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SOME MECHANICAL PROPERTIES OF PLANTAIN FRUIT

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Abstract. Using the Instron Testing Instrument (Model 1122) fitted with a flat-faced cylindrical plunger, prepared specimens of mature unripe plantain fruits (peeled and unpeeled) were compressed axially at 0.83, 1.67, 8.33, 16.67, 25.0, 33.33 x 10^{-5}m s^{-1} loading rates. From the force-deformation curves generated, some selected mechanical properties-bioyield parameters, rupture parameters and modulus of deformation-were evaluated.

The results show that for peeled specimens, all the determined mechanical properties increased with increase in loading rate and with fruit cross-sectional area. For the unpeeled specimens the bioyield parameters and modulus of deformation increased with increase in loading rates > 8.33 x 10^{-5}m s^{-1},while the rupture parameters decreased with increase in loading rates > 8.33 x 10^{-5}m s^{-1}. Only rupture strength, rupture energy and modulus of deformation for the unpeeled specimens decreased with increase in cross-sectional area. All the other parameters for the unpeeled specimens increased with increase in cross-sectional area. Also all the determined parameters were higher for the peeled than for the unpeeled specimens for loading rates > 8.33 x 10^{-5}m s^{-1}. The part played by the peel was also highlighted.

Keywords: bioyield and rupture parameters, loading rate, mechanical properties, modulus of deformation, plantain fruit

INTRODUCTION

Plantain (*Musa paradisiaca*) have high nutritional value [15,18] and are of great industrial importance in many humid tropical countries. The edible fruits are cooked by boiling, steaming, baking, roasting, or frying [5,16, 17,29] and may be processed into plantain chips, flour and puree [1,3,28]. Even the peels have been found useful in the production of alcohol fuel, e.g , ethanol [11]. Because of the high perishability of the plantain fruit and the inadequacy and relative ineffectiveness of handling, processing and storage facilities in most countries that produce the crop, there are high post-harvest losses of about 35-100% [2,5,8,19, 25,26]. Reduction of these losses require an understanding of the physical and mechanical properties that affect plantain handling at harvest and at post-harvest processing (peeling, frying, cooking and grinding), transportation and storage [10,13,22]. Determining the mechanical properties of plantain fruit can be used for different purposes such as the design of its processing machineries, the fruit texture and quality evaluation, as well as the production and control of impact damage on the fruit [4,14, 20,21,23].

The purpose of the study reported in this paper is to use the relationship between force and deformation of axially compressed unripe planting fruit specimens obtained at various loading rates and for different fruit diameters to estimate bioyield and rupture parameters which will help in designing machines and processes for minimising plantain fruit damage in collection, handling, processing and storage.

THEORETICAL CONSIDERATION

Biological materials have composition, moisture content and texture which vary continuously during growth, ripening and even in the course of storage. They constitute biomechanical systems of very complex construction, whose behaviour cannot be characterised by simple physical constants [22]. It is, therefore, important to introduce certain concepts and definitions such as bioyield point, rupture point, apparent modulus of elasticity or deformation (rigidity), toughness (rupture energy) and bioyield energy.

The bioyield point indicates the initial cell rupture in whole fruit and is used as a criterion for maximum allowable load that the plantain can sustain without showing any visible damage [24]. The rupture point indicates failure over a significant volume of material causing fracture planes or cracks in the macrostructure of the plantain. The apparent modulus of elasticity of deformation [30] which is referred to as the crop stiffness or rigidity is characterised by the tangent to the initial, more or less linear section of Fig. 1. The toughness (rupture energy) of the plantain is the work required to cause rupture in it. This is approximated by the area under the force-deformation curve up to the rupture point. The bioyield energy is the resilience (deformation work) of the plantain which is a measure of the ability of the fruit to store energy in the range of elasticity and is given as the area under the curve up to the bioyield point. The bioyield strength and strain are the stress and strain respectively measured at the bioyield point. The fruit strength shows the ability of the fruit to resist cracking [31]. The fruit energy concept has been used to design and specify cushioning materials for padding surfaces used for handling and transportation [6], while the modulus of deformation is associated with fruit stiffness and firmness. From the typical force-deformation curve shown in Fig. 1, the above parameters can be determined easily.

