Original article

The effect of test conditions on failure parameters during uniaxial compression of potato tissue

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Summary Uniaxial compression tests were performed on potato flesh. Cylindrical samples of diameters (19.05 and 25.4 mm) and heights (5, 10, 15 and 20 mm) were tested under non-lubricated, lubricated and increased friction conditions. The deformation rate effect was also examined by performing compression tests at 50, 100, 200 and 400 mm min^{-1}. In the present study, parameters derived from compression to failure were failure strain (ε), engineering stress (F/A_0), true stress (F/A_f), apparent elastic modulus (E) and energy at failure (U_v). As compared with non-lubricated friction condition, lubrication increased significantly the average ε value and decreased significantly the average F/A_f value, but appears to have lower significant effect on the average F/A_0, E and U_v values. Failure strain, engineering stress and energy at failure increased with deformation rate, whereas true stress and apparent elastic modulus decreased. Failure strain increased with sample diameter and decreased significantly with sample height, whereas the rest of the failure parameters decreased when both sample dimensions increased. As compared with non-lubricated friction condition, lubrication results in a higher influence of deformation rate on the averageε, F/A_0 and U_v values, a similar influence of sample diameter on the average F/A_f and E values, but a lower influence of sample height on all the failure parameters. In turn, increased friction results in a higher influence of deformation rate and mainly the sample height on the averageε, F/A_0 and U_v values, but a lower influence of sample diameter on all the failure parameters. Principal components analyses showed that principal component 1 is determined by ε, F/A_0 and U_v, and is strongly influenced by sample height, whereas component 2 is dominated by E, and is mainly influenced by sample diameter.

Keywords Deformation rate, friction, lubrication, potato tissue, principal components analysis, sample dimensions, uniaxial compression.

Introduction

The uniaxial compression test is the most popular means of deriving the stress–strain properties of soft foods and of biological materials in general; other methods like texture profile analysis (TPA) and stress relaxation are based on the compression test (Alvarez & Canet, 1998; Canet *et al*., 2005). The drawback of the compression test however is that the friction between the sample and the loading plates leads to an inhomogeneous stress–strain state in the sample (Charalambides *et al*., 2001). Thus, the force registered during the uniaxial compression test is attributed to the sum of the force actually involved in compressing the food plus the force required to overcome the surface friction as the sample expands between the plates (Canet & Sherman, 1988, 1990; Wagoner & Chenot, 2005). The consequence of this effect is the 'barrel shape' of a compression-loaded cylindrical specimen observed during tests. If compression is performed under conditions where there is no friction, the deformation is homogeneous and the sample retains its cylindrical shape (Charalambides *et al*., 2001). The frictional effects between the plates and the sample have been well documented in the literature (Johnson & Mellor, 1973; Dieter, 1986; Smith & Kobayashi, 1993). Specifically, the material next to the plates is restrained from radial movement, and the material appears to be stiffer than it truly is. This leads to 'apparent' as opposed to 'true' stress–strain calculations, when the usual expressions for stress and strain and the experimental force-deformation data are used (Canet *et al*., 2001; Charalambides *et al*., 2005).

The apparent stress–strain behaviour will also depend on the geometry, such behaviour being an indication of inhomogeneous deformation (which in compression can be the result of friction at the interface). It has been shown that sample dimensions influence the force-

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deformation data obtained when large forces are applied (Culioli & Sherman, 1976; Olkku & Sherman, 1979; Chu & Peleg, 1985; Canet & Sherman, 1988, 1990; Gil, 1991; Charalambides *et al.*, 2001, 2005). Also, previous works have shown that the rate of deformation can affect the measured rheological properties from compression tests (Goh & Sherman, 1987; Luyten *et al.*, 1992; Scanlon & Long, 1995; Alvarez *et al.*, 2002).

The influence of surface friction and lubrication on the compression behaviour at compression rates of 5–100 mm min^{-1}, of cylindrical samples of potato flesh (cv. King Edward) was previously examined for samples having length/diameter ratios of 0.2–0.8 (Canet & Sherman, 1988). In this study, the experiments of compression tests with potatoes (cv. Desiree) were performed with larger ranges, either of compression rate or of sample dimensions. Besides, in a previous work, a method was established for determining dimensionless area expansion ratio at failure, A_f/A_0 (actual maximum area of the deformed sample in contact with the loading platens/original area of the non-deformed sample) (Canet *et al.*, 2006). The determination of area expansion ratio at failure allows a direct determination of true stress (F/A_f) from engineering stress (F/A_0), justifying the use of this additional parameter in relation to failure under compression tests. A recent International Technical Specification describes a method for the determination of rheological properties by uniaxial compression tests at constant displacement rate of hard and semi-hard cheeses [ISO/TS 17996/IDF/RM 205:2006(E)]. However, such standardised testing protocol for potatoes does not exist and needs to be established.

Principal components analysis (PCA) is used to study the interdependencies and underlying relationships between variables (Piggot & Sharman, 1986), being widely applied in studies on semisolids or liquid products, such as wine and apple juices (Silva & Macalta, 1999; Varela *et al.*, 1999). PCA is also used to analyse the sensory properties of fruits and vegetables to investigate the relationship with instrumental measurements (Barreiro *et al.*, 1998).

The purpose of the present study was: (1) to establish how key failure parameters derived from compression tests on potatoes are influenced by the surface friction conditions, rate of deformation and sample diameter and height; and (2) to use PCA to reduce the number of failure parameters by means of linear combinations of the same.

