EFFECT OF LENGTH OF FALSE BANANA FIBRE (*ENSETE VENTRICOSUM*) ON MECHANICAL BEHAVIOUR UNDER TENSILE LOADING*

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The effect of gauge length of false banana fibre (*Ensete ventricosum*) on the tensile strength, volume energy, and modulus of elasticity under tensile loading was examined. Fibres of gauge length L_0 (mm) 10, 20, 40, 80, 160, and 320 mm were prepared and tested until rupture point at strain rate of 0.05 min^{-1}. Mathematical models describing the mechanical behaviour of the varying gauge lengths were presented. With the increasing gauge length of fibre, the tensile strength and volume energy decreased while the values of modulus of elasticity increased. The theoretical model describing the mechanical behaviour of Ensete fibre under tensile loading presented herein provides useful information for the fibres application in industry. The determined models could be used as a background for further research focused on Ensete fibre application.

stress; strain; elongation; deformation characteristic; natural; material

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INTRODUCTION

The design of new materials based on natural renewable resources is essential for both environmental and economic analyses (Alves et al., 2010). Presently, there has been a great interest in the application of natural fibres as a substitute for synthetic fibres. Natural fibres are environmentally friendly, biodegradable, and recyclable, thus reducing waste and environmental pollution (Kalia et al., 2013). Natural fibres are a good substitute for synthetic polymeric fibres since they are available in fibrous forms at low cost (Aseer et al., 2013). Literature indicates 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 can attain high specific strength and stiffness due to their low density. Another suitable plant with a great potential for the production of natural fibres is Ensete (*Ensete ventricosum*), also known as false banana (Tsehaye et al., 2006; Yemataw et al., 2014). The Ensete plant does not bear edible fruits and it is not categorized as common banana plants (genus *Musa*). One of the most important considerations using natural fibres as a construction material is the effect of their length on mechanical properties (Bledzki, Gassan, 1999). Mukherjee, Satyanarayana, (1986) showed that the tensile strength of flax and pineapple fibres (unlike that of glass fibre) strongly depends on the length of fibre. This stems from the differences of published strength of one type of natural fibre (Biswas et al., 2011, Faruk et al., 2012). From the general theory of fibrous materials it follows that the strength values of fibres decrease with increasing gauge length (Neckar, Das, 2012). The relationship between length of fibre and tensile strength has been investigated in commonly grown banana (*Musa sapientum*) (Kulkarni et al., 1983). The effect of length of Curauá fibres (*Ananas erectifloius*) and oil palm fibres (*Elaeis guineensis*) has been studied, too (Tomczak et al., 2007; Guo et al., 2014). Defoirdt et

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al. (2010) reported on the length effects of fibres from coir, bamboo, and jute. Currently, however, concerning the effect of length of Ensete fibre on mechanical behaviour under tensile loading, there is not adequate information. The aim of this experiment was to describe the effect of length of *Ensete ventricosum* fibre on tensile strength, volume energy, and modulus of elasticity under tensile loading.

MATERIAL AND METHODS

Sample

Samples of fibres produced from *Ensete ventricosum* (obtained from Hawassa region, Ethiopia) were used for the experiment. The moisture content Mc = (8.7 ± 0.84%) (d.b.) of the samples was determined using ASAE S410.1 DEC97 method (A S A E S t a n d a r d s , 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 ρ_t = (690 ± 35) kg m^{-3} was determined gravimetrically (B l a h o v e c , 2008). This means that the mass of individual samples from a batch of fibres was randomly selected and measured using the electronic balance and divided by the volume of sample. But the volume of the individual sample was determined by weighing the sample in toluene and applying the principle of buoyancy (K i m et al., 2012). The obtained results were expressed as the mean of three replicates.