The shape of the plantain is considered to be cylindrical with the thin peel covering the thick pulp which has a slight gap in the middle (Fig. 2). The pulp to peel ratio for mature unripe

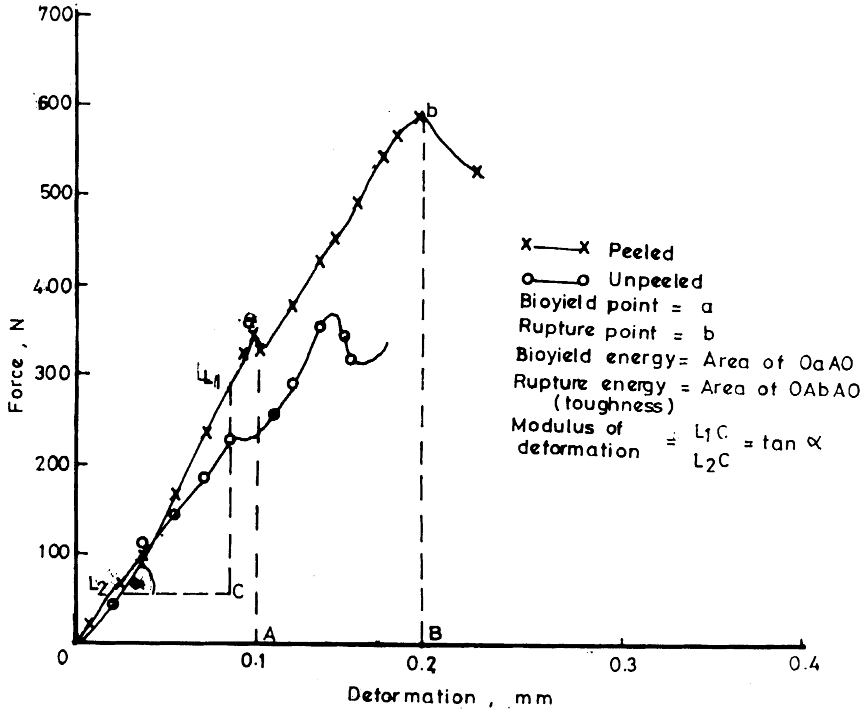

Fig. 1. Force-deformation curve for plantation fruits (peeled and unpeeled).

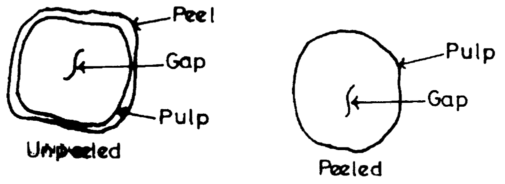

Fig. 2. Cross-section of the plantain fruit.

plantains has been found to vary between 1.1 and 1.8 by weight [3,27]. The pulp is larger and more homogenous than the peel which is composed of fibres bound together by the matrix. When the composite plantain fruit is cut and loaded axially, the stress on the composite will be shared by the various components, in a manner reflecting their volume fractions. The total load in the composite being the sum of the product of the yield stresses in the components and their volume fractions:

$$\sigma_t = \sum_{i=1}^{n} \sigma_i f_i \quad (1)$$

$$\sigma_t = \sigma_1 f_1 + \sigma_2 f_2 + \sigma_3 f_3 \quad (2)$$

$$1 = f_1 + f_2 + f_3 \quad (3)$$

$$f_1 \rangle f_2 \rangle f_3 \quad (4)$$

where σ_t - total yield stress, f - volume fraction, σ_i - component stress: and i 1, 2 and 3 represent pulp, fibre and peel matrix, respectively. Under axial loading, the composite unpeeled specimen deform to a barrel shape (Fig. 3), with the peel bulging out due to the presence of friction between the pressure plate and the end face of the specimen. The peel, being a weaker member of the composite because of its constituent matrix is not capable of withstanding much compressive stress and will rupture earlier than the pulp. The peeled specimen with the more homogenous pulp will withstand higher compressive load and deform later. The sensor will detect the matrix failure first in the bulging peel of the composite unpeeled specimen and later in the homogenous pulp in the peeled specimen. Plantains are subjected to forces during harvesting, transportation, storage, processing, etc, which are always accompanied by deformations, and must be sufficiently slight in order to avoid damage.

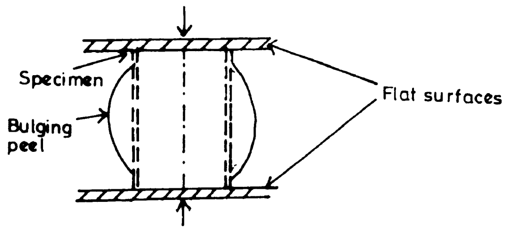

Fig. 3. Specimen placement between flatlat surfaces.

