Modelling the area expansion ratio on uniaxial compression of cylindrical potato samples

W. Canet, M. D. Alvarez*, M. J. Gil†

Department of Plant Foods Science and Technology, Instituto del Frío-CSIC,José Antonio de Novais no.10, E-28040 Madrid, Spain

[*] Corresponding author. Tel.: +34 91 549 23 00; fax: +34 91 549 36 27.

E-mail address: ifrat44@if.csic.es (M.D. Alvarez).

† M. J. Gil

Deceased (2004)

Abstract

Uniaxial compression tests were performed on potato flesh. Cylindrical samples of heights (5, 10, 15 and 20 mm) and diameters (25.4 and 19.05 mm) were tested under lubricated (mineral oil), non-lubricated (natural) and increased friction (emery paper) conditions. Sample flatness (force free area/loaded area) ranged between 0.79 and 4.20. Deformation rate effect was also examined by performing compression tests at 50, 100, 200 and 400 mm min^{-1}. In this study, parameter derived from compression to failure was failure strain (ε_r %). It was established a method for determining the area expansion ratio, AF/A_0 (actual maximum area in contact with the loading platens/original area) at several deformation levels (ε %). For that, loaded area was determined at deformation levels (20, 40 and 80 %) by planimetring of a graphic mark, and then adjusted by regression with respect to deformation level. From this regression, area expansion ratio at failure, AF_r/A_0 was obtained by replacing at each equation corresponding failure strain value. Cylindrical potato samples compression was accompanied by a significant cross-sectional area expansion, evidencing a far-ideal area expansion. For lubricated and non-lubricated friction conditions, increasing deformation rate and sample diameter increased AF_r/A_0, whereas increasing sample height decreased the ratio, mainly under non-lubricated condition. Lubrication causes an increase of AF_r/A_0 average value, near 5% with respect to that obtained with non-lubricated friction condition, meaning a lower influence of deformation rate and sample height, but a higher flatness influence. Effect due to surface lubrication was smaller than in previous compression tests on cheeses, which could be attributed to release of fluid from the damaged tissue of the potato flesh which relatively reduced lubricant effectiveness.

Keywords: Area expansion ratio; Failure; Lubrication; Flatness; Deformation rate; Regression; *Solanum tuberosum* L.

1. Introduction

Uniaxial compression test is the most popular means of deriving stress-strain properties of soft foods and biological materials in general; other methods like texture profile analysis (TPA) and stress relaxation are based on this (Alvarez & Canet, 1998). As a result, there have been a wide number of studies of the compressive strength of potatoes (Schoorl & Holt, 1983; Chu & Peleg, 1985; Khan & Vincent, 1993; Scanlon & Long, 1995; Alvarez, Canet, & Tortosa, 1997; Alvarez & Canet, 1997). The drawback of compression test however, is that friction between sample and loading platens leads to inhomogeneous deformation (Charalambides, Goh, Wanigasooriya, Williams, & Xiao, 2005). This leads to “apparent” as opposed to “true” stress-strain calculations. As a consequence of surface friction influence force registered during uniaxial compression represents the sum total of force actually involved in compressing the food plus force required to overcome surface friction as the sample expands between the plates. Atkin and Sherman (1984) showed that at small compressions the force required to overcome surface friction constituted a larger proportion of the total force registered than at high compressions. It has been showed that several factors influence stress-strain data obtained when large forces are applied (Canet & Sherman, 1988). For cylindrical samples, stress-strain curve will appear to be higher for smaller height/diameter ratio because the volume of affected material is a larger proportion of total sample volume (Charalambides, Goh, Wanigasooriya, Williams, & Xiao, 2005). To achieve identical compression in two specimens of different heights but of equal cross sectional area, a larger stress is required for the shorter sample on Gruyere and Mozzarella cheeses (Charalambides, Goh, Lim, & Williams, 2001). Sample dimensions influence on force-compression data there was been pointed out previously (Culioli & Sherman, 1976; Olkku & Sherman, 1979; Canet & Sherman, 1988, 1990).

