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Stress-Strain Constitutive Relation for Fresh Yam Tuber Tissue *(Dioscorea Rotundata)*

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Abstract

Identified post-harvest problem of yam tuber tissue is bruise damage. This occurs mainly during handling, transportation and storage of the tuber. Bruise is cell rupture or membrane disruption due to applied stress and its accompanying strain. Using incremental creep principles, a constitutive equation relating stress and strain for fresh yam tuber tissue was developed. This governing mathematical relation is for predicting strain (ε) (bruise failure) at given stresses (σ), given period (time, t) and moisture level (M). The equation developed was tested statistically using student t-statistic and was found to predict total strain on the produce to a close accuracy.

Keywords: bruise, viscoelastic, viscoplastic, bioyield point.

1.0 Introduction

The yam tuber, though the most useful part of the crop, is the most delicate and is highly susceptible to deterioration and damage. Researchers have discovered that post harvest looses ranging from 25 to 50% for high moisture laden crops are not unusual in some countries where refrigerator facilities are not available and appropriate chemical treatments, not used (Harvey, 1978; Rippon, 1980; Nwufo, 2004). Yam a third world country crop easily attains the upper limit of the loss percentage.

Among the factors that cause deterioration in yam tuber the most critical, common, and dangerous is the bruise damage (Nwandikom, 1999). Bruise is cell rupture or membrane disruption. The applied load on the crop distorts the internal cell, leading to cell extension (strain) and eventual breakage (rupture/failure). It usually occurs under low rate of compression or tension which implies, slow energy build up and varied energy transformations. Tubers are handled in heaps during transportation and also heaped in heaps in the store and when displayed in the market. These conditions encourage slow build up of stress and its accompanying strain from the dead loads till it gets to a critical magnitude that may cause bruise.

Bruise injury is dangerous because it brings about changes in colour, flavour, texture, internal structures and others, of the crop internally at times without being noticed on the outside. Mathurin and Degras (1978) postulated that crushing of tissue (bruise) in the inside, creates a condition that accelerates cellular respiration and oxygen demand. The process creates deficiency of oxygen in the crop which then results to colouration of the tissue. So the problems of black spot, black heart, rotten tissue and the like are attributed to bruise damage (Mohsenin, 1986). Also rate of physiological reaction and pathological infections increase at bruise site resulting to rottenness and deterioration of the crop.

This work is aimed at simulating the pattern of behaviour that causes bruise and investigate its reactions with a view to estimate or predict failure point, failure mode and failure strength on the product. Hence the objective is to derive the constitutive equation for fresh yam tuber tissue using incremental creep principles for predicting failure strain.

2.0 Theoretical Consideration

Incremental creep investigation involves creep and creep recovery program repeated on the same specimen with increasing stress pulses. A general representation of the rheological response of agricultural materials can be accomplished by

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separating the strain into components stated in equation (1) (Flugee, 1962; Mohsenin, 1962; Arnold and Mohsenin 1971).

$$\varepsilon_t(t,\sigma) = \varepsilon_e + \varepsilon_p(\sigma) + \varepsilon_{ve}(t,\sigma) + \varepsilon_{vp}(t,\sigma) + \varepsilon_{vi}(t,\sigma) \quad \ldots 1$$

where

ε_t = total strain

ε_e = elastic strain (instantaneous response)

ε_p = plastic strain (instantaneous response)

ε_{ve} = viscoelastic strain (recoverable with time)

ε_{vp} = viscoplastic strain (irrecoverable)

ε_{vi} = viscous strain (irrecoverable)

σ = stress

t = time

The elastic strain represents an instantaneous, time independent linear response recoverable after unloading. The plastic strain, also time independent, pertains to an instantaneous non-linear response to stress and is irrecoverable whereas the viscoelastic is time and stress dependent and represents the retarded elastic response. Since the instantaneous plastic strain and viscoplastic strain are not recoverable, they can be determined by taking the difference in the loading and unloading response. The remaining strain, namely the viscous strain represents the permanent deformation associated with flow and is dependent on the history or loading. For fresh yam tuber, it has been found that the total strain is composed of the elastic, viscoelastic and plastic or permanent strain (Anazodo, 1982; Nwandikom, 1984, 2000, 2004). Hence the equation is reduced to equation (2).

$$\varepsilon_t(t,\sigma) = \varepsilon_e + \varepsilon_{ve}(\sigma,t) + \varepsilon_p(\sigma) \quad \ldots 2$$

3.0 Materials and Methods

Mature tubers of *ji oguta* a popular cultivar of *D. Rotundata* of known harvesting and handling history were used for the experiment. Cylindrical specimen of diameter 20mm and length 18mm were taken from the middle and tail region of the tuber using cork borer. The samples were of moisture content ranges of 48%, 55%, 59% and 66% wet basis. A laboratory creeper developed at Federal University of Technology Owerri and calibrated using the standard instron machine was used to creep the specimen (Nwandikom 2004). The cylindrical shaped yam tuber tissue was subjected to the desired stress (load) for specific duration. At the end of the period, the load is removed to allow the specimen to recover. This constitutes one cycle of creep and creep recovery period. Same specimen is again subjected to same stress but for longer loading and unloading times. The loading and unloading cycle is continued as long as the material is viable. Six cycles were achieved successfully per specimen. The loading and unloading time ratios for the cycles are 1:6, 2:12, 4:24, 6:36, 8:48, 10:60 min: min. These constitute cycles 1, 2, 3, 4, 5, 6 respectively for each specimen at each stress level.