MATERIALS AND METHODS

Fresh mature unripe plantain bunches were purchased from the local market. Fairly straight unpeeled cylindrical fingers were selected and grouped according to three diameter sizes 3.80-4.19, 4.20-4.59, and 4.60-4.99 cm, measured using a vernier calliper at the middle of each fruit. There were 130 fingers in each diameter group. From the middle portion of each finger a length of 4.0 cm was cut out. The ends of each specimen were cut parallel to each other and perpendicular to the fruit axes using a sharp-edged knife in a special fixture. The specimens in each diameter group were subdivided into two sub-groups. Then the specimens in one sub-group were carefully peeled and their diameters measured. The remaining portions of each finger was used to determine the moisture content of the fruit by a standard oven method.

The Instron testing machine (Model 1122), which is a multipurpose automatic strain measuring device complete with an oscillography, was used for the uniaxial compression test on the plantain fruit specimens between two flats surfaces (Fig. 3) of the supporting jig. The cross-head and chart speeds were set as required and the full-scale load was set at 2000 N. The loading rates used in the study were 0.83, 1.67, 8.33, 16.67, 25.00, 33.33 x 10^{-5}m s^{-1}. Forty specimens from each of the peeled diameter groups were mixed and any 20 from the mixture were subjected to each loading rate starting with

1.67×10^{-5}m s^{-1}. One hundred and forty unpeeled specimens from the three diameter groups were used with 20 specimens subjected to the loading rates starting with 0.83×10^{-5}m s^{-1}. Twenty specimens from each sub-group of each diameter group were used to observe the variation of the bioyield and rupture parameters according to fruit cross-sectional area. The loading rates were cross-checked with a strain gauge and a stop watch. For each specimen (peeled and unpeeled), the instrument oscillography recorded and printed the stress-strain curve directly because the machine had an area compensator unit and took into consideration the unit of calibration along the Y-axis for stress and along the X-axis for strain. Energy was determined as the area under the stress-strain curve using a planimeter which was first calibrated. The slope of the straight portion of the curves were determined as the apparent modulus of elasticity or modulus of deformation.

RESULTS AND DISCUSSION

The force-deformation curves of all the specimens whose average moisture content was found to be 68.5 ± 2.3% d.b resemble that given in Fig. 1 with marked bioyield point, rupture point and a linear portion used in calculating the modulus of deformation. For these curves, the bioyield and rupture parameters were calculated, averaged and presented in Tables 1 and 2. From Table 1, it is observed that from $0.83\text{-}3.33 \times 10^{-5}$m s^{-1} loading rates the bioyield parameters as well as the modulus of

Table 1. Variations of mechanical properties of plantain fruit with loading rate

Loading rate (mm/min)	Bioyield strength (Pa)	Bioyield strain (mm/mm)	Bioyield energy (J)	Rupture strength (Pa)	Rupture strain (mm/mm)	Rupture energy (J)	Modulus of deformation (N/mm)
			Unpeeled				
0.5	0.342	0.353	0.041	0.484	0.412	0.110	0.939
	(0.028)	(0.042)	(0.003)	(0.011)	(0.024)	(0.006)	(0.012)
1.0	0.301	0.312	0.060	0.541	0.521	0.142	0.902
	(0.015)	(0.023)	(0.008)	(0.034)	(0.019)	(0.010)	(0.010)
2.0	0.243	0.301	0.069	0.610	0.585	0.161	0.880
	(0.041)	(0.054)	(0.004)	(0.042)	(0.044)	(0.009)	(0.022)
5.0	0.220	0.280	0.075	0.682	0.637	0.194	0.877
	(0.030)	(0.014)	(0.003)	(0.026)	(0.026)	(0.014)	(0.018)
10.0	0.254	0.308	0.080	0.628	0.609	0.179	0.966
	(0.022)	(0.019)	(0.006)	(0.036)	(0.015)	(0.016)	(0.026)
15.0	0.308	0.346	0.082	0.580	0.568	0.160	1.081
	(0.046)	(0.009)	(0.003)	(0.018)	(0.022)	(0.007)	(0.007)
20.0	0.376	0.402	0.085	0.509	0.560	0.144	1.194
	(0.055)	(0.026)	(0.005)	(0.021)	(0.036)	(0.005)	(0.009)
			Peeled				
1.0	0.148	0.189	0.040	0.410	0.542	0.191	0.838
	(0.021)	(0.047)	(0.006)	(0.026)	(0.051)	(0.008)	(0.021)
2.0	0.199	0.251	0.048	0.499	0.661	0.212	0.851
	(0.008)	(0.029)	(0.012)	(0.016)	(0.025)	(0.011)	(0.013)
5.0	0.311	0.359	0.069	0.801	0.821	0.310	0.896
	(0.036)	(0.063)	(0.010)	(0.039)	(0.032)	(0.021)	(0.008)
10.0	0.497	0.422	0.091	1.023	0.944	0.375	0.997
	(0.061)	(0.035)	(0.016)	(0.045)	(0.019)	(0.019)	(0.019)
15.0	0.624	0.448	0.108	1.120	1.108	0.416	1.165
	(0.019)	(0.019)	(0.009)	(0.029)	(0.021)	(0.026)	(0.026)
20.0	0.721	0.451	0.119	1.162	1.017	0.430	1.281
	(0.027)	(0.024)	(0.019)	(0.017)	(0.034)	(0.010)	(0.015)

