Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 54
ISSUE 1
September
2012

Experimental study on mechanical properties of pumpkin tissue

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Received 05.07.2012; published in revised form 01.09.2012

Analysis and modelling

ABSTRACT

Purpose: The purpose of this study was to calculate mechanical properties of tough skinned vegetables as a part of Finite Element Modelling (FEM) and simulation of tissue damage during mechanical peeling of tough skinned vegetables.

Design/methodology/approach: There are some previous studies on mechanical properties of fruits and vegetables however, behaviour of tissue under different processing operations will be different. In this study indentation test was performed on Peel, Flesh and Unpeeled samples of pumpkin as a tough skinned vegetable. Additionally, the test performed in three different loading rates for peel: 1.25, 10, 20 mm/min and 20 mm/min for flesh and unpeeled samples respectively. The spherical end indenter with 8 mm diameter used for the experimental tests. Samples prepare from defect free and ripped pumpkin purchased from local shops in Brisbane, Australia. Humidity and temperature were 20-55% and 20-250°C respectively.

Findings: Consequently, force deformation and stress and strain of samples were calculated and shown in presented figures. Relative contribution (%) of skin to different mechanical properties is computed and compared with data available from literature. According the results, peel samples had the highest value of rupture force (291 N) and as well as highest value of firmness (1411 Nm^{-1}).

Research limitations/implications: The proposed study focused on one type of tough skinned vegetables and one variety of pumpkin however, more tests will give better understandings of behaviours of tissue. Additionally, the behaviours of peel, unpeeled and flesh samples in different speed of loading will provide more details of tissue damages during mechanical loading.

Originality/value: Mechanical properties of pumpkin tissue calculated using the results of indentation test, specifically the behaviours of peel, flesh and unpeeled samples were explored which is a new approach in Finite Element Modelling (FEM) of food processes.

Keywords: Finite Element Modelling (FEM); Relative contribution; Firmness; Toughness and rupture force

Reference to this paper should be given in the following way:
M. Shirmohammadi, P. Yarlagadda, Experimental study on mechanical properties of pumpkin tissue, Journal of Achievements in Materials and Manufacturing Engineering 54/1 (2012) 16-24.

1. Introduction

The food processing and beverages industry is a largest manufacturing industry in Australia with a turnover of more than $71.4 billion in 2005-6, and a growth rate of 2 per cent over the past 10 years [1]. Increasing the quality and quantity of food products is an excellent enhancement for providing growing demand of food production. Energy consumption and material loss are two significant issues in development of food products.

Regarding the available reports, the energy consumed in US food processing sector in 2004 were distributed among five stages as shown in Fig. 1 [2]. According to this figure the processing and on farm production have consumed almost 40% of whole processing energy rate [2]. Accordingly, $810 million has been spent in US for Fuel and electricity of fruit and vegetable industry in 2002 [3]. As a result more efficient processing lines will lead the industry to enhance the quality and quantity of food production in order to response increasing rate of global demand for food products.

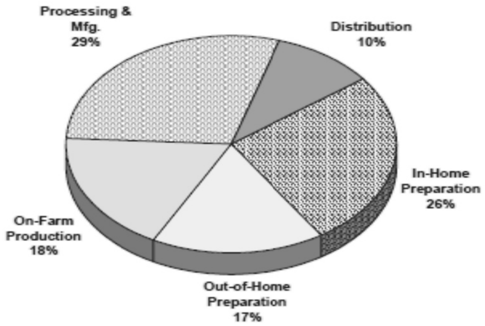


Fig. 1. Share of energy in U.S. food processing industry [2]

The rate of material loss varies attributable to the type of crop and operations, the waste rate during industrial processes in mango, banana and orange has been reported 30-50%, 20% and 30-50% respectively [4]. Additionally, mechanical damages such as bruise, pressure and dynamic collision are the major causes of material and quality loss during post harvesting and processing chain. Dynamic and static collision create 20% loss in potato production lines [5] which undeniably will be higher in softer produce such as banana, mango and tomato. As an example, rate of loss in apple production lines raise up to 50% [6], it appears as internal discoloration and off flavours in damaged parts because of bruising and pressure [7]. Moreover, drop, vibrations and impact cause up to 25% loss in post harvesting and 50-60% loss in processing period of agricultural produce [8].

Peeling is one of the essential stages of post harvesting and food processing operations. Regarding the method of peeling and the type of crops this process can create high rate of loss which generally is not desirable in processing industries. For instance in peeling process of potato, losing the peel is a disadvantage as the main source of protein stores underneath of skin [7]. Studying the behaviours of agricultural crops under different industrial operations will help researchers and designers to optimise and design new technologies to diminish unwanted deformations and total energy usage. The presented work is a part of research on FE analysis and simulation of tissue damage during mechanical peeling of tough skinned vegetables. The goal of this study is to investigate the response of pumpkin tissue under compressive indentation.