Materials and methods

Test material

Data were obtained using Spanish potato tubers (*Solanum tuberosum*, *L.*, cv. Desiree), having weights (g) within the confidence interval ($255.69 \le \mu \le 311.81$) and specific weights (g cm^{-3}) within the interval ($1.0681 \le \mu \le 1.0737$); $P \le 0.01$. The material was stored for 2 months at about 5 °C and 85% relative humidity to avoid sprouting and accumulations of sugars before the experiment (Smith, 1987). Each day prior to testing, potatoes were reconditioned at room temperature for about overnight. Then, cylinder-shaped samples, having diameters, ∅ 19.05 and 25.4 mm were cut from the central region of potatoes by cork borers and then trimmed to heights, *h* of 5, 10, 15 and 20 mm (Gil, 1991). The exact height of each sample was recorded to within ± 0.1 mm. In order to avoid drying, the samples were kept between wet sponges for less than 20 min prior to testing.

Uniaxial compression test

A minimum of ten samples of each geometry ($n = 10$) were compressed at room temperature (20–21 °C) between the metal platens of a model 1140 Instron Universal Testing Machine (Instron, Canton, Mass., USA) using a 5-kN load cell and a 57-mm diameter flat compression plunger (Canet *et al.*, 2006). Experiments were carried out at constant deformation rates, R_d of 50, 100, 200 and 400 mm min^{-1}. The force-deformation behaviour was recorded with a standard Instron recorder at a speed of 1:10 with respect to the deformation rate. Compression tests were carried out using three frictional conditions. Firstly, 32 tests (four deformation rates × two diameters × four heights) were performed where no lubricant was applied to the loading platen–sample interface before testing (non-lubricated friction condition). Additional 32 tests were carried out with each sample's upper and lower surfaces lubricated with mineral oil, having a viscosity of 30 mm^2 s^{-1} (lubricated friction condition). Finally, 32 tests were carried out with increased friction by inserting two sheets of emery paper (grit size 150) between the loading platens and upper and lower surfaces of each sample (increased friction condition). Therefore, a total of 960 cylindrical specimens were tested.

The force-deformation data were converted into compressive stress and Cauchy strain. Five parameters were identified to characterise the compression stress–strain curves (Smith & Kobayashi, 1993; Luginbühl, 1996; Canet *et al.*, 2001, 2005):

1. The Cauchy strain at failure (failure strain) is defined as ε = (final height - initial height)/(initial height).
2. The apparent failure stress, defined as engineering stress $\sigma = F/A_0$ (force at failure divided by the original cross section expressed in kPa).
3. The true failure stress defined as true stress, $\sigma_t = F/A_f$ (force at failure divided by the surface area at failure expressed in kPa). This failure parameter was only

determined under non-lubricated and lubricated friction conditions as published before (Canet *et al.*, 2006).

4. The apparent elastic modulus E was determined from the linear portion of the derived compressive stress–strain curve and is expressed in kPa.
5. The apparent energy at failure U_v, defined as the total work of deformation divided by the original sample volume and expressed in kJ m^{-3}.

Statistical analysis

Different statistical analyses for determining the variation of failure parameters with friction conditions, deformation rate and sample dimensions were carried out by using STATGRAPHICS (version 5.0, STSC Inc., Rockville, MD, USA). The failure parameters were subjected to the different multifactor analyses of variance (ANOVA) and PCA showed in the Table 1. In the multifactorial analyses, where significant differences were present, individual combinations were compared using Bonferroni multiple range tests (99%). The factorial analyses were used to study the effect of test conditions on the failure parameters, whereas the PCA analyses were carried for investigating the interdependence of the same via identification of new, uncorrelated variables (Alvarez & Canet, 2000).

Results and discussion

Friction, deformation rate and sample dimension effects

As shown in Table 2, for non-lubricated and increased friction conditions, there is a significant ($P \le 0.01$) effect of deformation rate, and sample diameter and height on

Table 1 Statistical analysis carried out in the study on the failure parameters

Description	Factors	Levels of the factors	Failure parameters	Data number (*n*)
*Multifactor analyses of variance (*ANOVA*)*				
Three-way ANOVA		*Non-lubricated friction condition*		
	Deformation rate	50, 100, 200 and 400 mm min^{-1}	ε, F/A_0, F/A_f, E, U_v	320
	Sample diameter	19.05 and 25.4 mm		
	Sample height	5, 10, 15 and 20 mm		
Three-way ANOVA		*Lubricated friction condition*		
	Deformation rate	50, 100, 200 and 400 mm min^{-1}	ε, F/A_0, F/A_f, E, U_v	320
	Sample diameter	19.05 and 25.4 mm		
	Sample height	5, 10, 15 and 20 mm		
Three-way ANOVA		*Increased friction condition*		
	Deformation rate	50, 100, 200 and 400 mm min^{-1}	ε, F/A_0, F/A_f, E, U_v	320
	Sample diameter	19.05 and 25.4 mm		
	Sample height	5, 10, 15 and 20 mm		
Two-way ANOVA	Lubrication	Non-lubricated and lubricated friction conditions	ε, F/A_0, F/A_f, E, U_v	640
	Deformation rate	50, 100, 200 and 400 mm min^{-1}		
Two-way ANOVA	Lubrication	Non-lubricated and lubricated friction conditions	ε, F/A_0, F/A_f, E, U_v	640
	Sample diameter	19.05 and 25.4 mm		
Two-way ANOVA	Lubrication	Non-lubricated and lubricated friction conditions	ε, F/A_0, F/A_f, E, U_v	640
	Sample height	5, 10, 15 and 20 mm		
Two-way ANOVA		*Non-lubricated friction condition*		
	Sample diameter	19.05 and 25.4 mm	ε, F/A_0, F/A_f, E, U_v	320
	Sample height	5, 10, 15 and 20 mm		
Two-way ANOVA		*Lubricated friction condition*		
	Sample diameter	19.05 and 25.4 mm	ε, F/A_0, F/A_f, E, U_v	320
	Sample height	5, 10, 15 and 20 mm		
Two-way ANOVA		*Increased friction condition*		
	Sample diameter	19.05 and 25.4 mm	ε, F/A_0, F/A_f, E, U_v	320
	Sample height	5, 10, 15 and 20 mm		
One-way ANOVA	Friction condition	Non-lubricated, lubricated and increased friction conditions	ε, F/A_0, F/A_f, E, U_v	960
One-way ANOVA	Lubrication	Non-lubricated and lubricated friction conditions	ε, F/A_0, F/A_f, E, U_v	640