Each value is mean of twenty observations. Figures in bracket are standard mean deviations.

Table 2. Variations of mechanical properties of plantain fruit with fruit cross-ectional area

Cross-sectional area (cm^2)	Bioyield strength (Pa)	Bioyield strain (mm/mm)	Bioyield energy (J)	Rupture strength (Pa)	Rupture strain (mm/mm)	Rupture energy (J)	Modulus of deformation (N/mm)
				Unpeeled			
11.95	0.278 (0.016)	0.350 (0.006)	0.041 (0.010)	0.713 (0.041)	0.540 (0.028)	0.201 (0.008)	1.129 (0.039)
13.95	0.312 (0.009)	0.351 (0.011)	0.062 (0.006)	0.532 (0.029)	0.582 (0.011)	0.152 (0.016)	0.932 (0.033)
15.95	0.340 (0.020)	0.441 (0.029)	0.101 (0.005)	0.481 (0.031)	0.601 (0.019)	0.130 (0.010)	0.807 (0.041)
				Peeled			
5.45	0.368 (0.028)	0.321 (0.034)	0.061 (0.008)	0.459 (0.083)	0.703 (0.042)	0.259 (0.062)	1.311 (0.054)
7.45	0.431 (0.064)	0.380 (0.041)	0.079 (0.021)	0.730 (0.055)	0.900 (0.071)	0.331 (0.049)	1.420 (0.069)
9.45	0.620 (0.049)	0.442 (0.022)	0.130 (0.014)	0.842 (0.039)	1.001 (0.058)	0.410 (0.055)	1.637 (0.071)

Each value is a mean of twenty observations. Figures in bracket are standard mean deviations.

deformation were higher for the unpeeled than for the peeled parameters [2]. However, for the loading rates >8.33 x 10^{-5}m s^{-1}, the reverse is the case. This indicates that for lower loading rates peeling of the fruit reduces the bioyield parameters. For the rupture parameters, only the rupture strength is higher for the unpeeled than the peeled at the lower loading rates $\leq$ 3.33 x 10^{-5}m s^{-1} .

Figure 4 shows the variation of bioyield parameters: strength, strain and energy with loading rates for (a) peeled and (b) unpeeled unripe plantain fruit specimens. For the peeled specimens these parameters increased linearly with an increase in loading rate, having linear correlation coefficients of 0.991, 0.891 and 0.982, respectively (Table 3). For the unpeeled, only bioyield energy increased with an increase in loading rate. The other two parameters (strength and strain) first decreased with loading rates $\leq$ 8.33 x 10^{-5}m s^{-1} and then increased with loading rates > 8.33 x 10^{-5}m s^{-1} with the lowest value being 0.220 Pa for bioyield strength and 0.028 mm/mm for bioyield strain. These values are lower than those obtained by Ajibola [2] probably because of the dimensions of the specimens used. Also, he worked with lower loading rates of 0.50 - 2.5 x 10^{-5}m s^{-1}.