2. Mechanical behaviours of agricultural crops under loading

There are prior studies focused on mechanical properties of food tissues, the typical force deformation curve for agricultural crops has been figured out by Mohsenin (Fig. 2) [9].

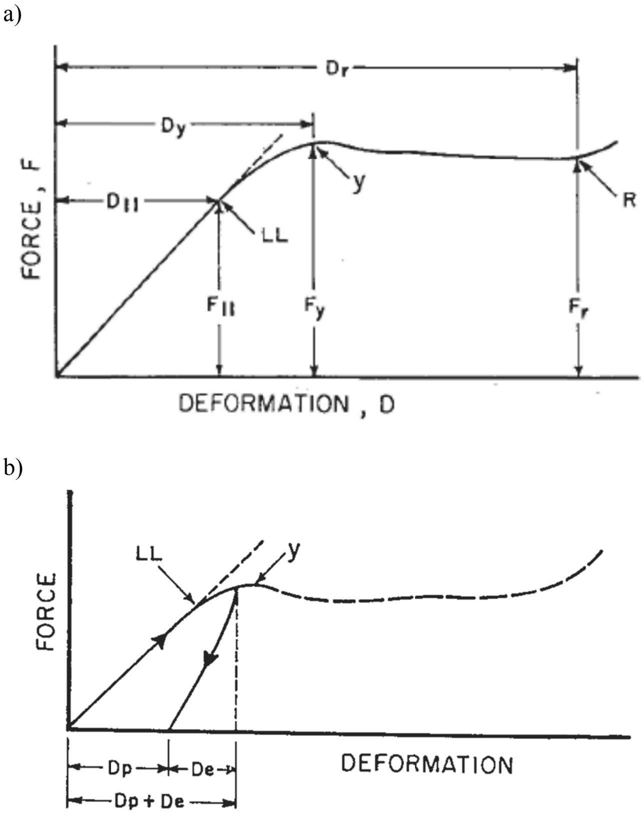


Fig. 2. (a) Force deformation curve for agricultural products - (b) Degree of elasticity from the loading-unloading curve. D_e= elastic or recoverable deformation; D_p=plastic or residual deformation; $D_e/(D_p+D_e)$ [9]

According to these graphs, linear part of diagram shows the elastic behaviours of material where deformation and damages are temporarily and they will disappear after unloading. However regarding the nature of agricultural crops, any source of force - even very small amount- can create damages such as internal discolouration which will definitely diminish the quality and customer acceptability of these crops. As it shown in Fig. 2, with "LL", the ratio of stress strain this zone is equal to the modulus of elasticity, in addition "stiffness or rigidity is indicated by the slope of initial straight line portion of the curve" [9]. Plasticity is the capacity of material to take permanent deformation and change, according to the Fig. 2, plasticity region is D_p which is after bioyield to the point of rupture [9].

Degree of elasticity defines as division of elastic deformation over sum of elastic and plastic deformation which is possible to calculate from force deformation curve.

In a study done by Emadi et al. [10] on peel and unpeeled samples of cantaloupe melon, Honeydew melon and Watermelon, compression test has been done using a 8 mm in diameter cylindrical probe in the speed of 20 mm/min (Fig. 3).

The experimental test have been done by Grotte et al. on peel and flesh of Fuji, Golden Delicious, Grammy Smith and Pink

Lady apple with hemispherical tip indenter with diameter of 4 mm is shown in Fig. 3 (b). The indentation test performed at a constant velocity of 20 cm per minutes. The results (Fig. 3) shown that the maximum deformation and rupture force are 31.91 and 72.60 for Granny Smith and Golden Delicious respectively. The force deformation curve for pumpkin samples under resented in Fig. 3 (c) [12].

Consequently, the results of calculated mechanical properties of melon, apple and pumpkin demonstrated in Tables 1 to 3.

3. Material and method

Indentation test performed for one variety of pumpkin as a part of FE modelling and simulation of tissue damage during mechanical peeling of tough skinned vegetables. The main scope of the study was calculating essential properties of skin, flesh and unpeeled sample in order to use these properties and establish the FE model. The test completed according the available ASABE standard for compression test of convex shape food materials [14]. The spherical indenter with diameter of 8 mm used to compress samples in loading speed of 1.25, 10 and 20 mm/ min. Jap variety of pumpkin was purchased from local shops in Brisbane (Queensland Australia). The pumpkins used were ripe and defect free. For the duration of sampling and testing stage, the temperature and humidity were 20-25°C and 20-55% respectively. Pumpkins keep in laboratory condition 24-48 hours before test.

The average thickness of samples was 5 mm for peel and 50 mm for unpeeled and flesh samples.