Also, deformation rate effect on rheological parameters was evidenced before (Canet & Sherman, 1990; Gil, 1991; Luyten, Vliet, & Walstra, 1992; Scanlon & Long, 1995; Alvarez, Canet, & López, 2002). Fracture strengths of potato tissue were lower at higher loading rates (Scanlon & Long, 1995), and increasing compression rate also lowered real stress values derived from compression tests (Canet & Sherman, 1990).

Compression is often continued until failure occurs, and additional parameters are derived from failure data (Hamann, 1983). Failure stress, defined as force per unit surface area at failure is often calculated incorrectly based on the force divided by the original surface area of the non-deformed sample (A_0), since methods for estimating actual surface area of the deformed sample at failure (AF_r) are difficult, time consuming, tedious and are not always applicable. From the knowledge of the actual loaded area, a linear relationship for modelling area expansion was applied (Olkku & Sherman, 1979). Determination of area expansion ratio at failure allows a direct determination of true failure stress from theoretical failure stress, therefore pointing out the worth of the acquaintance of this additional parameter related to failure under compression tests. Likewise, AF_r/A_0 represents and signifies a suitable tool for analysis in the case of comparing expansion during deformation of cylindrical shaped samples with different diameter.

Regardless of the purpose made, a standardisation of these tests with potatoes has not been done. The main objectives of the present study were (1) to establish a method for determining and modelling the area expansion ratio at several levels of deformation and subsequently at failure, and (2) to find out how this additional parameter related to failure is affected by friction conditions, deformation rate and sample dimensions. A secondary objective was to fit second order polynomial equations to draw three dimensional plots pointing out the effect of the factors studied on the parameter area expansion ratio. Having the comparable results, data presented here can serve as material for standardisation potato compression tests.

2. Material and methods

2.1. Test material

Data were obtained using Spanish potato tubers (*Solanum tuberosum*, *L*., cv. Desiree), having weights (g) within the confidence interval (255.69 ≤ μ ≤ 311.81) and specific weights (g cm^{-3}) within the interval (1.0681 ≤ μ ≤ 1.0737); P ≤0.01.The material was stored in a chamber at 5±1 °C and 85% relative humidity throughout the experiment (Smith, 1987).

2.2. Sample dimensions

Cylindrical shaped samples (diameter, ∅ 25.4 and 19.05 mm) were cut from the central region of potatoes with 1-inch and three-quarter-inch diameter cork borers, respectively, and then trimmed to heights, h of 5, 10, 15 and 20 mm (Gil, 1991). Sample flatness average values, λ defined as the force free area/loaded area ratio (4h/∅) were of 1.05, 2.10, 3.15 and 4.20 for the increasing heights and the lowest diameter (19.05 mm) and of 0.79, 1.57, 2.36 and 3.15 for the highest diameter (25.4 mm), respectively.

2.3. 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 5kN load cell and a 57 mm diameter flat compression plunger. Experiments were carried out at constant deformation rates, R_d of 50, 100, 200 and 400 mm min^{-1}. Force-deformation behavior was recorded with a standard Instron recorder at a speed of 1:10 with respect to deformation rate. Compression tests were carried out using three frictional conditions. Firstly, thirty two tests (four heights × two diameters × four deformation rates) were performed where no lubricant was applied to the loading platen-sample interface before testing (non-lubricated friction condition). Additional thirty two tests were made with each sample's upper and lower surfaces lubricated with mineral oil of low viscosity (lubricated friction condition). Finally, thirty two tests were carried out with friction increased by inserting two sheets of emery paper (granulator 150) between Instron loading platens and upper and lower surfaces of each sample (increased friction condition). In this first series of tests, a total of nine hundred and sixty cylindrical specimens were compressed. From force-deformation curves failure strain average value (ε_r %), defined as the ratio of height at failure to original sample height, was derived and used to calculate actual area average value in contact with loading platens at failure (AF_r) as described below.

