}$$

where: E_{Ci} – initial modulus of elasticity for creep, N tex^{-1}; σ – stress of fibre, N tex^{-1}; ε_i – initial strain of fibre, –,

$$E_{C\infty} = \frac{\sigma}{\varepsilon_\infty} \tag{4}$$

where: $E_{C\infty}$ – finite modulus of elasticity for creep, N tex^{-1}; σ – stress of fibre, N tex^{-1}; ε_∞ – finite strain of fibre, –.

The energy of creep test was calculated as an area below a curve 'stress – strain' from zero to a maximum value of the deformation according to an Eqn. 5:

$$W_{Ci} = \frac{1}{2}\sigma\varepsilon_i + \sigma(\varepsilon_\infty - \varepsilon_i) \tag{5}$$

where: W_{Ci} – energy of creep test, N tex^{-1}; σ – stress of fibre, N tex^{-1}; ε_i – initial strain of fibre, –, ε_∞ – finite strain of fibre, –.

Short term stress relaxation

The stress relaxation experiments were performed on tensile device (Labortech, MPTest 5.050, Czech Republic). The samples with initial length L_0 = 100 ± 1 mm was initially loaded at a rate α = 3.1 N s^{-1} until a limit constant deformation ε_0, which corresponded to the loads of 30%, 60% and 90% of the average YBL (15 times per load levels).

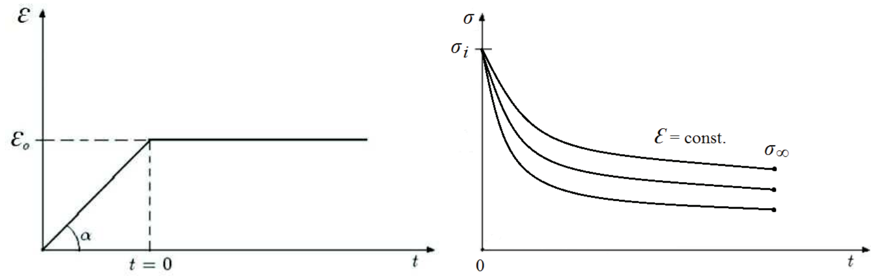

Figure 2. Typical loading history (left) and measured curves (right) in a stress relaxation test.

The tests until the run-out time of 1,000 s were conducted. The initial modulus of elasticity for relaxation E_{Ri} and finite modulus of elasticity $E_{R\infty}$ were calculated using Eqn. 6 and Eqn. 7:

$$E_{Ri} = \frac{\sigma_i}{\varepsilon} \tag{6}$$

where: E_{Ri} – initial modulus of elasticity for relaxation, N tex^{-1}; σ_i – initial stress of fibre, N tex^{-1}; ε – strain of fibre, –,

$$E_{R\infty} = \frac{\sigma_\infty}{\varepsilon} \tag{7}$$

where: $E_{R\infty}$ – finite modulus of elasticity for relaxation, N tex^{-1}; σ_∞ – finite stress of fibre, N tex^{-1}; ε – strain of fibre, –.

The initial energy of relaxation test was calculated as an area below a curve 'stress – strain' from zero to a maximum value of the deformation according to an Eqn. 5:

$$W_{Ri} = \frac{1}{2}\sigma_i \varepsilon \tag{8}$$

where: W_{Ri} – initial energy of relaxation test, N tex^{-1}; σ_i – initial stress of fibre, N tex^{-1}; $\mathcal{E}$ – strain of fibre, –.

RESULTS AND DISCUSSION

SEM image of cross-section of Ensete fibre which was used in this study can be seen in Fig. 3. Fig. 4 shows the creep strain as a function of time under tensile stress at different load levels (level 1: F_0 = 4.3 N; level 2: F_0 = 8.6N; level 3: F_0 = 12.9 N). The rupture force in a tensile test with prescribed load history $F(t) = \alpha t$ is dependet of the rate α (Mattos & Chimisso, 2011). For the rate α = 3.1 N s^{-1}, the average YBL obtained in the tensile tests was 14.3 ± 1.7 N. Very similar values were determined also in polyethylene fibres (Lechat et al., 2011).

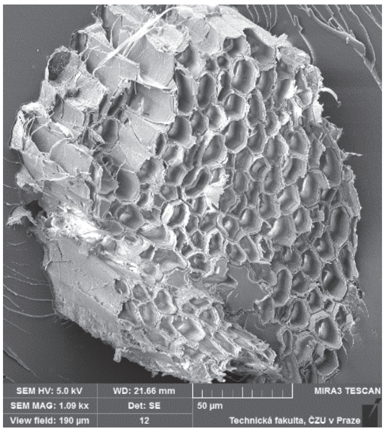

Figure 3. SEM image of Ensete fibre.