	Dataset		
Principal components analyses (PCA)			
PCA	Non-lubricated, lubricated and increased friction conditions	ε, F/A_0, E, U_v	960
PCA	Non-lubricated and lubricated friction conditions	ε, F/A_0, F/A_f, E, U_v, A_f/A_0	640

Table 2 Multifactor analyses of variance (three-way ANOVA) for the failure parameters (ε, F/A_0, F/A_f, E, U_v) under non-lubricated, lubricated and increased friction conditions

		Non-lubricated friction condition		**Lubricated friction condition**		**Increased friction condition**	
Source of variation	**Failure parameters**	***F*-ratio**	**Sig. level**	***F*-ratio**	**Sig. level**	***F*-ratio**	**Sig. level**
Main effects							
A: deformation rate	ε	20.137	0.0000	44.479	0.0000	85.908	0.0000
	F/A_0	17.026	0.0000	48.901	0.0000	89.670	0.0000
	F/A_f	59.913	0.0000	89.670	0.0000	–	–
	E	20.251	0.0000	21.932	0.0000	30.519	0.0000
	U_v	27.031	0.0000	53.531	0.0000	125.769	0.0000
B: diameter	ε	7.874	0.0054	5.607	0.0186*	60.848	0.0000
	F/A_0	212.591	0.0000	196.567	0.0000	195.008	0.0000
	F/A_f	693.797	0.0000	744.981	0.0000	–	–
	E	44.200	0.0000	82.468	0.0000	39.307	0.0000
	U_v	37.438	0.0000	42.321	0.0000	16.018	0.0000
C: height	ε	467.853	0.0000	416.956	0.0000	1304.654	0.0000
	F/A_0	256.011	0.0000	92.676	0.0000	1782.949	0.0000
	F/A_f	179.028	0.0000	58.483	0.0000	–	–
	E	20.254	0.0000	17.702	0.0000	17.132	0.0000
	U_v	575.233	0.0000	321.603	0.0000	2038.842	0.0000

*Non-significant differences between means ($P \leq 0.01$); factors and levels: deformation rate (50, 100, 200 and 400 mm min^{-1}); diameter (19.05 and 25.4 mm); height (5, 10, 15 and 20 mm); ($n = 320$).

all the failure parameters (ε, F/A_0, F/A_f, E, and U_v, and ε, F/A_0, E, and U_v, respectively). For lubricated friction condition, there is additionally a significant ($P \leq 0.01$) effect of deformation rate and sample diameter and height on the average F/A_0, F/A_f, E, and U_v values; sample diameter did not have significant effect on the average ε value. As compared with samples compressed without lubricant, lubrication results in a higher significant influence of deformation rate, a non-significant influence of sample diameter and a lower significant influence of sample height on the failure strain. Increased friction results in a very much higher significant influence of the three factors on the average ε value (Table 2). In turn, as compared with non-lubricated friction condition, lubrication results in a higher significant influence of deformation rate and a lower significant influence of sample diameter and height on the engineering stress (Table 2), whereas increased friction results in a very much higher significant influence of deformation rate and sample height and a lower significant influence of sample diameter on the average F/A_0 value. Also lubrication results in a higher significant influence of deformation rate and sample diameter, but a lower influence of sample height on the true stress (F/A_f). Likewise, as compared with samples compressed without lubricant, lubrication results in a similar influence of deformation rate and sample height and a higher significant influence of sample diameter on the average E value. Increased friction results in a similar significant influence of the three factors studied on the apparent elastic modulus (Table 2). Finally, as compared with samples compressed without lubricant, lubrication results in a higher significant influence of deformation rate, a similar influence of sample diameter, and a lower influence of sample height on the average U_v value, and increased friction results in a very much higher significant influence of deformation rate and sample height and a lower sample diameter influence on the average U_v value.