Additional compression tests were carried out to establish a method for determining area of expansion ratio, AF/A_0 (actual maximum area of the deformed sample in contact with the loading platens/original area of the non-deformed sample). Loaded area (AF) was determined at 20, 40 and 80 % deformation levels by planimetring (n = 3) of a graphic mark obtained over thin paper with an inked textile sheet, using cellophane paper to avoid contact between product and paper to mark. Ninety six tests were carried under lubricated friction conditions (thirty two tests (four heights × two diameters × four deformation rates) up to 20, 40 and 80% deformation levels, respectively). Ninety six tests were carried out as before but under non-lubricated friction conditions; at last thirty two tests were made up to 80% deformation percentage under friction increased. In this second series of tests, a total of six hundred and seventy two cylindrical samples were compressed. From these, loaded area (*AF*) was obtained and then adjusted by single linear regression with respect to deformation level (ε %) by using a modification of the equation proposed by Olkku and Sherman (Olkku & Sherman, 1979; Canet & Sherman, 1988):

$$AF = b_0 + b_1(\varepsilon/100-\varepsilon)$$

Under lubricated and non-lubricated friction conditions, constants b_0, b_1 and R^2 for each regression (Tables 1, 2) were determined from twelve value pairs (AF, ε) as follow: three pairs ($AF_0 = A_0$, 0 %), three pairs (AF_1, 20 %), three (AF_2, 40 %), and finally three pairs (AF_3, 80 %). For increased friction, constants b_0, b_1 and R^2 (Table 3) were determined from a number variable of pairs ($AF_0 = A_0$, 0, 10, 20,…, ε_r %) up to failure strain at each combination of levels of the factors considered, and three pairs (AF_3 , 80 %).

2.4 Statistical analysis

Different statistical analyses for determining variation of area expansion ratio at failure, AF_r/A_0 with deformation rate, sample height and diameter and lubrication were carried out by using STATGRAPHICS (version 5.0, STSC Inc., Rockville, MD, USA). Area expansion ratio values was subjected to the following statistical analyses: one multifactor analysis of variance (ANOVA Four ways) being factors considered friction, deformation rate, and sample height and diameter taking into account two friction levels (lubricated and non-lubricated conditions); two multifactor analyses of variances (ANOVA Three ways) being factors considered deformation rate and sample dimensions under conditions of lubricated and non-lubricated friction respectively; five multifactor analyses of variances (ANOVA Two ways) being factors considered friction (lubricated and non-lubricated conditions) and deformation rate, friction (lubricated and non-lubricated conditions) and sample diameter, friction (lubricated and non-lubricated conditions) and sample height, and finally sample diameter and height at each friction condition (lubricated and non-lubricated); late, one analysis of variance (ANOVA One way) was carried out for studying friction effect separately with two levels (lubricated and non-lubricated friction conditions). Where significant differences were present, individual combinations were compared using Bonferroni multiple range tests (99.9 and 99 %). STATGRAPHICS software was also used for estimating summary statistics of the variable area expansion ratio at failure, AF_r/A_0, as well as the above mentioned simple linear regressions (AF) = f (ε).

Finally, at each friction condition used, multiple regression analyses were carried out in order to establish relationships between dependent (AF_r/A_0) and independent variables (flatness and deformation rate) and to draw three dimensional plots pointing out factors studied effect on area expansion ratio at failure. Relationship between dependent and independent variables was expressed in terms of a second order polynomial equation as follow:

$$Y = b_0 + b_1X_1 + b_2X_2 + b_{11} X_1^2 + b_{22} X_2^2 + b_{12} X_1 X_2$$

where Y = response (AF_r/A_0), X_1 = flatness, X_2 = deformation rate (mm min^{-1}) and b_0, b_1, b_2, b_{11}, b_{22}, b_{12} = constants measuring linear, quadratic and interaction effects, respectively.