Compressive loading carried out using Instron Universal testing Machine (IUTM), and the results of force deformation collected from the computer attached to the machine. Afterward, rupture force, firmness, toughness, stress, strain and relative contribution (%) of skin to different mechanical properties calculated. The test has been performed in three different loading rates for peel including 1.25 mm/min, 10 mm/min and 20 mm/min and one loading speed of 20 mm/min, for flesh and unpeeled specimens. The following formulas adapted to obtain rheological properties of peel, flesh and unpeeled samples [9, 15-17]:

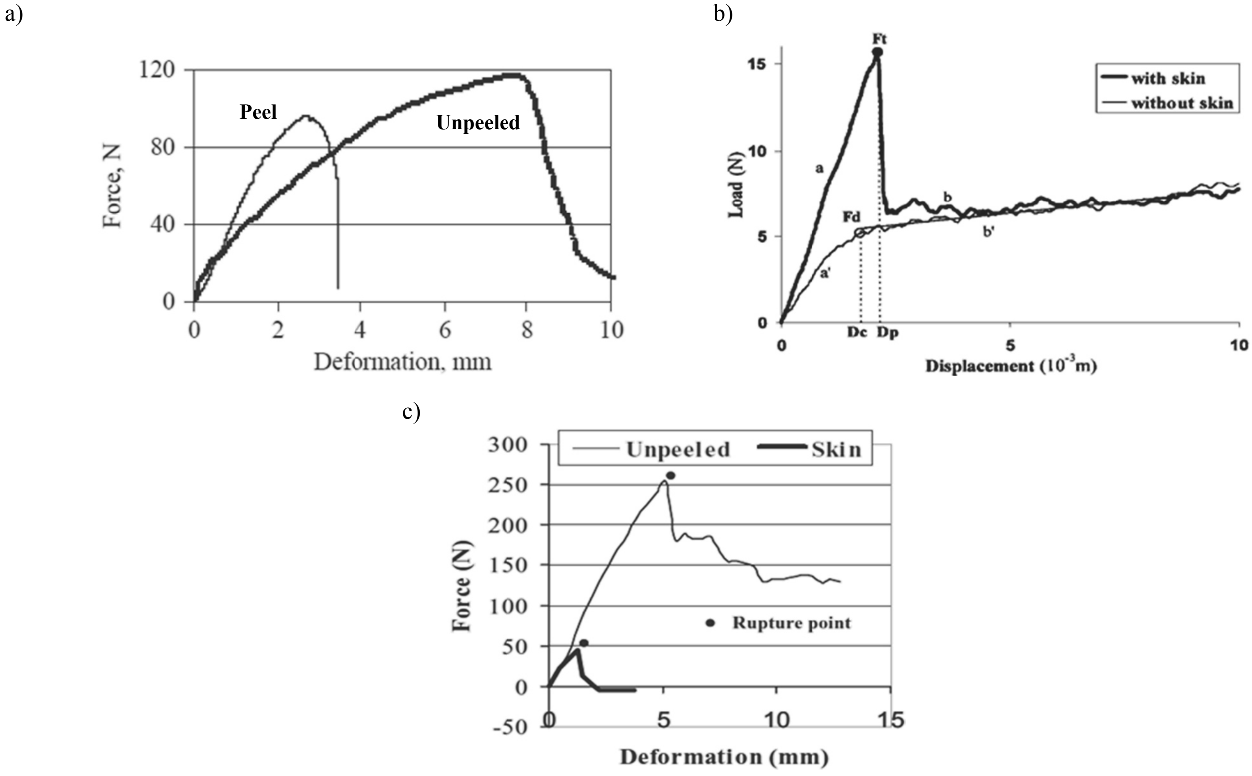
$$\sigma = \frac{F}{A} \tag{1}$$

$$T = \frac{1}{2} F_r D_r \tag{2}$$

$$\varepsilon = \frac{\Delta l}{l} \tag{3}$$

$$\text{Firmness} = \frac{F}{D} \tag{4}$$

where, σ, ε, F, A, Δl, l, F_r, D_r and T are compressive stress, strain, load, cross sectional area, deformation, initial length, rupture force, deformation in rupture point and toughness.


a)

b)

c)

Fig. 3. Force deformation curve for (a) cantaloupe melon [10], (b) apple [11] and (c) pumpkin [12]

Table 1.
Relative contribution (%) of peel to different mechanical properties of unpeeled melon (Mean ± Standards Deviation [10]

Varieties	Rapture force, N	Toughness, Nmm	Cutting force, N	Maximum shearing force, N	Shear strength, N/mm^2
Cantaloupe melon	89 ± 06^{a1a2}	28 ± 14^{b1}	102 ± 17^{c1}	95 ± 08^{d1}	141 ± 30^{e1}
Honeydew melon	82 ± 16^{a1}	21 ± 18^{b1}	102 ± 25^{c1}	89 ± 17^{d1}	336 ± 86^{e2}
Watermelon	97 ± 02^{a2}	50 ± 15^{b2}	100 ± 14^{c1}	97 ± 08^{d1}	178 ± 43^{e1}