Tension test

To determine the relationship between tension force and deformation, a compression device MPTest 5.050 (Labortech, Opava, Czech Republic) was used to record the course of the deformation function. Selected samples of Ensete fibres (Fig. 1) were glued onto small paper frames using a two-component epoxy glue Epox Rapid (Fig. 3) with precisely defined gauge length of fibre L_0 (mm). Fibres of gauge length L_0 = 10, 20, 40, 80, 160, and 320 mm were tested. The prepared samples (Fig. 4) were inserted into grips of the testing machine where they were cut to allow free straining of fibres. Fibres of all lengths were tested until rupture at strain rate of 0.05 min^{-1} under temperature of 20°C. The experiment was repeated twenty times for each fibre gauge length. Fibres were analyzed for fibre diameter and thickness by image analysis using an optical microscope Zeiss Jenavert (Carl Zeiss, Jena, Germany). The dimensions were determined at 10 places of each fibre gauge length before tension test (Fig. 4).

The fibre cross section area was calculated by Eq. (1)

$$S = \pi \cdot \left(D \cdot t - t^2\right) \tag{1}$$

where:
S = cross section area (mm^2)
D = outer diameter of fibre (mm)
t = thickness of fibre (mm).

Stress-strain curve

Determined values of tension force and deformation were transformed into stress and strain using Eqs 2 and 3, respectively.

$$\sigma = \frac{F}{S} \tag{2}$$

$$\varepsilon = \frac{x}{L_0} \tag{3}$$

where:
σ = stress of fibre (MPa)
F = tension force (N)
S = appropriate cross section area of fibre (mm^2)
ε = strain of fibre (-)
x = elongation of fibre (mm)
L_0 = initial length of fibre (mm).

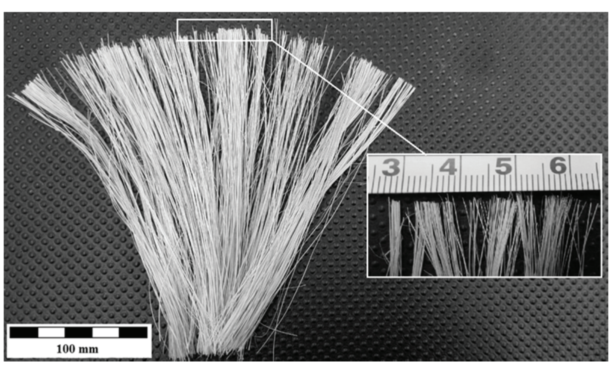

Fig. 1. *Ensete ventricosum* fibres

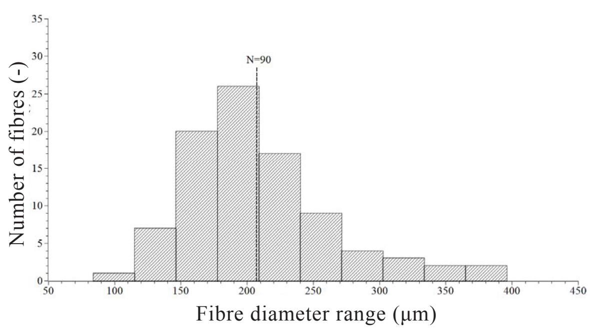

Fig. 2. Frequency distribution of false banana (*Ensete ventricosum*) fibres based on diameter

Table 1. Mechanical properties of Ensete fibre (data are means ± SD)

L_0 (mm)	σ_F (MPa)	ΔL_F (mm)	ε_F	E_F (MPa)	λ_F (J m^{-3})
10	605.67 ± 100.62	562 ± 73	0.056 ± 728·١٠$^{-5}$	21 696 ± 3 688	14.801 ± 2.801
20	537.48 ± 87.64	643 ± 95	0.032 ± 487·١٠$^{-5}$	30 471 ± 4 452	11.666 ± 2.102
40	325.72 ± 56.48	768 ± 109	$0.019 \pm 266 \cdot 10^{-5}$	54 272 ± 10 977	5.354 ± 0.906
80	297.96 ± 51.02	1 287 ± 211	$0.016 \pm 256 \cdot 10^{-5}$	64 551 ± 13 097	2.919 ± 0.526
160	253.57 ± 46.42	2 432 ± 304	$0.015 \pm 173 \cdot 10^{-5}$	85 755 ± 19 678	2.540 ± 0.492
320	254.54 ± 55.03	5 127 ± 665	$0.016 \pm 209 \cdot 10^{-5}$	83 374 ± 19 921	2.268 ± 0.528