Two-way ANOVA analyses (Table 3) showed that there were significant differences between the average ε values owing to the main effects of lubrication and deformation rate, and lubrication and sample height; whereas, when lubrication and sample diameter were considered in the analysis, the last factor did have non-significant effect on the failure strain. Figure 1a shows that as for non-lubricated and lubricated friction conditions, failure strain increases when the deformation rate and the sample diameter are increased and decreases when sample height is increased. Besides, as compared with samples compressed without lubricant, lubrication results in higher average ε values at 200 and 400 mm min^{-1}, at each sample height tested. Note as mainly, ε values at the lowest height (5 mm) are significantly superior to the rest of heights (Figs 1a and 2a). When two-way ANOVA was carried out for the factors sample diameter and height (Table 3), under non-lubricated and lubricated friction conditions, neither sample diameter had significant effect on the failure strain (Fig. 2a). However, as compared with non-lubricated friction condition, increased friction results in a significant influence of sample diameter (Fig. 2a) and a

Table 3 Multifactor analyses of variance (two-way ANOVA) for the failure parameters (ε, F/A_0, F/A_f, E, U_v) and factors, such as lubrication and deformation rate, lubrication and sample diameter, lubrication and sample height, and sample diameter and height under non-lubricated, lubricated and increased friction conditions, respectively

Source of variation	Failure parameters	*F*-ratio	Sig. level	Source of variation	*F*-ratio	Sig. level	Source of variation	*F*-ratio	Sig. level
Main effects									
A: lubrication	ε	15.542	0.0001	A: lubrication	14.940	0.0001	A: lubrication	43.257	0.0000
	F/A_0	0.383	0.5430*		0.3425	0.5216*		0.611	0.4432*
	F/A_f	27.255	0.0000		39.483	0.0000		30.172	0.0000
	E	0.106	0.7481*		0.105	0.7494*		0.105	0.7491*
	U_v	0.374	0.5478*		0.360	0.5550*		1.094	0.2959*
B: deformation rate	ε	10.211	0.0000	B: diameter	2.158	0.1423*	B: height	403.640	0.0000
	F/A_0	17.206	0.0000		127.565	0.0000		144.800	0.0000
	F/A_f	27.972	0.0000		402.237	0.0000		48.100	0.0000
	E	22.734	0.0000		76.284	0.0000		25.448	0.0000
	U_v	13.205	0.0000		13.163	0.0003		434.667	0.0000
Interaction									
AB	ε	0.407	0.7479*	AB	0.025	0.8767*	AB	1.603	0.1876*
	F/A_0	1.309	0.2706*		0.049	0.8276*		10.228	0.0000
	F/A_f	0.402	0.7518*		0.616	0.4411*		5.857	0.0006
	E	6.915	0.0001		0.734	0.4012*		2.191	0.0879*
	U_v	0.535	0.6581*		0.007	0.9338*		11.839	0.0000
	Non-lubricated friction condition			*Lubricated friction condition*			*Increased friction condition*		
	Failure parameters	*F*-ratio	Sig. level	Failure parameters	*F*-ratio	Sig. level	Failure parameters	*F*-ratio	Sig. level
Main effects									
A: diameter	ε	4.297	0.0390*	ε	2.659	0.1040*	ε	18.170	0.0000
	F/A_0	158.359	0.0000	F/A_0	117.316	0.0000	F/A_0	62.920	0.0000
	F/A_f	348.367	0.0000	F/A_f	349.996	0.0000	F/A_f	–	–
	E	36.203	0.0000	E	66.124	0.0000	E	22.330	0.0000
	U_v	22.639	0.0000	U_v	21.135	0.0000	U_v	3.644	0.0572*
B: height	ε	255.288	0.0000	ε	197.702	0.0000	ε	389.588	0.0000
	F/A_0	190.705	0.0000	F/A_0	55.311	0.0000	F/A_0	575.273	0.0000
	F/A_f	89.893	0.0000	F/A_f	27.476	0.0000	F/A_f	–	–
	E	16.589	0.0000	E	14.194	0.0000	E	9.733	0.0000
	U_v	347.841	0.0000	U_v	160.608	0.0000	U_v	463.781	0.0000
Interaction									
AB	ε	8.800	0.0000	ε	3.243	0.0223*	ε	4.066	0.0074
	F/A_0	7.121	0.0001	F/A_0	4.539	0.0039	F/A_0	16.885	0.0000
	F/A_f	22.176	0.0000	F/A_f	14.234	0.0000	F/A_f	–	–
	E	1.943	0.1226*	E	1.881	0.1326*	E	7.641	0.0001
	U_v	0.618	0.6036*	U_v	0.703	0.5508*	U_v	0.736	0.5313*

*Non-significant differences between means ($P \leq 0.01$); factors: lubrication (non-lubricated and lubricated friction conditions); deformation rate (50, 100, 200 and 400 mm min^{-1}); diameter (19.05 and 25.4 mm); height (5, 10, 15 and 20 mm); (n = 640 and n = 320).

higher significant influence of sample height on the failure strain (Table 3). At last, as compared with non-lubricated friction condition, lubrication causes a significant increase of the failure strain, but it is not significantly influenced by increased friction (Table 4). Considering all the variables studied, sample height had the more significant effect on the failure strain. In turn, lubrication effect did not have any significant influence on the engineering stress when considered together the deformation rate, sample diameter and height effects (Table 3). Besides, although the average engineering stress increased with increasing deformation rate, only differences between 50 and 100 mm min^{-1} and between 100 and 200 mm min^{-1} were significant (Fig. 1b). However, at each friction condition used, when considering sample diameter and height as main effects, both factors and their interaction had significant effect on the engineering stress (Table 3). The average F/A_0 value was found to decrease when sample diameter and height are increased. Under all friction conditions, the average F/A_0 values corresponding to the lowest diameter and height were significantly higher than for the rest of the sample dimensions used (Fig. 2b). Also, the failure stress, calculated on the basis of the original sample surface area, decreased with increasing sample length/diameter ratio at a constant diameter, when all other variables were kept constant (Canet & Sherman, 1988). Again, one-way ANOVA showed that friction