Note: Values with the same letter and number are not significantly different (probability $p < 0.05$) by least significant difference (LSD), (a1a2 is not different than a1 or a2)

Table 2.
Contributions of the skin to the firmness properties for four apple varieties. Tested after a 210-Day storage at 2°C. Mean ± Standard Deviation [11]

	Contribution of the Skin (%)			
Variety	Deformation	Rapture force	Firmness	Toughness
Fuji	8.40 ± 11.04 (a)	67.26 ± 5.95 (a)	58.44 ± 5.2 (a)	65.35 ± 6.06 (a)
Pink Lady	14.53 ± 9.07 (b)	61.67 ± 3.71 (b)	56.87 ± 5.01 (a)	68.26 ± 7.32 (a)
Golden Delicious	25.24 ± 8.89 (c)	72.60 ± 2.16 (c)	61.19 ± 5.26 (a)	78.51 ± 3.59 (b)
Granny Smith	31.90 ± 8.23 (d)	67.95 ± 5.70 (a)	59.51 ± 5.20 (a)	81.41 ± 2.88 (c)

Note: Values in parentheses with the same letter are not significantly different ($P < 0.05$), (ANOVA: soft INRA-LAMPE, Avignon)

Table 3.
Relative contribution of skin to different mechanical properties for three pumpkin varieties (Jarrahdale, Jap and Butternut) Mean ± Standard deviation [13]

	Properties									
Varieties	Rapture force, N		Toughness, Nmm		Cutting force, N		Max shear strength force, N		Shear strength, N/mm^2	
Jarrahdale	16 ± 9	a1	2.10 ± 1.20	b1	54 ± 13	c1	28 ± 8	d1	153 ± 56	e1
Jap	23 ± 7	a1	1.80 ± 0.80	b1	85 ± 23	c2	43 ± 28	d2	145 ± 41	e1e2
Butternut	73 ± 6	a2	22 ± 9	b2	85 ± 9	c2	67 ± 9	d3	102 ± 16	e2

Note: Values with the same letter and number are not significantly different ($p > 0.05$) by LSD (e1e2 is not different than e1 or e2)

4. Result and discussion

4.1. Force- deformation curve

The results of force deformation curve for peel, flesh and unpeeled specimens have been presented in Fig. 4 and Fig. 5.

From the obtained data, the following properties calculated and compared with available literature.

4.2. Rupture gorce

Rupture in biological materials happens in bio yield point where the initial cell rupture starts taking place [9,10,12]. The details of maximum compressive load for skin, flesh and unpeeled samples presented in Fig. 6, according to this data rupture point for flesh, unpeeled and skin are 188.5, 274, and 291 N respectively. The results of rupture force for unpeeled sample is similar to the results have been reported for Jap variety of pumpkin by Emadi et. Al. 250 N [12]. The rupture force for pumpkin peel was close to the results of study by Shirmohammadi et al which reported rupture force of 310 N [18]. However, the results were higher than rupture force calculated for watermelon peel and honey melon unpeeled samples, 175 and 183 respectively [10] which can be due to the tough structure of pumpkin peel and flesh in comparison with watermelon and honey melon.

4.3. Firmness

Firmness definition has been identified as: The required force to achieve a specified deformation (Bourne 1967 & Schomer et al. 1962 in [16]), the extension occurs under standard load (Kattan 1957, Parker et al. 1966, Whittenberger et al. 1950 & Whittenberger 1951 in [16]), as well as the slope of force deformation curve from zero to the point of rupture and or failure (Ang et al.1960, Burkner et al.1967 in [16] and [11,16]). Regarding to these definitions, increasing the ratio of force deformation means the improvement in tissue firmness (Fig. 8). In the other word, if for a particular crop in a given range of loading the deformation rate is low, the tissue has high firmness. The firmness of pumpkin samples calculated using the following formula and the results have been presented in Table 5:

$$F = \frac{F}{D} \tag{5}$$

where F_r, D_r and F are rupture force (N), deformation (m) in rupture point and firmness (Nm^{-1}).

Consequently, firmness of skin, flesh and unpeeled pumpkin for the results of compressive loading at 20 mm/min calculated as 107.7, 21.42 and 26.6 N/mm.