3. Results and discussion

Fig. 1 shows variation of actual surface in contact with the loading platens (AF) with deformation level (ε), as well as friction conditions and deformation rate effects on the failure parameter for compression tests carried out under several conditions used. As expected, AF average value increases with increasing deformation level and sample dimensions (Fig. 1c, d), as well as with increasing deformation rate for all friction conditions. At 80% deformation level and, mainly in samples with lowest flatness, $\lambda = 1.05$ and 0.79 (Fig. 1a, c), it can be appreciated as lubrication causes an increase of *AF* average value, while increased friction determines a decrease of the parameter. Samples with highest flatness, $\lambda = 4.20$ and 3.15 (Fig. 1b, d) means a lower significant influence of friction conditions and deformation rate on *AF* average value.

Tables 1-3 show regression equations for *AF* adjusted with respect to deformation level for each friction condition used, respectively. Under all friction conditions, the square of the correlation coefficients, R^2 were ≥ 0.98. Tables also include the AF_r values obtained by replacing at each equation the corresponding failure strain value (ε_r %) derived from force-deformation curves. By comparing values showed in the Tables 1 and 2, it can be observed as for both lubricated and non-lubricated conditions, with increasing deformation rate increased AF_r for the samples with small and large dimensions. In addition, lubrication increased AF_r average values with respect to natural friction condition. Equations and data contained in Tables 1-3 let having comparable results encompassing a wide spectre of usual conditions used in compression tests. Besides sample dimensions used in this study are commonly utilized in potato compression tests, and therefore they can serve as material for that scientists in potato research determine actual area in contact with the loading platens, either at different deformation levels, *AF* or at failure, AF_r under similar friction conditions.

For each combination of levels of the factors studied, the area expansion ratio at failure, AF_r/A_0 was easily determined from AF_r values showed in Tables 1 and 2. Ratio estimation was only possible for samples subjected to compression tests under lubricated and non-lubricated friction conditions. For increased friction, condition imposed for determining the actual surface in contact with the loading plates ($AF_r = A_0$, up to failure) determined that AF_r/A_0 value was unity (Table 3). The area expansion ratio calculated on potato compression tests, $AF/A_0 = b'_0 + b'_1 \cdot x$; $b'_0 = b_0/A_0 \neq 1$; $b'_1 = b_1/A_0 \neq 1$; $x = \varepsilon/(100-\varepsilon)$, and its value at failure, AF_r/A_0 represent a measurement of the proximity of the potato tissue to the incompressible solid. The last being deformed without friction with the platens from side to side the stress is transmitted, presupposed the same condition of deformation rate and sample dimensions (diameter and height). The ideal occurs when both slope and intercept are unity ($b'_1 = b'_0 = 1$), but potato compressions were accompanied by a significant cross-sectional area expansion. Evaluation of the increase in area for potato samples at two deformation rates used is shown in Figure 2. It can be observed as the material did not behave ideally through 20 % deformation ($\varepsilon/100-\varepsilon = 0.25$) at 50 mm min^{-1} and through 30 % ($\varepsilon/100-\varepsilon = 0.43$) at 400 mm min^{-1}. In contrast, gelled seafood product from frozen surimi (kamaboko) had near-ideal area expansion even at compressions of 60% while retaining its highly elastic texture (Konstance, 1991). In potato tissue, AF/A_0 and AF_r/A_0 average values evidence the far-ideal behaviour of the expansion of the area of contact sample-platens, AF.

Table 4 shows results of the analysis of variance of four ways for area expansion ratio at failure with lubricated and non-lubricated friction conditions. For confidence level of 99.9 % ($P \leq 0.001$), did exist significant differences between means due to factors friction, diameter, deformation rate and height (arranged by decreasing F-*ratio* values) and interactions deformation rate-height (BD), diameter-height (CD), friction-diameter (AC), friction-deformation rate-diameter (ABC) and deformation rate-diameter (BC) (in the same way ordered by decreasing F-*ratio*, F_0 values). Interactions effect was very limited with respect to main effects as evidenced from greatly lower F-*ratio* values. In turn, Table 5 shows results of the analyses of variance of three ways carried out for the AF_r/A_0 average values under lubricated and non-lubricated friction conditions. For lubricated friction condition, there were significant differences between means due to factors sample diameter, deformation rate and sample height (ordered by decreasing F-*ratio* values), as well as interactions diameter-height