L_0 = initial length of fibre, σ_F = rupture stress, ΔL_F = rupture elongation, ε_F = rupture strain, E_F = modulus of elasticity, λ_F = volume energy

Modulus of elasticity

Modulus of elasticity was determined as the slope of a line specified by the fitting stress-strain curve. The slope of the fitted line was calculated by Marquardt Levenberg algorithm (Marquardt, 1963; Lourakis, 2005) using the computer program MathCAD 14 (PTC Software, Needham, USA) (Pritchard, 1998).

Volume energy

Volume energy is the area under the stress-strain curve from the zero strain to maximum strain and it was calculated by Eq. 4.

$$\lambda_F = \sum_{n=0}^{n=i-1} \left[\left(\frac{\sigma_{n+1} + \sigma_n}{2} \right) \cdot \left(\varepsilon_{n+1} - \varepsilon_n \right) \right] \tag{4}$$

where:
λ_F = volume energy (J m^{-3})
i = additional amount of strain in which stress was determined by step measurement of 0.001 mm (-)
σ_n = tension stress at appropriate strain (MPa)
σ_{n+1} = tension stress at sequential strain (MPa)
ε_n = strain (-)
ε_{n+1} = sequential strain (-).

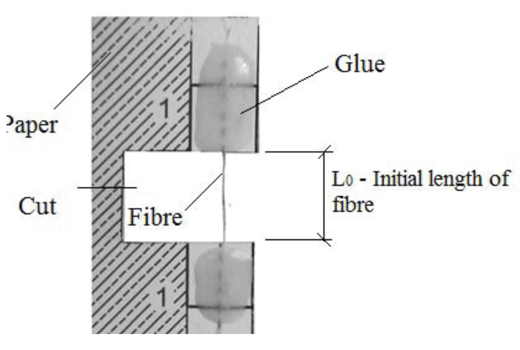

Fig. 3. Experimental sample of *Ensete ventricosum* fibre glued onto paper frames

RESULTS

The value of the coefficient of variation, usually determined in biological materials, was less than 6% implying that all determined geometrical properties are similar throughout the length of each fibre (Mohsenin, 1970; Stroshine, 2000; Blahovec, 2008). A view of the fibre sample with the positions at which geometrical properties were measured is given in Fig. 4. The distribution curve of geometrical diameters of fibres was determined (Fig. 2). For each fibre the dependency between tension force and elongation was recorded, and transformed into stress-strain curve using Eq. 2 and Eq. 3. The calculated relationship of tension stress vs strain for each gauge length of fibre is presented as average value (Table 1). The average values of tension stress for each gauge length of fibres are shown in Fig. 5. The volume energy for each examined fibre was determined by Eq. 4 and it is presented for individual fibres gauge lengths (Table 2). The values of modulus of elasticity for individual gauge lengths of fibres were determined as the slope of the line which was specified by fitting stress-strain curve. The calculated values of modulus of elasticity for individual gauge lengths of fibres are presented in Fig. 7. The individual measured and calculated values for tension stress (Fig. 5) and volume energy (Fig. 6) were fitted by exponential curve using Marguardt Levenberg algorithm and they are described by Eq. 5 and Eq. 6.

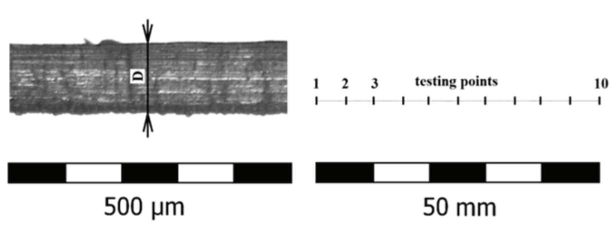

Fig. 4. Longitudal view of the sample of *Ensete ventricosum* fibre

Table 2. Mathematical model of tensile strength and volume energy of Ensete fibre