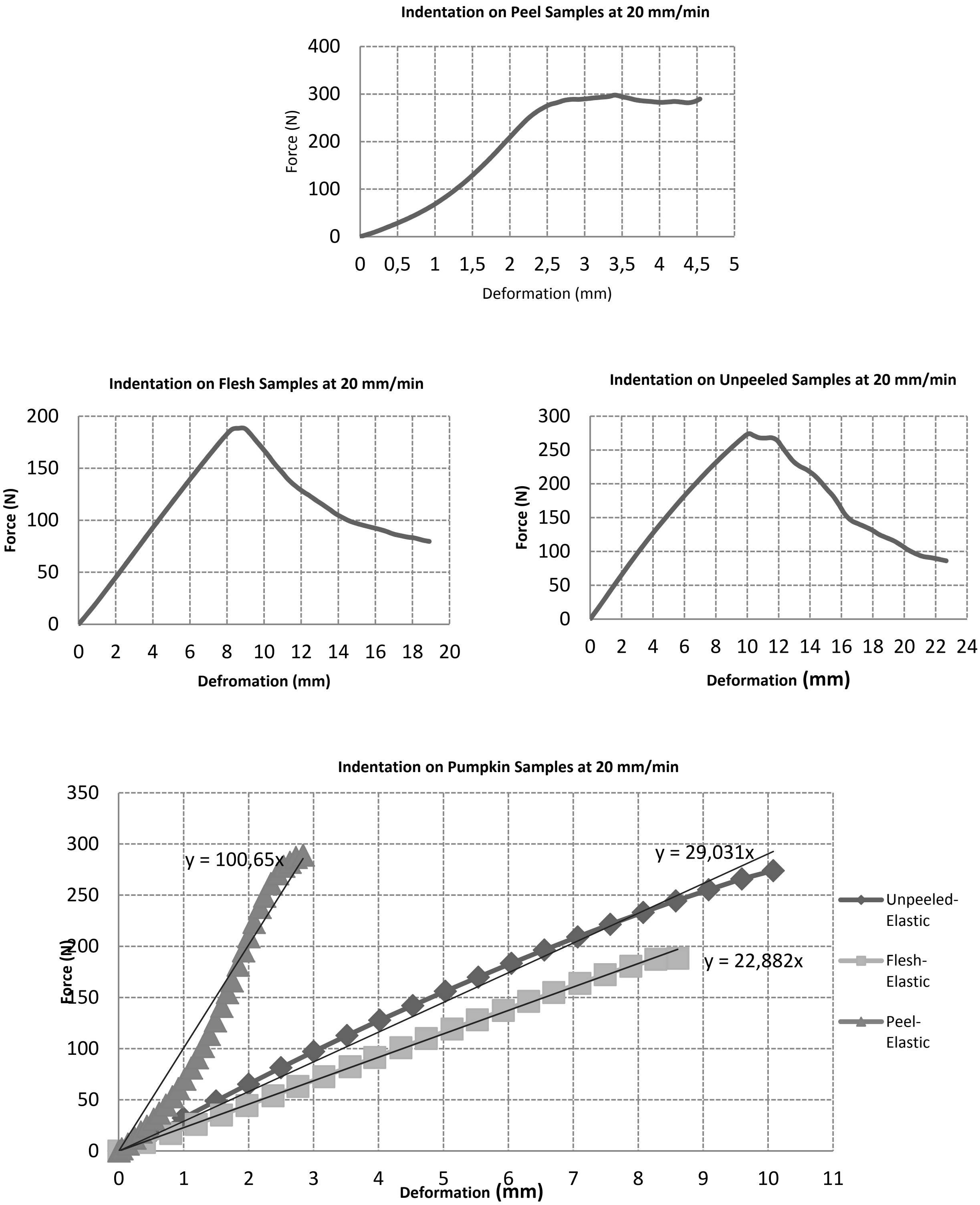


Fig. 4. Force deformation curve of skin, flesh and unpeeled samples in compressive loading