The stress levels are 385kPa, 462kPa, 539kPa, 616kPa, 693kPa, 770kPa, 847kPa, 924kPa and 1001kPa. The choice was based on the fact that the yield stress of *D. Rotundata* ranges from 0.39MPa to 2.24MPa (Nwandikom, 1984). Each test was replicated three times. There were 9 x 4 x 3 experiments and 9 x 4 x 3 x 6 cycles. The strains were calculated as in equations (3) to (6).

$$\text{Total strain } (\varepsilon_t) = \text{maximum deformation} \div 18 \quad \ldots 3$$

$$\text{Plastic Strain } (\varepsilon_p) = \text{minimum deformation} \div 18 \quad \ldots 4$$

$$\text{Recoverable strain } (\varepsilon_r) = \text{Total strain} - \text{plastic strain} \quad \ldots 5$$

$$\text{Recoverable strain} = \text{elastic strain } (\varepsilon_e) + \text{viscoelastic strain } (\varepsilon_{ve}) \quad \ldots 6$$

4.0 Results and Discussion

Figure 1, are samples of the standardized plots of deformation vs. time graph for stress pulses of 616kPa, 539kPa and 770kPa at 59% moisture content, showing loading and unloading cycles. The three major deformation types influencing the rheological behaviour of the product, elastic, viscoelastic and plastic strain types were identified. The portion of the plot in each cycle that indicated an upward jump at almost t = 0 at creeping and the portion at creep recovery that shows a quick downward fall before gradually easing off, is the elastic deformation. Each of those movements are almost equal. The portion with steady increasing parabolic trend after the upward jump is the viscoelastic deformation. Then the irrecoverable portion of the deformation diagram is the plastic deformation.

The elastic strain values of the experiments were calculated using the relationships stated above. The values ranged from 0.056 to 0.144. A plot of elastic strain versus stress showed proportionality value of 1.44 x 10^{-4}, the inverse of which is the modulus of elasticity of 6950kPa. This value is within the range of values obtained by Nwandikom, 1984, 1990, 2000 and Nwandikom and Mittal, 1988. So,

$$\varepsilon_e = 1.44 \times 10^{-4} \sigma \quad \ldots 7$$

The viscoelastic strain values were computed from the plots, their ranges are shown in Table 1.

Table 1: Viscoelastic strain values ranges

Moisture Content (%)	Viscoelastic Strain Ranges	Derived Equation
48	0.015 to 0.144	$e^{-8.67}\sigma(1-e^{-0.21t})$
55	0.014 to 0.147	$e^{-8.73}\sigma(1-e^{-0.24t})$
59	0.015 to 0.156	$e^{-8.61}\sigma(1-e^{-0.26t})$
66	0.023 to 0.218	$e^{-8.45}\sigma(1-e^{-0.29t})$

The derived equations were obtained using standard curve fittings technique of the general equation shown in equation (8)

$$\varepsilon_{ve} = e^{-\alpha}\sigma(1-e^{-\beta t}) \quad \ldots 8$$

The average α-value is 8.62 with coefficient or variability of 1.4%. The βt value varied with moisture content. Using the method of least square, the slope of the graph of β to moisture is 0.0045 with $R^2 =$ 96%. The general equation for viscoelastic strain in yam tuber tissue in terms of moisture content, time and stress becomes:

$$\varepsilon_{ve} = e^{-8.62}\sigma(1-e^{-0.0045Mt}) \quad \ldots 9$$

The plastic strain values obtained were statistically analysed using the F-test, it was found that stress, time, moisture and combined stress and moisture influence the plastic strain. To derive the plastic strain portion of the equation, a general relation shown in equation (10) was assumed:

$$\varepsilon_p = K\sigma^p t^q M^r \quad \ldots 10$$

p,q and r are indices to the stress (σ), time (t) and moisture (M) and k is coefficient of proportionality. The maximum and minimum mean values of the plastic strain were chosen on the time axis (0.019 and 0.042). From these values the stress, moisture and time relating to these values were picked and four equations were formed:

Log 0.019 = log k + plog 385 + qlog 2 + rlog 48 …11

Log 0.042 = log k + plog 385 + qlog 10 + rlog 48 …12

Log 0.042 = log k + plog 693 + qlog 10 + rlog 55 …13

Log 0.019 = log k + plog 693 + qlog 4 + rlog 48 …14

Solving equations (11) to (14), values of q, r, p and k were obtained as 0.04928, 2.515, 0.5853 and 0.000026 respectively. The general equation for plastic strain is

$$\varepsilon_p = 0.000026\sigma^{0.58} t^{0.049} M^{2.52} \quad \ldots 15$$

The constitutive equation becomes:

$$\varepsilon_t = 1.44 \times 10^{-4}\sigma + e^{-8.62}\sigma(1-e^{-0.0045Mt}) + 2.6 \times 10^{-5}\sigma^{0.58} t^{0.049} M^{2.52} \quad \ldots 16$$

The derived equation was tested using the t-statistic to compare the means of experimentally obtained total strain against time. It was observed that the differences between their means were not significant.