$F(x) = A \cdot e^{B \cdot x} + C$	A_1, A_2 (MPa, J m^{-3})	B_1, B_2 (mm^{-1})	C_1, C_2 (MPa, J m^{-3})	F_{rat}	F_{crit}	P_{value}	R^2
$\sigma_F (L_0)$ (MPa)	548.165	–0.041	256.303	$-2.019.10^{-14}$	4.965	0.99	0.969
$\lambda_F(L_0)$ (J m^{-3})	*3.884*	–0.049	0.476	$3.668.10^{-15}$	4.965	0.99	0.989

σ_F = tension stress, λ_F = volume energy, L_0 = initial length of fibre, A = first coefficient of exponential curve, B = second coefficient of exponential curve, C = third coefficient of exponential curve, F_{rat} = value of the F test, F_{crit} = critical value that compares a pair of models, P_{value} = hypothesis of the study outcomes significant level, R^2 = coefficient of determination

$$\sigma_F(L_0) = A_1 \cdot e^{B_1 \cdot L_0} + C_1 \tag{5}$$

$$\lambda_F(L_0) = A_2 \cdot e^{B_2 \cdot L_0} + C_2 \tag{6}$$

where:
σ_F = rupture stress (MPa)
λ_F = volume energy (J m^{-3})
L_0 = gauge length of fibre (mm)
A_1; A_2 = first coefficients of exponential curve (MPa; J m^{-3})
B_1; B_2 = second coefficients of exponential curve (mm^{-1})
C_1; C_2 = third coefficients of exponential curve (MPa; J m^{-3}).

The individual coefficients from Eq. 5 and Eq. 6 are shown in Table 2. From ANOVA statistical analysis (Table 2) it follows that the measured values of tension stress and volume energy and the results from the general exponential models (Eq. 5 and Eq. 6) were statistically significant at the significance level 0.05. It means that the values of F_{crit} (critical value comparing a pair of models) were higher than the F_{rat} values (value of the F-test) for all the measured Ensete fibres and values of P_{value} (significance level at which the hypothesis of equality of models can be rejected) were higher than 0.05 which is also confirmed by very high coefficients of determination R^2. The determined values of the modulus of elasticity of fibres (Fig. 7) were fitted by Eq. 7 using Marguardt Levenberg algorithm:

$$E_F(L_0) = A_3 \cdot \left(e^{B_3 \cdot L_0} - 1\right) \tag{7}$$

where:
E_F = modulus of elasticity (MPa)
L_0 = gauge length of fibre (mm)
A_3 = first coefficient of exponential curve (MPa)
B_3 = second coefficient of exponential curve (mm^{-1}).

It is evident that the measured values of modulus of elasticity can be described by an exponential curve (Eq. 7) which is confirmed by the ANOVA statistical analysis results (Table 3) at significance level 0.05.

DISCUSSION

As shown in Fig. 5, tensile strength decreased with the increasing gauge length. This corresponds with the general theory of fibrous materials, because the increasing length of fibres increases the probability of the occurrence of various defects in the fibres