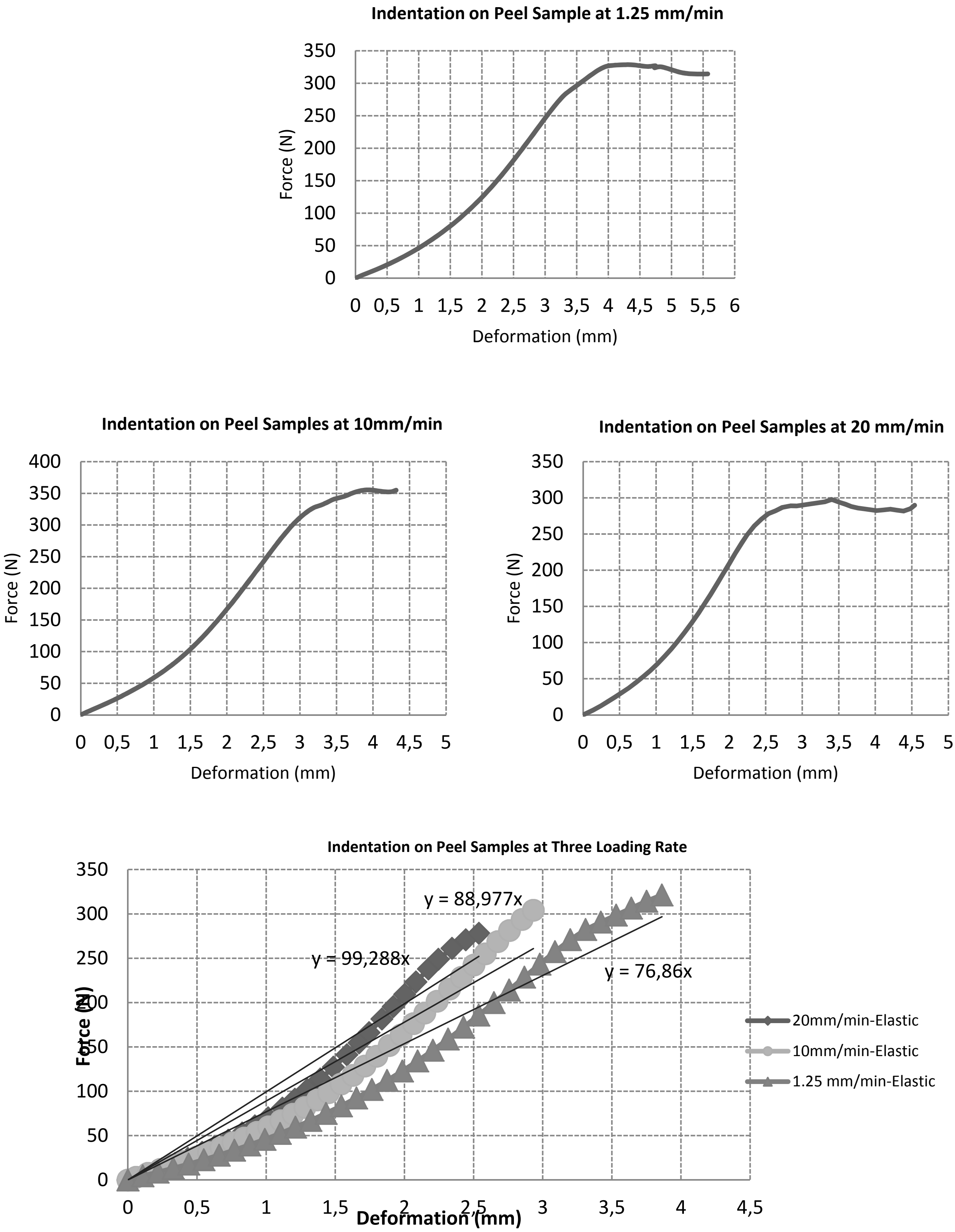


Fig. 5. Force deformation curve for skin in different compressive loading

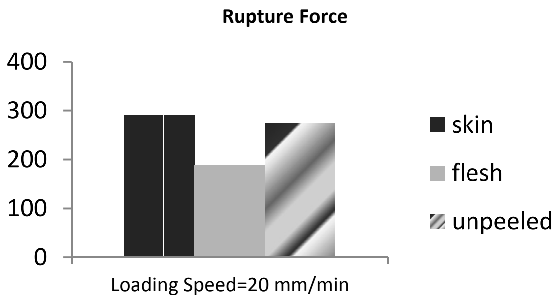


Fig. 6. Rupture Force for Skin, Flesh and Unpeeled samples

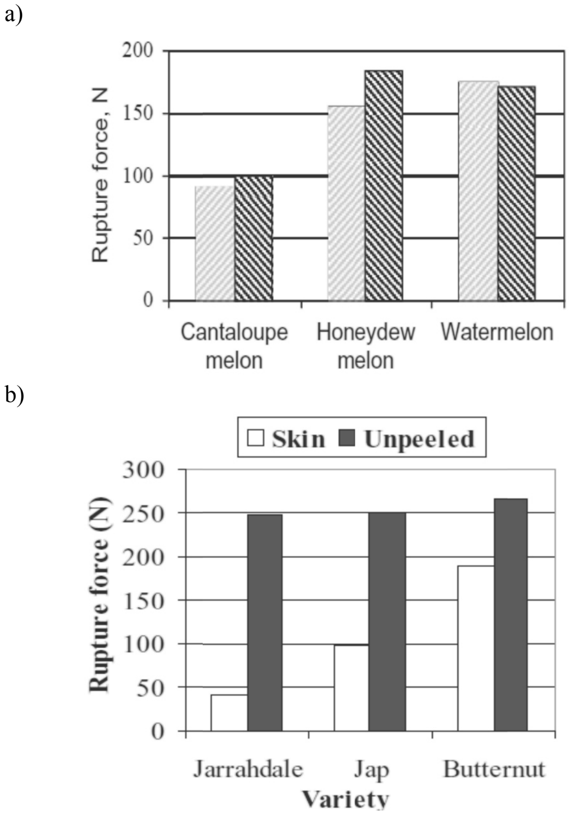


Fig. 7. Rupture force for melons: unpeeled ▨ and peel ▨ (a) [10] and pumpkin (b) [12]