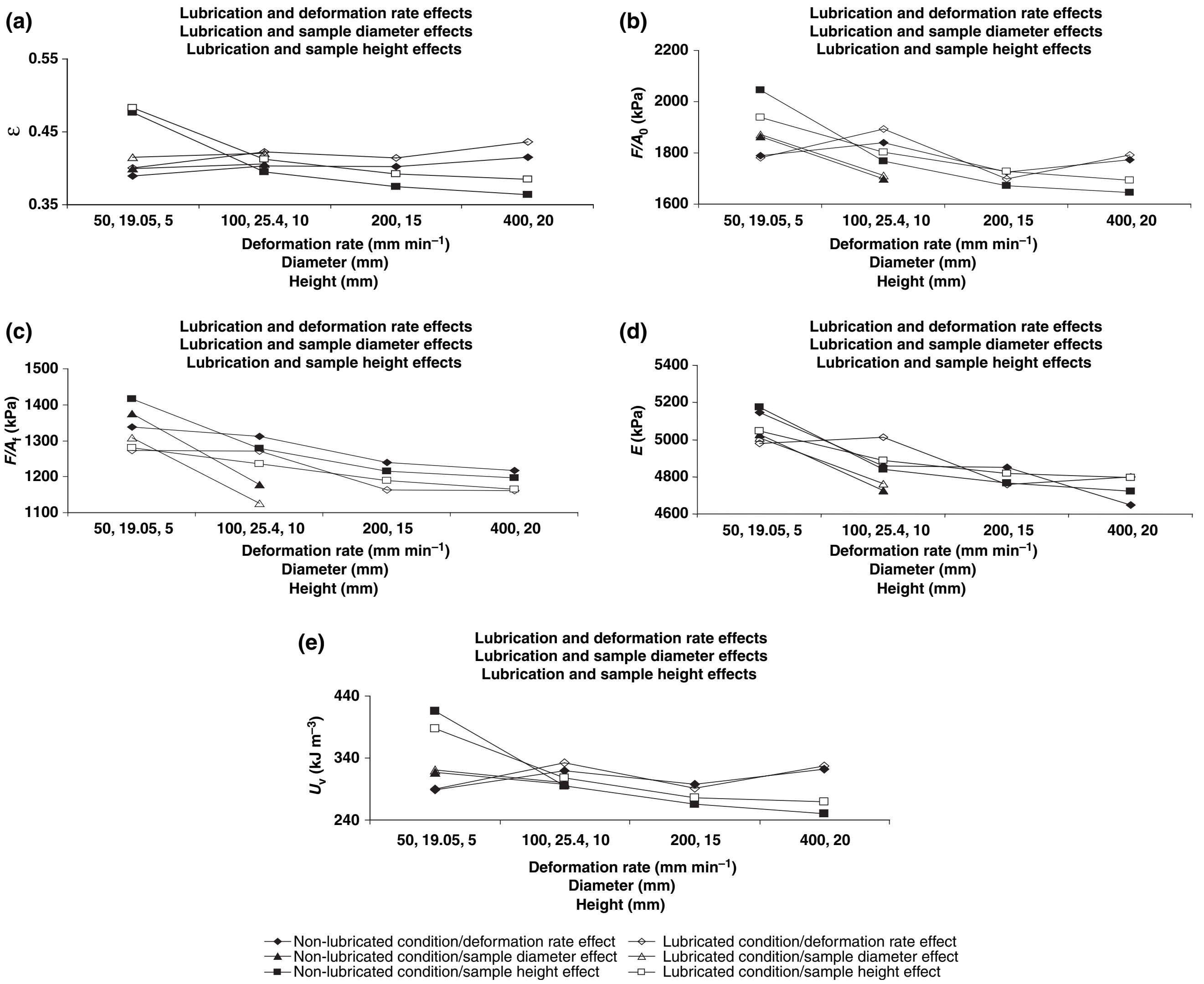


Figure 1 Effects of lubrication, deformation rate and sample dimensions on the failure parameters.

condition did not have significant effect on the engineering stress (Table 4). Between the factors studied, sample height had a more significant effect on engineering stress.

There were significant differences between the average values of the true stress (F/A_f) when all the main effects like lubrication and deformation rate, lubrication and sample diameter and lubrication and sample height were considered in the analyses (Table 3). The significance of the factors studied was very much higher for the true stress than for the engineering one, demonstrating that the use of the original area of the non-deformed sample (A_0) replacing the actual maximum area of the deformed sample (A_f) for estimating the failure stress is not a reasonable assumption for the uniaxial compression of potato tissue. This finding contradicts other results found in cheese (Charalambides *et al.*, 2001, 2005). As compared with non-lubricated condition, lubrication results in a lower average F/A_f value, which decreases when the deformation rate and the sample dimensions increase (Fig. 1c). The surface lubrication lowered true stress values as compared with those obtained under non-lubricated friction condition by eliminating the component of the applied force required to overcome the friction between the sample and the compression plate surfaces (Gil, 1991). A previous study showed that lubrication increased the actual area in contact with the loading plates (A_f), which was attributed to the same phenomenon (Canet *et al.*, 2006). The two-way ANOVA carried out for factors sample diameter and height, for non-lubricated and lubricated friction conditions