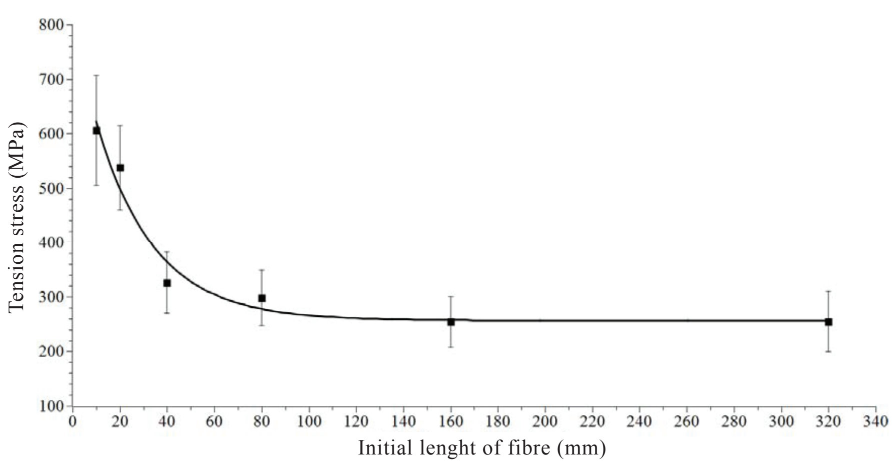

Fig. 5. Effect of gauge length of *Ensete ventricosum* fibre on tensile strength

Table 3. Mathematical model of the modulus of elasticity of Ensete fibre

$F(x) = A \cdot \left(e^{B \cdot x} - 1\right)$	A_3 (MPa)	B_3 (mm^{-1})	F_{rat}	F_{crit}	P_{value}	R^2
$E_F(L_0)$ (MPa)	$-8.368.10^4$	−0.024	0.000129	4.964	0.99	0.96

E_F = modulus of elasticity, L_0 = initial length of fibre, A_3 = first coefficient of exponential curve, B_3 = second coefficient of exponential curve, F_{rat} = value of the F test, F_{crit} = critical value that compares a pair of models, P_{value} = hypothesis of the study outcomes significant level, R^2 = coefficient of determination

and so it decreases their tensile strength (Bledzki, Gassan, 1999; Neckar, Das, 2012; Trujillo et al., 2014). For shorter fibres not only higher strength but also lower variance was found (Table 1). From Fig. 5 and Eq. 5, it is clear that the mechanical behaviour of Ensete fibres under tension loading depends on the gauge length of fibres, which can be divided into two regions. The first region is given by the range of fibre gauge length from 0 to 40 mm. In this region, tensile strength linearly decreases with the increasing length of fibre. Similar mechanical behaviour was shown also in the banana fibre of the genus *Musa sapientum* (Kulkarni et al., 1983). A significant reduction of strength in the range of fibre length of 40 mm was determined also in flax fibres, pineapple fibres (Mukherjee, Satyanarayana, 1986), and palm fibres (Guo et al., 2014). The second region, which is characterized by fibre length of more than 40 mm, exhibits already insignificant reduction in tensile strength. This region can be marked as a "strength limiting defect" which applies to Ensete fibres with gauge length of 40 mm or higher. For synthetic fibres the 'strength limiting defect' occurs with much smaller fibre lengths, which is associated with a different distribution of defects in synthetic fibrous material (Lim et al., 2011). From Fig. 7 it is evident that the modulus of elasticity of Ensete fibres depends on gauge length of fibres. The measured values of modulus of elasticity (Fig. 7) increased with the increasing gauge length. A very similar dependence between the modulus of elasticity and the gauge length of fibres is shown in bamboo fibres (Defoirdt et al., 2010; Biswas et al., 2011). Similar mechanical behaviour has also the jute fibre (Biswas et al., 2011).

CONCLUSION

Eqs. 5 and 6 describe the effect of gauge length of false banana fibre (*Ensete ventricosum*) for tensile strength. The statistically significant coefficients of mechanical behaviour of the above equations are indicated in Table 1. Eq. 7 also describes the effect of gauge length of fibre on the values of the modulus of elasticity. The coefficients of mechanical behaviour are presented in Table 3. The fibre with a length of 10 mm exhibited the best mechanical properties and also the smallest variance. The presented models of mechanical behaviour hopefully provided background information for further research focused on the Ensete fibre application.