4.4. Toughness

Toughness is the work causes rupture in bio materials [9,16], it is defined as the area under force deformation curve up to rupture point (formula (3), Fig. 8). Calculated toughness for unpeeled and flesh samples of Jap variety of pumpkin have been shown in Fig. 9. Toughness of flesh and unpeeled sample were 829.4 and 1411.1 N.mm respectively which are higher than the results for cantaloupe melon and watermelon [10].

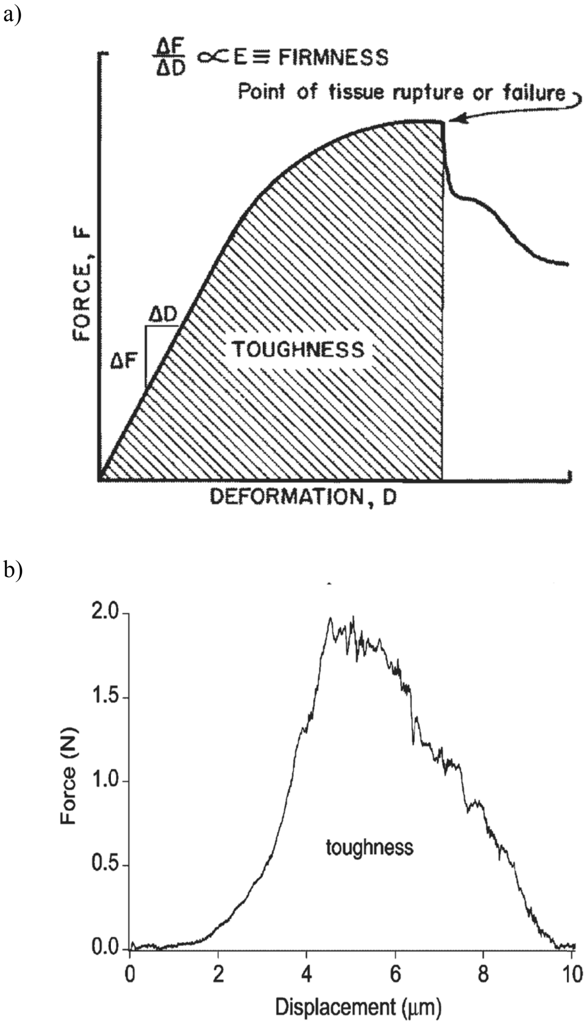


Fig. 8. (a) Firmness and toughness from force deformation details of food particles under compressive loading [16], (b) Toughness of a raisin sample using force deformation curve [19]