The rupture parameters of strength, strain and energy for the peeled specimens, like those of the bioyield, all increased linearly with an increase in loading rates, having linear correlation coefficients of 0.934, 0.913 and 0.946, respectively (Table 3). This behavioural trend (Fig 5a) agrees with the theory of normal behaviour of viscoelastic material like processed apple [10]. For the unpeeled specimens, the three rupture parameters increased as the loading rate increased from 0.83 to 8.33 x 10^{-5}m s^{-1} and decreased with further increased loading rate (Fig. 5b). That the rupture parameters decreased for the unpeeled, and increased for the peeled, for loading rates >8.33 x 10^{-5}m s^{-1} may again be attributed to the peel which having bulged out (Fig. 3) deforms rather faster than when still attached to the pulp. The highest values of the rupture parameters for the unpeeled specimens are 0.682 Pa for strength, 1.06 x 10^{-5}m s^{-1} for strain and 0.194 J for energy.

The behaviour of the bioyield strength and strain when the loading rate is < 8.33 x 10^{-5}m s^{-1} and the rupture strength, strain and energy when the loading rate >8.33 x 10^{-5} m seems inconsistent with normal viscoelastic behaviour because of the presence of the peel. The peel of plantain has a thickness consisting of fibre materials which differ substantially from those of the pulp it covers. Even though the peel has been found to have a higher penetration resistance than the pulp [3,4], it is possible that the deviations from normal viscoelastic behaviour of unpeeled plantain bioyield and rupture parameters may be attributable to the presence of the peel.

When the bioyield and rupture parameters were analysed using the specimens' cross-sectional areas (Table 2), it was observed that for the bioyield (Fig. 6a), all parameters an

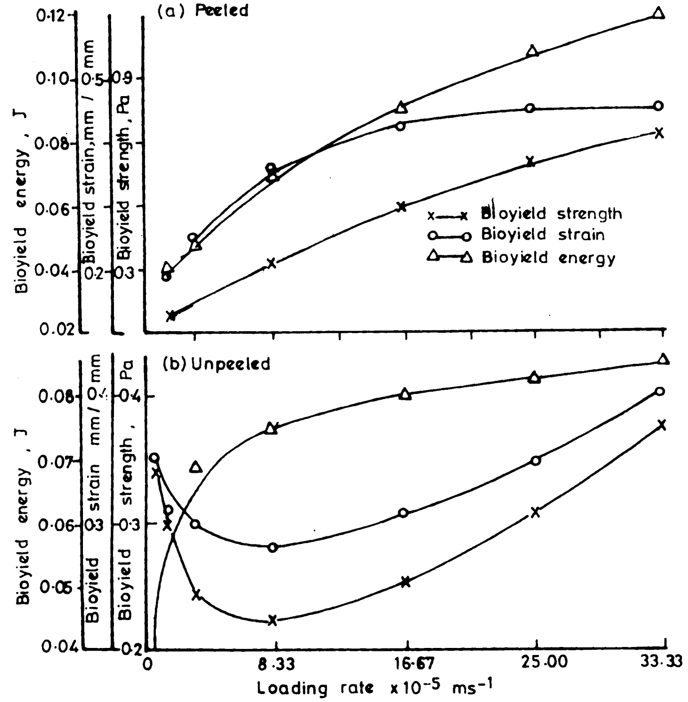

Fig. 4. Variations of bioyield parameters (a) peeled and (b) unpeeled plantain fruit.

Table 3. Linear regression equations of the peeled plantain mechanical properties with loading rate and cross-sectional area

Parameter	Loading rate (mm/min)	Cross-sectional area (cm^2)
Bioyield strength (Pa)	0.147 +0.031x ; r = 0.991	0.004 + 0.063b ; r = 0.961
Bioyield strain (mm/mm)	0.239 + 0.013x ; r = 0.891	0.156 + 0.030b ; r = 0.999
Bioyield energy (J)	0.042 + 0.004x ; r = 0.982	-0.039 + 0.012b ; r = 0.964
Rupture strength (Pa)	0.485 + 0.040x ; r = 0.934	-0.036 + 0.096b ; r = 0.972
Rupture strain (mm/mm)	0.624 + 0.024x ; r = 0.913	0.313 + 0.075b ; r = 0.983
Rupture energy (J)	0.209 + 0.013x ; r = 0.946	0.052 + 0.038b ; r = 0.999
Modulus of deformation (N/mm)	0.794 + 0.024x ; r = 0.993	0.849 + 0.082b ; r = 0.982