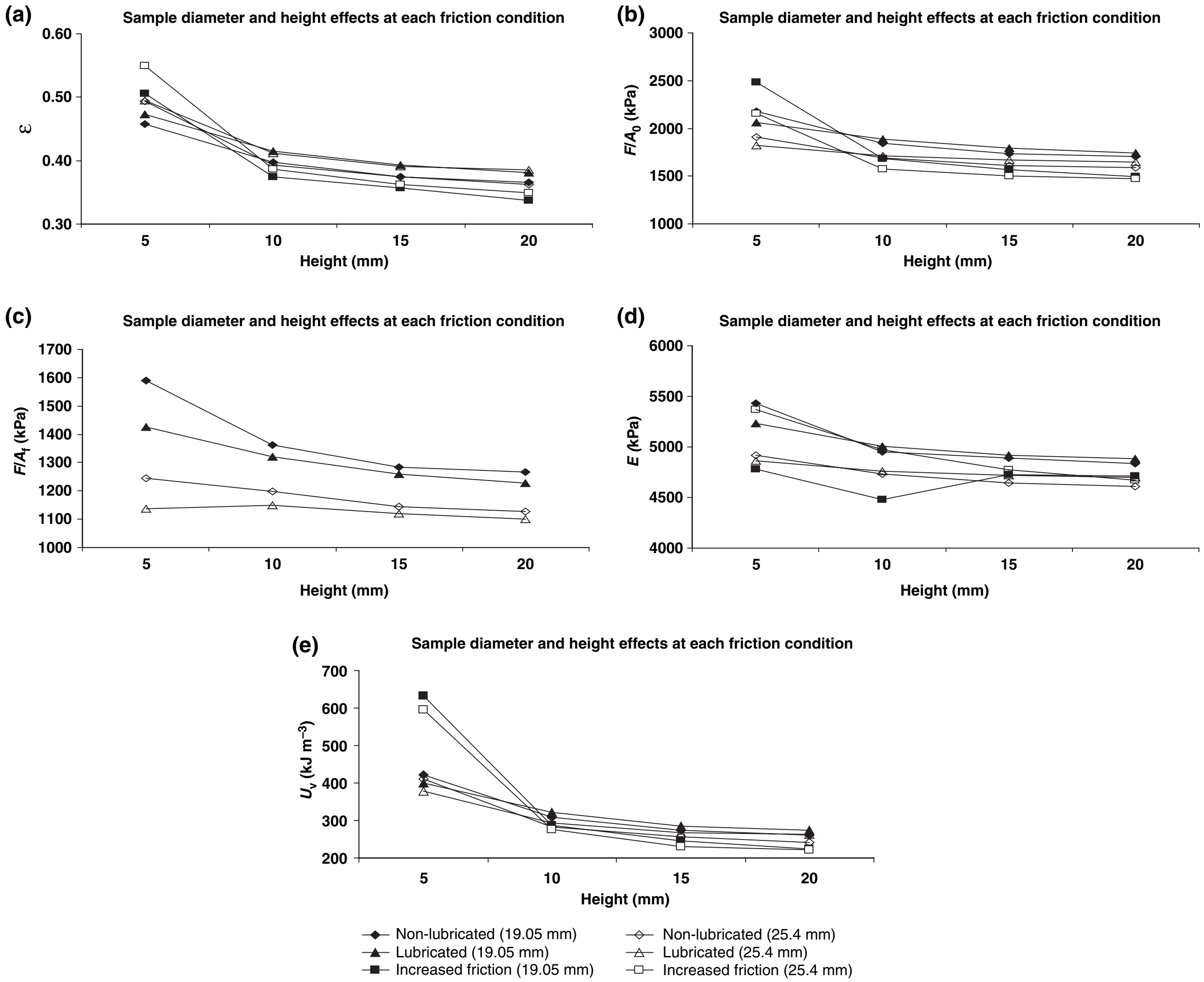


Figure 2 Effects of sample dimensions (diameter and height) on the failure parameters at each friction condition used.

indicated that both factors and their interaction had significant effect on the true stress (Table 3). For both friction conditions, the average F/A_f value is significantly decreased when both sample dimensions are increased (Fig. 2c). Finally, one-way ANOVA also demonstrated that as compared with non-lubricated friction condition, lubrication results in a significant decrease in the true failure stress (Table 4). Considering the factors studied, the sample diameter had the more significant effect on the true failure stress.

Lubrication did not have any significant effect on the apparent elastic modulus when this effect was considered together with deformation rate and sample diameter and height effects (Table 3). However, two-way ANOVA shows that there is a significant effect of deformation rate, sample diameter and height on the *E* average value, decreasing with increasing deformation rate, sample diameter and height (Fig. 1d). At each friction condition used, both sample diameter and height had significant effect on the apparent elastic modulus (Table 3), which is significantly higher at the smallest sample dimensions (Fig. 2d). Besides, friction condition had non-significant effect on the *E* average value when all friction conditions and only non-lubricated and lubricated friction conditions are considered (Table 4). Among the factors studied, sample diameter had the more significant effect on the apparent elastic modulus.