(BC), deformation rate-height (AC) and deformation rate-diameter (AB). For non-lubricated friction condition, there were significant differences between means due to factors deformation rate, sample diameter and height (ordered from the highest to the lowest F-*ratio* values) and interactions deformation rate-height (AC) and diameter-height (BC). Under both friction conditions, triple interaction did have non-significant effect on the AF_r/A_0 ratios. In comparing results under both friction conditions (F_0 values), it could be deduced that lubrication increased strongly sample diameter effect, reducing slightly sample height and deformation rate effects on the area expansion ratio. In other words, influence of deformation rate and sample height is more pronounced under non-lubricated friction condition.

The analyses of variance of two ways (Table 6) showed that there were significant differences between AF_r/A_0 average values due to main effects friction and deformation rate, friction and sample diameter and friction and sample height respectively, although interactions between factors did not have significant effect. Lubrication determined an increase of AF_r/A_0 average value for all and each one of the levels of the factors deformation rate (50, 100, 200 and 400 mm min^{-1}), sample diameter (19.05 and 25.4 mm) and sample height (5, 10, 15 and 20 mm). Either under lubricated or in a way more significant under non-lubricated friction conditions, increasing deformation rate determined an increase of AF_r/A_0 average value with respect to that corresponding to rate, R_d = 50 mm min^{-1}. With lubrication friction conditions, the AF_r/A_0 at 50 mm minm^{-1} (1.4158) was lower and significantly different of the value obtained at 200 mm minm^{-1} (1.4723). In turn, the AF_r/A_0 average values at 50, 100 (1.4454) and 200 mm minm^{-1} were lower and differed significantly of value corresponding to R_d = 400 mm minm^{-1} (1.5668). For non-lubricated friction conditions, the AF_r/A_0 average values at 50 (1.3490), 100 (1.3614) and 200 (1.3868) mm minm^{-1} were lower and differed significantly of value obtained at 400 mm minm^{-1} (1.4962). In both friction conditions, interactions of deformation rate with sample diameter and height determined significant differences between means. For both lubricated and non-lubricated friction conditions, the increase of sample diameter from 19.05 to 25.4 mm caused an increase of AF_r/A_0, which was more significant under lubricated condition. On the contrary, for both lubricated and non-lubricated friction conditions, the increase of sample height caused a decrease of AF_r/A_0 average value, slightly more significant under non-lubricated condition. In both friction conditions, AF_r/A_0 average value for the height of 5 mm was higher and significantly different from the rest of the heights.

Table 6 shows that under lubricated conditions there was significant differences between AF_r/A_0 average values due to main factors sample diameter and height, as well as to the interaction between both. Also under non-lubricated conditions, both factors had a significant effect on the AF_r/A_0 average value, although in this case the interaction was not significant. Lubrication caused an increasing of the influence of sample diameter (F_0 = 114.68 against F_0 = 56.08, table 6), whereas decreased slightly the influence of sample height (F_0 = 16.20 against F_0 = 19.78). Under both friction conditions, and for a sample diameter of 19.05 mm, there was non-significant differences ($P \leq 0.001$) between the average values of AF_r/A_0 for the different heights (5, 10, 15 and 20 mm). For non-lubricated friction, considering a superior significance level ($P \leq 0.01$), a significant difference between the AF_r/A_0 values for the extreme sample heights (5 and 20 mm) can be detected. In turn, under both friction conditions and for sample diameter of 25.4 mm, an increase of the sample height caused a decrease in the AF_r/A_0 value, mainly under lubrication, although only differences between 5 mm and the rest of the heights were significant. Finally, under non-lubricated friction condition and at each height level considered, the increase in diameter causes an increase of the AF_r/A_0 value, only significant for the lowest height. However, under lubricated friction conditions, the AF_r/A_0 values corresponding to the highest diameter and heights of either 5 or 10 mm were higher and significantly distinct of those corresponding to the lowest diameter.