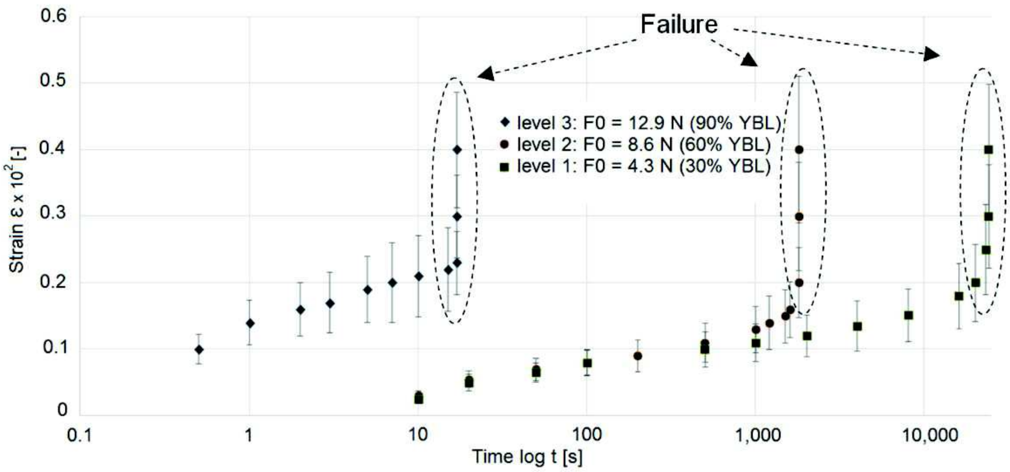

Figure 4. Measured creep curves of Ensete fibres.

From Fig. 4 it is possible to observe that a typical experimental curve of natural fibres shows three stages: (i) a ‘primary creep’ phase during hardening of material leads to a decrease in the rate of flow which is initially very high. Primary creep is the time-dependent recoverable portion of the delayed deformation. This response of viscoelastic materials is thought to be due primarily to configurational changes in molecular structure produced by the applied load. Alfrey discusses the mechanisms of such molecular movement.; (ii) a ‘secondary creep’ phase is a portion of the total sample deformation which is nonrecoverable at the test conditions after removal of the load. Permanent deformation is caused by viscous flow, irreversible crystallization, and molecular chain rupture (Ferry, 1961). In this phase is the rate of flow almost constant. ; (iii) a ‘tertiary creep’ phase during which the strain rate increases up to failure. It can be verified that the load level strongly affects the creep deformation rate and creep lifetime (Mattos & Chimisso, 2011). Table 1 shows the experimental lifetimes t_r of Ensete fibres obtained for different load levels.

Table 1. Experimental creep lifetimes for different load levels

F_0 (N)	t_r (s)
4.3	24,311 ± 7,489
8.6	1,831 ± 462
12.9	17.6 ± 5.5

From the creep curves (Fig. 4) the modulus of elasticity using Eqn. 3 and Eqn. 4 for different load level were calculated. Table 2 presents initial modulus of elasticity, finite modulus of elasticity and creep energy of Ensete fibres for different load levels.

Table 2. Initial modulus of elasticity, finite modulus of elasticity and creep energy of Ensete fibres

F_0 (N)	E_{Ci} (N tex^{-1})	$E_{C\infty}$ (N tex^{-1})	W_{Ci} (mN tex^{-1})
4.3 (30% YBL)	12.23 ± 3.18	11.46 ± 2.54	6.0913 ± 1.1574
8.6 (60% YBL)	20.08 ± 5.83	19.22 ± 3.44	14.2348 ± 3.4151
12.9 (90% YBL)	18.58 ± 4.11	17.91 ± 3.22	34.1797 ± 6.4929

Similar values of initial modulus of elasticity was shown also in jute fibre (Kozlowski, 2012). From Table 2 it is evident that the difference between the initial modulus and finite modulus of elasticity reaches low values. This is due to a very small value of strain of natural fibres in tensile loading (Kozlowski, 2012). In natural fibre the cellulose chains lie approximately parallel to the long axis of the fibre.When load is applied on a fibre, the stress is transmitted from one chain to its neighbour by means of intermolecular forces. These forces are strongest in the crystalline areas, where the chains lie in closest proximity to each other (Ray et al., 2009). The creep depends on the fibre mobility in the stress concentration region. Therefore, closer arrangement of the molecular chains (higher crystallinity) reduces the creep deformation (O´Shaughnessy, 1948).

Fig. 5 shows stress relaxation curves for different load levels. The test rate α and the deformation rate are affect the failure pattern of the fibres and thereby, the relaxation mechanism. Table 3 presents initial modulus of elasticity, finite modulus of elasticity and initial energy of stress relaxation of Ensete fibres for different load levels.