Lubrication had no significant effect on the energy at failure when considered together with deformation rate

Table 4 Analyses of variance (one-way ANOVA) and comparisons between means for the failure parameters (ε, F/A_0, F/A_f, E, U_v) with three and two friction levels, respectively

Source of variation	Failure parameters	*F*-ratio	Sig. level	Non-lubricated	Lubricated	Increased friction
A: friction	ε	6.185	0.0021	40.2545a	41.8193b	40.3112a
	F/A_0	3.071	0.0468*	1781.9984a	1791.4188a	1741.1987a
	F/A_f	417.005	0.0000	1276.7956a	1217.3753b	1741.1987c
	E	2.372	0.0938*	4876.2962a	4886.5216a	4811.3403a
	U_v	7.367	0.0007	307.0100a	310.2594a	339.3234b
A: lubrication	ε	14.936	0.0001	40.2545a	41.8193b	
	F/A_0	0.355	0.5578*	1781.9984a	1791.4188a	
	F/A_f	24.248	0.0000	1276.7956a	1217.3753b	
	E	0.094	0.7625*	4876.2962a	4886.5216a	
	U_v	0.354	0.5584*	307.0100a	310.2594a	

*Non-significant differences between means ($P \le 0.01$); factors: friction (non-lubricated, lubricated and increased friction conditions); lubrication (non-lubricated and lubricated friction conditions).

[a, b] Different letters in the same row for each source indicate significant differences (n = 960 and n = 640, respectively).

and sample diameter and height effects (Table 3), although two-way ANOVA shows that there is a significant effect of deformation rate, sample diameter and height on the average U_v value, which increased when deformation rate was increased and decreased when sample dimensions were increased (Fig. 1e). The values of energy at failure corresponding to heights of 5 and 10 mm are significantly higher than those corresponding to the heights of 15 and 20 mm. For non-lubricated and lubricated friction conditions, sample diameter and height did have significant effect on the energy at failure (Table 3), whereas only sample height had significant effect for increased friction condition. Sample height was the factor that more significantly influenced the energy at failure, with average U_v values significantly higher at the lowest height (Fig. 2e). As compared with non-lubricated friction condition, lubrication did not have significant influence on the energy at failure, but it is significantly increased under increased friction (Table 4).

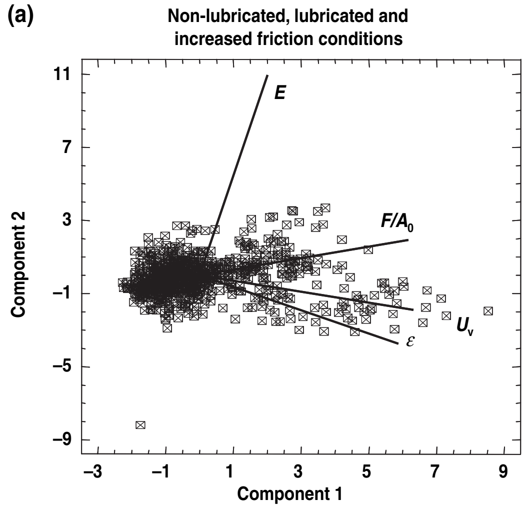
The influence of surface lubrication was smaller than would be anticipated from previous studies with Gouda cheese (Culioli & Sherman, 1976). These authors did not derive any compression parameter from the stress-compression curves generated under non-lubricated, lubricated and increased friction conditions. However, comparisons between them indicate that lubrication and friction effects had a high and significant influence on the force-compression behaviour. In this study, lubrication did not have significant effect on the engineering stress, the apparent elastic modulus and the energy at failure (U_v). Lubrication resulted in an increase of the failure strain (approximately 4%) and in a decrease of the true stress (approximately 5%) as compared with those values obtained under non-lubricated condition (Table 4). The relatively small effect exerted by surface lubrication on the failure strain and the true stress could be attributed to the release of fluid from the damaged tissue of the potato flesh, which relatively reduced lubricant effectiveness (Canet & Sherman, 1988, 1990; Canet *et al.*, 2006).

Principal components analyses

Table 5 shows the two components extracted at each analysis having eigenvalues greater than or equal to 1.0. Figure 3 shows the biplots of the two principal components for the failure parameters. Each plot contains the scatterplot of the principal components and a line for each failure parameter reflecting how each parameter contributes to the components. PCA revealed that two principal components accounted for ≥95% of the total variability (Table 5), when four failure parameters (ε, F/A_0, E, U_v) were included in the PCA analyses (Fig. 3a), whereas the total variability explained by the first and second axes was slightly lower ($<90\%$) when six parameters (ε, F/A_0, F/A_f, E, U_v, A_f/A_0) were considered (Fig. 3b). The area of expansion ratio at failure (A_f/A_0) could be considered as a geometrical variable but is not a failure parameter by itself, which

Table 5 Principal components analyses (PCA) under different friction conditions and with different number of failure parameters

Component number	All friction conditions (with four failure parameters)		Non-lubricated and lubricated friction conditions (with six failure parameters)	
	Eigenvalue	Percent of variance	Eigenvalue	Percent of variance
1	2.7546	68.865	3.2819	54.698
2	1.0465	26.162	1.9388	32.314



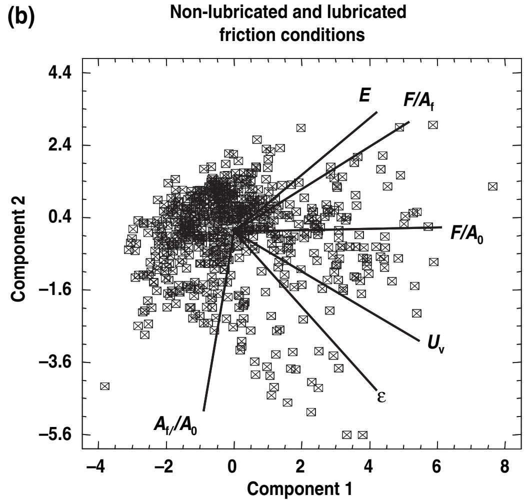


Figure 3 Biplots for the first two principal components from the two principal components analyses (PCA) carried out.