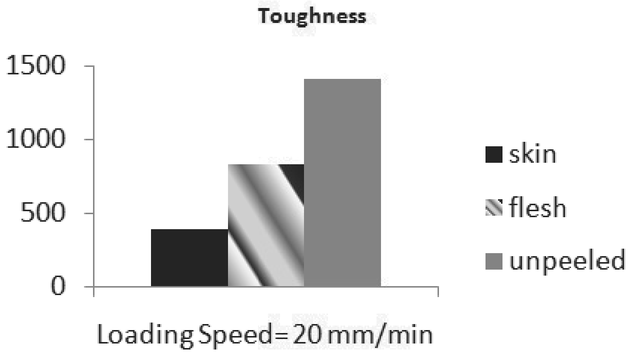


Fig. 9. Toughness of flesh and unpeeled samples in 20 mm/min loading rate

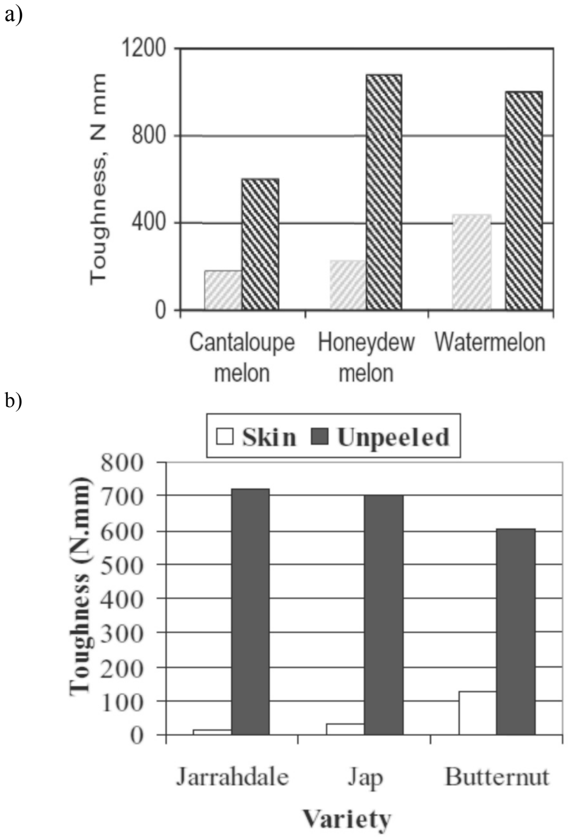


Fig. 10. Toughness for melons: unpeeled ▩ and peel ▨ (a) [10] and pumpkin (b) [12]

4.5. Relative contribution of skin and flesh to different mechanical properties of pumpkin

According Emadi [20], relative contribution of skin to the unpeeled properties is computable from:

$$\begin{matrix}\textit{Relative}\\\textit{Contribution}\\\textit{of Skin to the}\\\textit{Unpeeled Sample}\end{matrix} = \frac{\text{the value of properties of skin}}{\text{the value of properties of unpeeled}} \times 100$$

Relative contribution of peel or flesh properties will give the ratio of mechanical properties of skin to the unpeeled properties. This data is helpful to compare the same properties obtained from different agricultural crops, in order to counteract the unwanted effects of different experimental conditions. In this study, relative contribution of both skin and flesh to the unpeeled properties examined. The outcomes have been presented in Table 4 and Table 5 respectively.

According to these results, contribution of pumpkin skin and flesh to deformation in rupture point were 26 and 85 percent respectively. The contribution of skin to the toughness was lower than the value for flesh which is due to the lower thickness of skin compare to the flesh samples. However, the contribution of skin to the rupture force was 106 percent which is higher than the value for flesh (68 percent).

Table 4.
Mechanical properties of pumpkin peel flesh and unpeeled

Sample	Speed of Loading (mm/min)	Rupture Force (N)	Firmness (Nm^{-1})	Toughness (Nmm)
Peel	1.25	314	82.63	596.6
	10	350	102.94	595
	20	291	107.78	392.85
Flesh	20	188.5	21.42	829.4
Unpeeled	20	274	26.60	1411.1

Table 5.
Relative contribution of skin and flesh of Jap pumpkin to different mechanical properties of unpeeled Pumpkin in 20 mm/min compressive loading speed

Jap	Deformation (Rupture point) (mm)	Rupture Force (N)	Toughness (Elastic region) (Nmm)
Peel	26.21	106.20	27.84
Flesh	85.44	68.80	58.78

4.6. Application of investigated properties

Applying Finite Element Modelling and simulation of engineering operations is an innovative trend among researchers and designers of industrial technologies. Applying these models is helping researchers to measure and calculate different properties and characteristics under loading which sometimes is very difficult to be calculate with experimental tests [21] of materials These models are applicable to study rate of energy consumptions, tool wear and material loss in real world operations [15, 18]. This applications will help to achieve precise understanding of interrelationship of different variable involve the processes to improve tool design and select optimum conditions [22]. These models are less costly and time demanding than common experimental methods. However calculating material properties of food particles is essential for developing an appropriate model of food processing and post harvesting operation. The presented study in this paper performed experimental tests on pumpkin tissue to get material properties of peel, flesh and unpeeled specimens. The results of empirical tests will be applied in developing the FE model of mechanical peeling of tough skinned vegetables. To date this work is the first effort on modelling mechanical peeling of tough skinned vegetable and the main aim of the current work is obtaining more details of force-deformation, energy rates, and deformation of tissue after establishing the proposed model. It is also one of the few studies which attempted to combine the results of experimental studies of material properties to model an industrial stage. The results of both experiments and models will be helpful to expand available database on rheological behaviours of food particles during different loading stages through food operations.

5. Conclusion and future work

The compressive indentation performed on skin, flesh and unpeeled samples of pumpkin. The result of test which was force and deformation details obtained and mechanical properties of sample computed. Regarding to the calculations, rupture force were 291, 188.5 and 274 N for skin, flesh and unpeeled samples respectively. Toughness of flesh was 829.4 N.mm which was lower that toughness of unpeeled of unpeeled samples (1411.1 N.mm). Firmness also estimated for skin, flesh and unpeeled samples, 107.7, 21.42 and 26.6 N/mm respectively. Relative contribution of calculated properties also estimated as: 26.21% and 85.44% relative contribution of deformation for peel to unpeeled values. Relative contribution of rupture force for flesh and peel were 68.8% and 106.2% respectively, in addition to the relative contribution of toughness for skin and flesh which was 27.84% and 58.78%.

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