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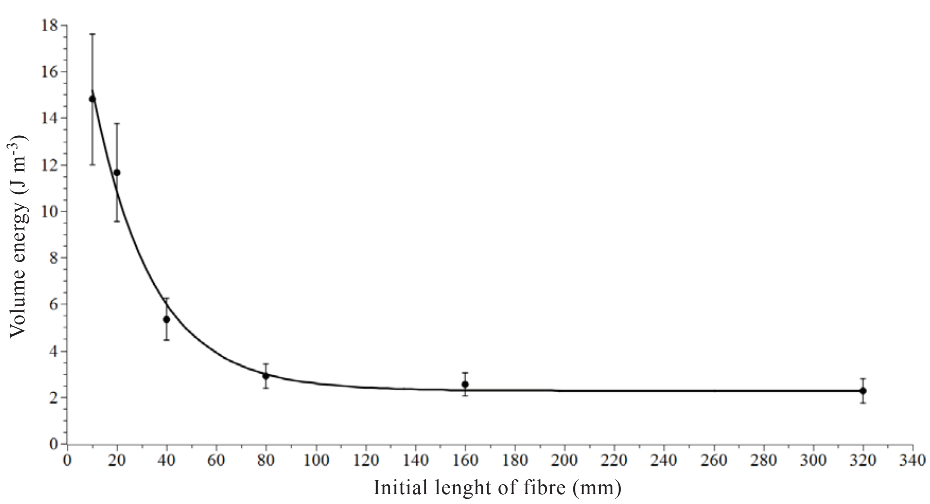
Fig. 6. Effect of gauge length of *Ensete ventricosum* fibre on volume energy



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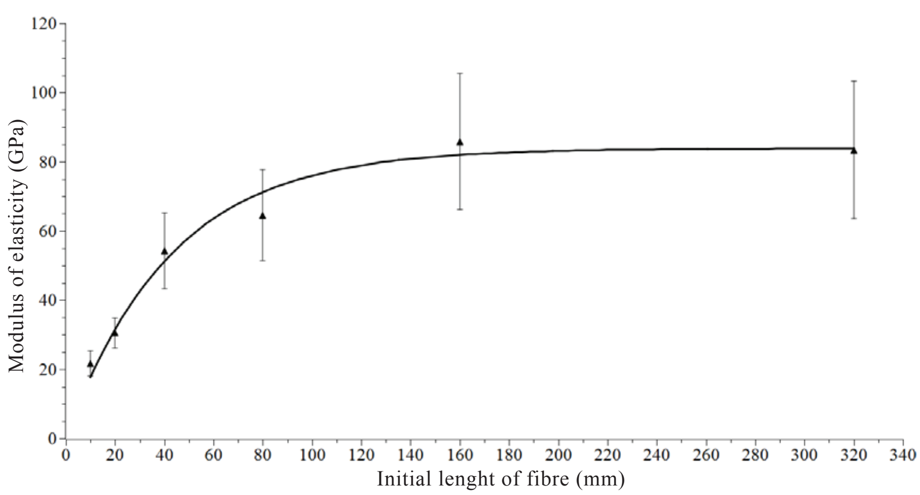

Fig. 7. Effect of gauge length of *Ensete ventricosum* fibre on modulus of elasticity

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Nomenclature: A_1 = first coefficient of exponential curve of rupture stress (MPa), A_2 = first coefficient of exponential curve of volume energy (J m^{-3}), A_3 = first coefficient of exponential curve of modulus of elasticity (MPa), B_1 = second coefficient of exponential curve of rupture stress (mm^{-1}), B_2 = second coefficient of exponential curve of volume energy (mm^{-1}), B_3 = second coefficient of exponential curve of modulus of elasticity (mm^{-1}), C_1 = third coefficient of exponential curve of rupture stress (MPa), C_2 = third coefficient of exponential curve of volume energy (J m^{-3}), D = outer diameter of fibre (mm), E_F = modulus of elasticity (MPa), F = maximal force (N), F_{crit} = critical value that compares a pair of models (-), F_{rat} = value of the F test (-), i = additional amount of strain (-), L_0 = fibre gauge length (mm), P_{value} = hypothesis of the study outcomes significant level (-), R^2 = coefficient of determination (-), S = cross section area (mm^2), t = thickness of fibre (mm), x = elongation of fibre (mm), ε = strain of fibre (-), ε_n = strain (-), ε_{n+1} = sequential strain (-), λ_F = volume energy (J m^{-3}), σ = stress of fibre (MPa), σ_F = rupture stress of fibre (MPa), σ_n = tension stress at appropriate strain (MPa), σ_{n+1} = tension stress at sequential strain (MPa)

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