5.0 Conclusion

A constitutive equation for fresh yam tuber relating strain to stress, period or stress and moisture content was developed by using incremental creep prin-

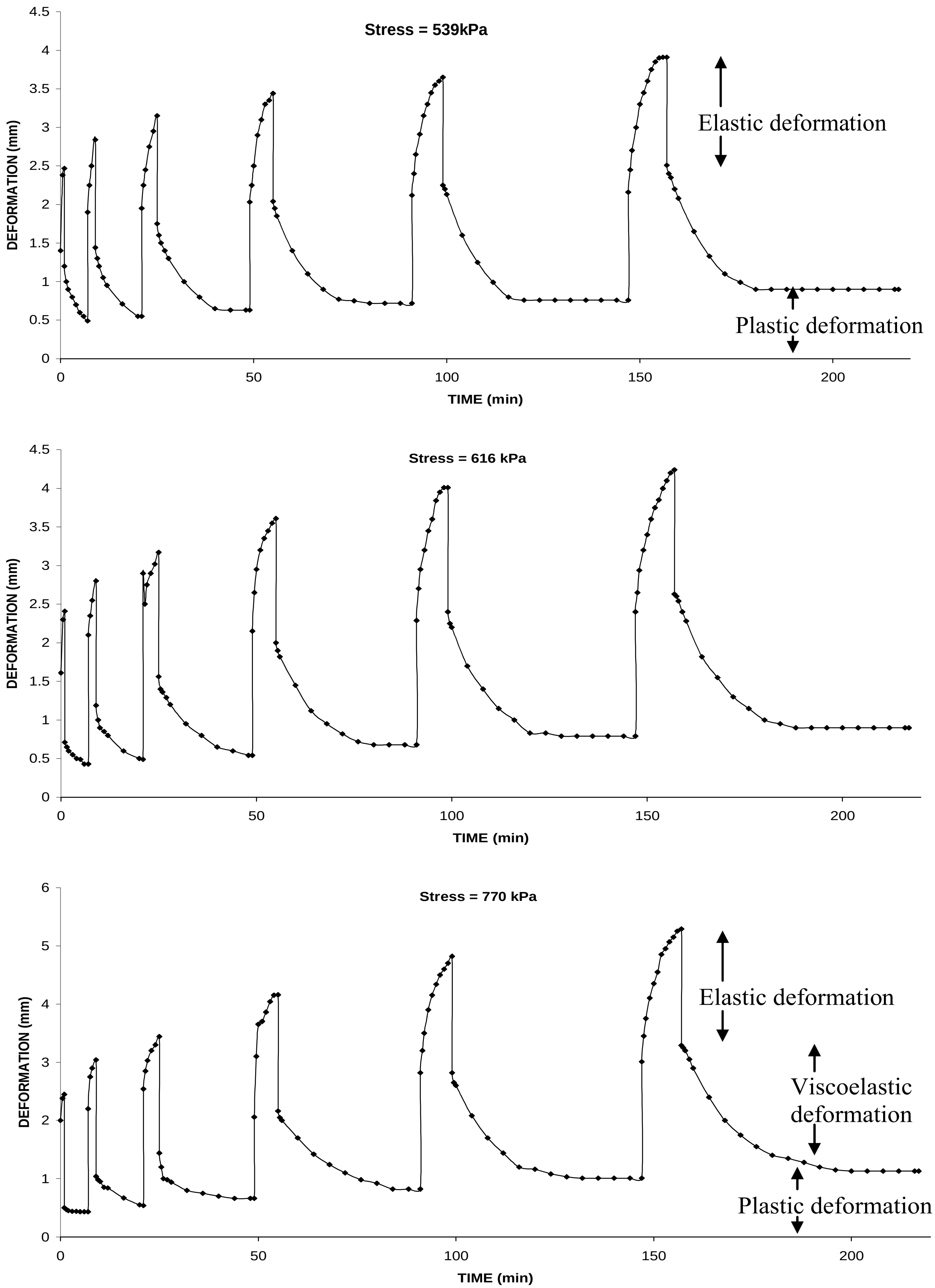

Figure1: Yam tuber deformation time graph for stress pulses of 539kPa, 616kPa and 770kPa at 59% moisture content.

ciples. This mathematical relation is for predicting bruice failure on the product. Experimentally determined bruice was compared with that generated with the developed constitutive equation using t-test. The differences were found to be insignificant.

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