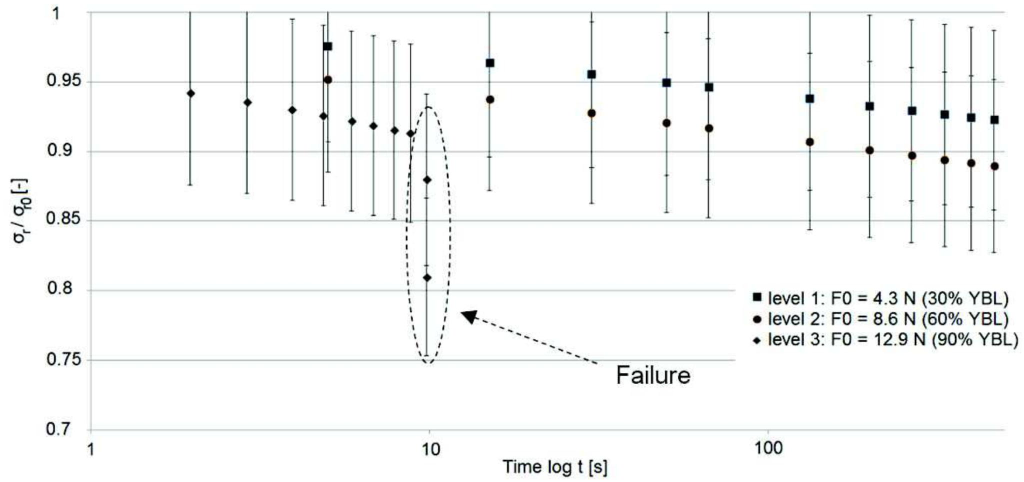

Figure 5. Measured stress relaxation curves of Ensete fibres.

Table 3. Initial modulus of elasticity, finite modulus of elasticity and initial energy of stress relaxation of Ensete fibres

F_0 (N)	E_{Ri} (N tex^{-1})	$E_{R\infty}$ (N tex^{-1})	W_{Ri} (mN tex^{-1})
4.3 (30% YBL)	12.35 ± 3.11	11.13 ± 2.21	5.3667 ± 1.1497
8.6 (60% YBL)	20.64 ± 6.04	17.67 ± 3.68	13.0754 ± 3.2217
12.9 (90% YBL)	17.98 ± 3.97	16.31 ± 3.18	31.7886 ± 5.7811

The stress relaxation curves at 30%, 60% and 90% load levels were given in Fig. 5. The extent of fibre failure accurrence will differ at different strains. On application of stress, physical and chemical rearrangements may occur but on relaxation, the mechanism is only physical. At higher strain levels, the highly fractured portions of the fibre leads to higher relaxation, owing to its physical rearrangement at long duration (Sreekala et al., 2001). The rate of relaxation becomes higher for high strain strain levels at long durations. At very low strain levels, commendable failure of fibre does not happen. In such a system, the relaxation rate will be very low. At very high strain levels, there is also the possibility for a slow relaxation as the failure has already occurred. Nonetheless, a medium-strained fibre passes through complicated failure mechanisms. Hence, the major relaxation takes place and a higher rate will be recorded. From Fig. 5 is vissible, that the general trends are the same for all three, however, maintaining higher strain level brings about higher relaxation. The values of stress relaxation of Ensete fibres are lower than in the case of oil palm fibres. Higher values of stress relaxation reached also the fibres from Jute and Sisal (Gaston et al., 2010).

CONCLUSIONS

The aim of this study was to describe the creep and stress relaxation behaviour of the fibres from the plant false banana *Ensete Ventricosum*. It was ascertained following:

- The average yarn breaking load (YBL) of Ensete fibres after 20 tests was 14.3 ± 1.7 N.
- The short term creep curves of Ensete fibre under tensile stress at different load levels (30% YBL: F_0 = 4.3 N; 60% YBL: F_0 = 8.6N and 90% YBL: F_0 = 12.9 N) were determined. Experimental creep lifetimes for different load levels: 24,311 ± 7 489 s (30% YBL), 1,831 ± 462 s (60% YBL) and 17.6 ± 5.5 s (90% YBL) were determined. Initial modulus of elasticity, finite modulus of elasticity and creep energy at different load levels were also determined.
- The short term stress relaxation curves of Ensete fibre under tensile stress at different strain levels (30% of maximal strain; 60% of maximal strain and 90% maximal strain) for time of 1,000 s were determined. Initial modulus of elasticity, finite modulus of elasticity and initial energy of relaxation of Ensete fibres were also determined.

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