justifies that its inclusion in the PCA analysis decreased the percentages of each failure parameter explained by the first two principal axes. Table 6 gives the weights of the linear combinations that form the two principal components. When four failure parameters were taken into account for data totality, including all friction conditions (Fig. 3a), all the failure parameters positively weight component 1, and this factor is almost equally weighted on the failure strain (ε), engineering stress (F/A_0) and energy at failure (U_v) ratings. The failure strain and energy at failure slightly and negatively weight component 2, which is positively dominated by the apparent elastic modulus (E). Certainly, the relationship between internal cell pressure and apparent elastic modulus has been well established for potato tissue (Canet, 1980; Canet & Sherman, 1988, Gil, 1991; Alvarez & Canet, 1998), and this link appears to keep either under non-lubricated and lubricated conditions or especially under increased friction condition. It is worth nothing that by considering only non-lubricated and lubricated friction conditions, component 2 is not dominated by the apparent elastic modulus. If compression is performed under conditions where there is friction, the cell walls are in an apparently high state of tension and with a high internal cell pressure, which reinforce the idea of the connection existing between internal cell pressure and apparent elastic modulus.

From Table 6, considering all friction conditions (Fig. 3a), the first component equals:

$$0.5441(\varepsilon) + 0.5721(F/A_0) + 0.1867(E) + 0.5846(U_v)$$

This linear combination appears to reflect a single factor related to the mechanical response of the potato tissue to deformation and cell-wall rupture (Alvarez & Canet, 1998), which besides would be strongly influenced by the sample height as found for the failure strain, the engineering stress and the energy at failure separately.

The second component is given by:

$$-0.3163(\varepsilon) + 0.1630(F/A_0) + 0.9209(E) - 0.1592(U_v)$$

and can be related to the internal cell pressure, being strongly influenced by sample diameter.

In turn, in addition to the four failure parameters derived directly from the force-deformation curves, the area expansion ratio at failure (A_f/A_0) and the true stress (F/A_f) are considered in the analyses (Fig. 3b). Also, all the failure parameters positively weight com-

Table 6 Equations of the principal components under the two principal components analyses (PCA) carried out

	All friction conditions (with four failure parameters)		**Non-lubricated and lubricated friction conditions (with six failure parameters)**	
	Component 1	**Component 2**	**Component 1**	**Component 2**
ε	0.5441	−0.3163	0.3982	−0.4529
F/A_0	0.5721	0.1630	0.5338	0.0919
F/A_f	–	–	0.4264	0.4165
E	0.1867	0.9209	0.3484	0.3848
U_v	0.5846	−0.1592	0.4979	−0.2688
A_f/A_0	–	–	0.0742	−0.6266

ponent 1, and this factor is almost equally weighted on the engineering stress and the energy at failure ratings. Note the variable A_f/A_0, positive but inconsiderately weight component 1 (Table 6). However, although the apparent elastic modulus (E) and the true stress (F/A_f) positively weight component 2, this factor is negatively dominated by the area expansion ratio (A_f/A_0). Components 1 and 2 were almost equally weighted on the failure strain although with different sign. This means that the greater the observed area in contact with the loading plates with respect to original area, the lower either the apparent elastic modulus or the true stress. A previous study showed that indeed high correlations are established between the true stress and apparent elastic modulus for non-lubricated and lubricated friction conditions (Canet *et al.*, 2006).

Conclusions

Deformation rate (R_d) and sample dimensions (∅ and h) influenced the failure parameters derived from uniaxial compression of potato. As compared with non-lubricated friction condition, surface lubrication increased the failure strain (approximately 4%) and decreased the true failure stress (approximately 5%), but appeared to have a low effect on the rest of the failure parameters. Under non-lubricated friction condition, the average ε value was found to increase when the deformation rate and the sample diameter were increased (approximately 7% and 2% respectively), and to decrease when the sample height is increased (approximately 24%). The average F/A_0 and U_v values were found to increase when the R_d is increased (approximately 8% and 11%, respectively), and mainly to decrease when the ∅ and h are increased (approximately 9% and 6%, respectively for ∅, and 20% and 40%, respectively for h). The average F/A_f and E values were found to decrease significantly when the R_d, ∅ and h were increased (approximately 9% and 10%, respectively for R_d, 14% and 6%, respectively for ∅, and 15% and 8%, respectively for h). As compared with non-lubricated condition, lubrication results in a higher influence of the deformation rate on the average ε, F/A_0 and U_v values, a similar influence of sample diameter on the average F/A_f and E values, but a lower influence of sample height on all the failure parameters. Increased friction results in a higher influence of R_d and h on the average ε, F/A_0 and U_v values, and a lower influence of ∅ on all the failure parameters. Sample height is the factor that had the more significant effect on the ε, F/A_0 and U_v parameters, dominating the component 1 derived from PCA analyses. Sample diameter had the more significant effect on the F/A_f and E parameters, mainly E dominating component 2. In an industrial environment, experiment setting can be suggested as follows: the surface of sample is not to be lubricated, deformation rate should be intermediate-high (R_d = 200 mm min^{-1}), and samples have to be made with large diameter (∅ = 25.4 mm) and intermediate-high height (h = 15 mm).

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