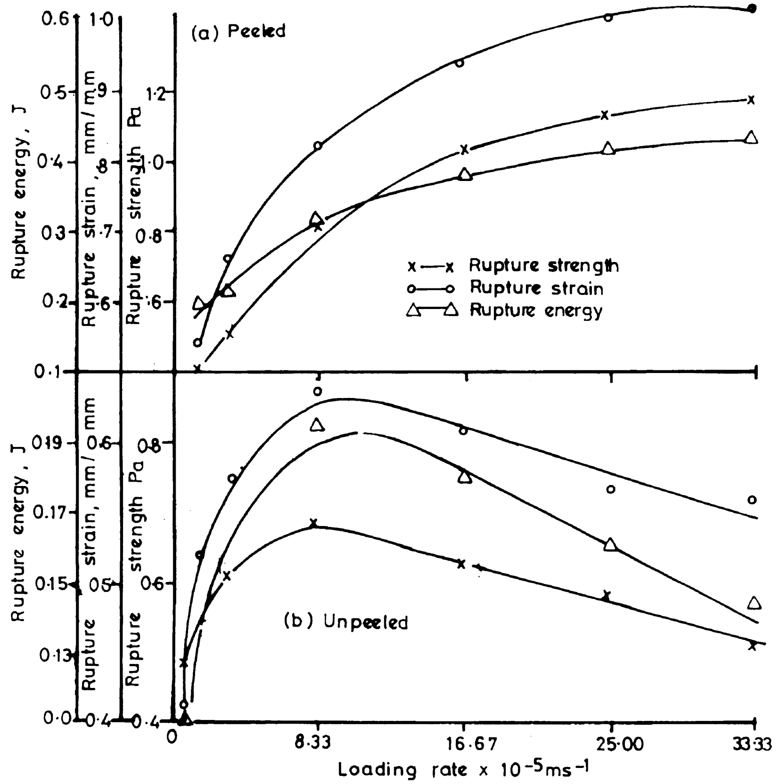

Fig. 5. Variations of rupture parameters for (a) peeled and (b) unpeeled plantain fruit.

increased with an increase in fruit cross-sectional area, whether peeled or unpeeled. For the rupture (Fig. 6b), all the parameters for the peeled specimens, and only rupture strain for the unpeeled specimens, increased with an increase in cross-sectional area. Both strength and rupture energy decreased with an increase in cross-sectional area. For both peeled and unpeeled plantain specimens, there were linear correlation coefficients ranging from 0.871 to 0.999 between the bioyield and rupture parameters with cross-sectional area. The values of the coefficients for rupture strength and rupture energy are -0.951 and -0.977 respectively for unpeeled specimens (Table 4). For the peeled specimens, the positive linear correlation between the measured mechanical parameters and cross-sectional area is understandable since the specimens were loaded axially. For the unpeeled, the negative correlation between rupture strength and rupture energy may be due to their dependence on cross-sectional area which the presence of the peel increases thus lowering the values of these parameters.

Figure 7 shows the variation of modulus of deformation with loading rate and cross-sectional area for both peeled and unpeeled unripe plantain specimens. For the peeled specimens, the modulus of deformation increased linearly with both loading rate (r = 0.993) and cross-sectional area (r = 0.982) which is consistent with viscoelastic theory. For loading rates

Table 4. Linear regression equations of the unpeeled plantain mechanical properties with cross-sectional area

Parameter	Cross-sectional area (cm^2)
Bioyield strength (Pa)	0.094 + 0.016b ; r = 0.998
Bioyield strain (mm/mm)	0.063 + 0.023b ; r = 0.871
Bioyield energy (J)	-0.141 + 0.015b ; r = 0.985
Repture strength (Pa)	1.384 - 0.059b ; r = -0.951
Rupture strain (mm/mm)	0.362 + 0.015b ; r = 0.977
Rupture energy (J)	0.409 - 0.018b ; r = -0.977
Modulus of deformation (N/mm)	2.079 - 0.081b ; r = -0.992

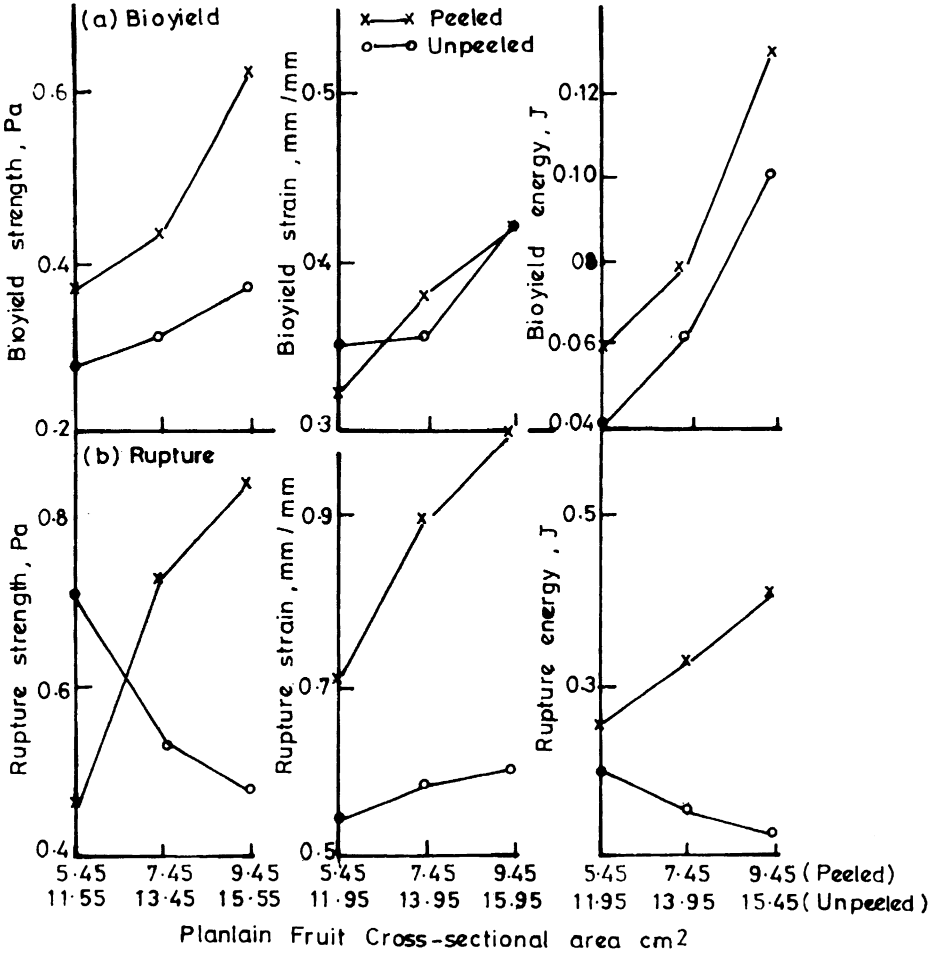

Fig. 6. Variation of plantain bioyield and rupture parameters with cross-sectional area of the fruit.

$< 8.33 \times 10^{-5}$m s^{-1} the modulus of deformation is higher for the unpeeled than the peeled specimen as was observed by Ajibola [2] whose values are higher than those obtained in this report due probably to the length of the specimens used. The values of this parameter are higher for the peeled than the unpeeled for loading rates $> 8.33 \times 10^{-5}$m s^{-1}. Also for loading rates $> 8.33 \times 10^{-5}$m s^{-1}, the parameter increased linearly. Between 0.83 and 5.83 x 10^{-5}m s^{-1} modulus of deformation for unpeeled specimens decreased from 0.939 to 0.870 N/mm. This directional change of modulus of deformation in relation to the loading rate is not common for most viscoelastic materials but has been observed in some products [10]. The rate dependency of this parameter, being a firmness index rather than a strength index, is of less physical importance than the rupture parameters in terms of mechanical damage studies. With the unpeeled specimens the modulus of deformation decreased linearly with cross-sectional area ($r = -0.992$) because of the presence of the peel and its direct effect on increasing cross-sectional area of the specimen.

The result of this investigation confirms that the sensitivity to damage of numerous agricultural products is influenced by the presence of the peel. For potato tuber, the modulus of elasticity is higher in the central part

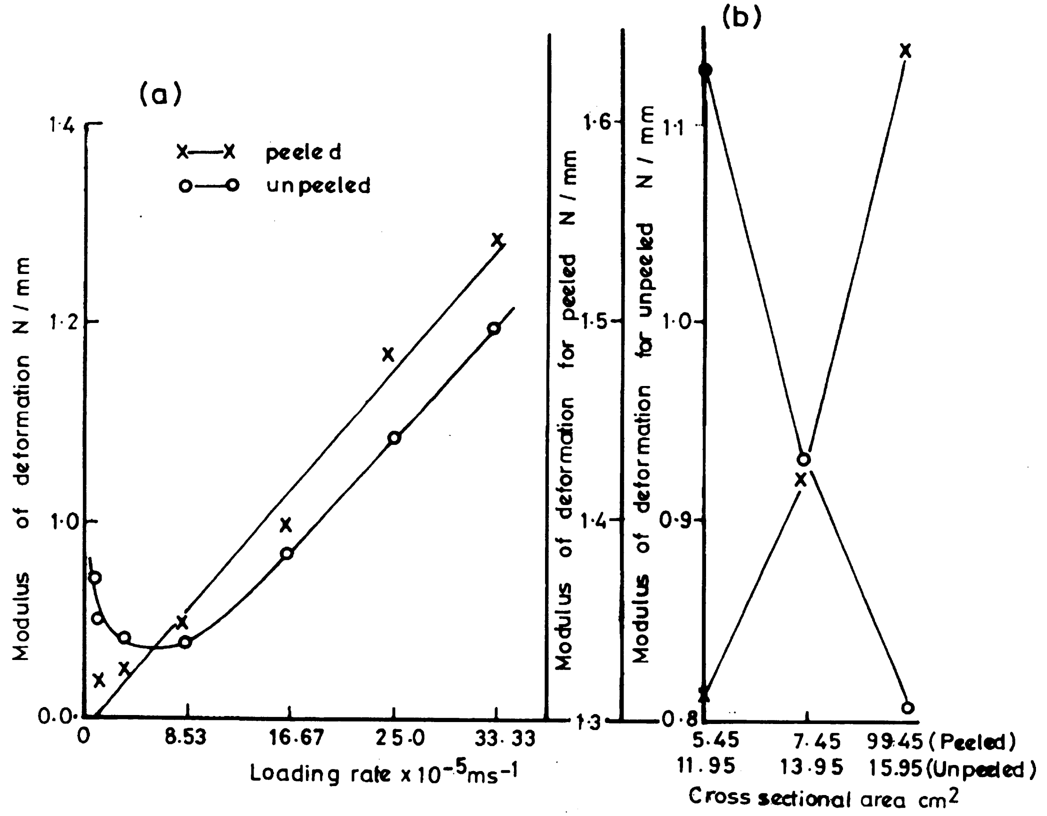

Fig. 7. Variation of modulus of deformation with (a) loading rate and (b) cross-sectional area.

than close to the peel, due to differences in moisture content between the centre and near the peel [9]. Also the relationship between the tensile strength of apple peel and its strain is not linear [7], thus giving a directional change in modulus of deformation for unpeeled specimens. At slow rates of loading, the peel is still attached to the pulp in the unpeeled specimen and its modulus of deformation is higher than for the peeled. However, at high rates of loading, the peel bulges [12] indicating failure in the peel matrix leading to lower values of the bioyield and rupture parameters in the unpeeled composite plantain fruit than in the peeled. The peel, therefore, plays an important role in the mechanical behaviour of the plantain fruit. Because the results of this investigation were obtained using cylindrical test specimens of length 4.0 cm, they may be useful in studying general regularities and are not suitable for evaluating the behaviour of a whole plantain fruit.

CONCLUSIONS

1. The force-deformation curve for mature unripe cylindrical specimens of plantain fruit has marked bioyield and rupture points with a linear portion before the bioyield point for both the peeled and unpeeled specimens.

2. For the peeled specimens, all bioyield and rupture parameters of strength, strain and energy as well as modulus of deformation increased with increase in loading rate and cross-sectional area.

3. For the unpeeled specimens, there are directional changes in all bioyield and rupture parameters as well as modulus of deformation as loading rate increased. This directional

change may be due to the presence of the peel and occurs at 8.33 x 10^{-5}m s^{-1} loading rate.

4. For loading rates < 8.33 x 10^{-5}m s^{-1}, all the bioyield and rupture parameters as well as modulus of deformation, except rupture strain and rupture energy, were higher for the unpeeled than for the peeled plantain specimens.

5. For loading rates < 8.33 x 10^{-5}m s^{-1}, all the bioyield and rupture parameters, except bioyield strength and bioyield strain, increased with increase in loading rate for the unpeeled plantain specimens.

6. For the unpeeled specimens also all bioyield and rupture parameters, except rupture strength, rupture energy, and modulus of deformation, increased with increase in cross-sectional area.

7. The peel of mature unripe plantain specimens plays an important role in their mechanical behaviour as evidenced by the differences in values of measured parameters for peeled and unpeeled specimens, and the directional change in the modulus of deformation.

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