Certainly, by considering a factorial double model (sample diameter and height as factors, Table 6), it was found that sample diameter caused this increasing for any level of the factor height, although only was significant for heights of 5 and 10 mm (5, 10 and 20 mm, when $P \leq 0.01$) under lubricated conditions and for heights of 5 mm (5 and 20 mm, when $P \leq 0.01$) under normal friction conditions.

At last, also the analysis of variance of one way showed that there were significant differences between means due to friction (Table 7), corroborating that lubrication causes an significant increase of AF_r/A_0 average value with respect to non-lubricated friction conditions. Factorial double models (friction-deformation rate; friction-diameter and friction-height) showed in the Table 6, confirm that lubrication causes significant increasing in the area expansion ratio, for all the specific levels of the factors deformation rate and sample diameter and height. By comparing between factorial triple models (deformation rate, diameter and height, Table 5), it is concluded that lubrication enlarged sample diameter effect, lessening deformation rate and sample height effects.

For each friction condition used, AF_r/A_0 average values were fitted by multiple regression to XY polynomial functions, being X_1 = flatness and X_2 = deformation rate. Model fitting results were:

$$Y_1 = 1.4785 - 0.0690X_1 + 0.0006X_2 + 0.0132X_1^2 + 3.0722\text{E-}7X_2^2 - 0.0001X_1X_2$$

$$Y_2 = 1.3968 - 0.0547X_1 + 0.0005X_2 + 0.0115X_1^2 + 7.9519\text{E-}7X_2^2 - 0.0002X_1X_2$$

Where Y_1 corresponds to lubricated and Y_2 corresponds to non-lubricated friction conditions respectively. Fig. 3 shows three dimensional plots of failure area expansion ratio in function of flatness, λ and deformation rate, R_d drawn from equations. Graphically, it can be observed as lubrication causes an increase of the AF_r/A_0 average value (1.4723), near 5% with respect to that obtained with non-lubricated friction conditions (1.3964). Lubrication means a lower significant influence of the deformation rate (F_0 = 259.23), and on the contrary the influence of sample flatness (F_0 = 108.7) is higher with lubrication (Fig. 3a). The average value of AF_r/A_0 in non-lubricated friction conditions is increased when the rate increases (F_0 = 295.97), as the lower the flatness. The flatness increase (F_0 = 83.93) causes a reduction of the ratio AF_r/A_0 values, more significant at the highest rates (Fig. 3b).

Average values of AF_r/A_0 obtained in lubricated and non-lubricated friction conditions (1.4723 and 1.3964, respectively) are difficult to compare with the few data existing in the literature, corresponding to products of distinct nature (Culioli & Sherman, 1976; Olkku & Sherman, 1979) or to tests carried out under different experimental conditions. In potato compression tests without lubrication, Diehl, Hamann, and Whitfields (1979) pointed out an increase of the sample diameter of the 15% equivalent to an AF_r/A_0 value of 1.3225, while Canet and Sherman (1988) obtained the lowest value (1.2807).

The difference between the value of the theoretical stress under lubricated and non-lubricated tests represents the friction component of the total force per surface unit developed during compression, which is eliminated with lubrication (Gil, 1991). With lubricated friction conditions, the significant increase of the AF_r/A_0 average value found for all the levels considered of any factors deformation rate and sample dimensions, it can be ascribed to the elimination of the component of the applied force required to overcome the friction between sample and compression platen surfaces. In potato tissue, surface lubrication effect was smaller than in previous compression and relaxation tests on Gouda cheese (Goh & Sherman, 1987). Canet and Sherman (1988) suggested that the fluid released when compressing potato samples is itself sufficient to inhibit the effect of lubrication. Another possible explanation would be that the released fluid could itself act as a surface lubricant for the samples, although then if it did one would expect lubricated and non-lubricated samples to yield the same AF_r/A_0 average values.

Conclusions

In uniaxial compression tests carried out under non-lubricated friction conditions, the increase of deformation rate and sample diameter causes an increase of the failure area expansion ratio (AF_r/A_0), as the higher the rate (400 mm min^{-1}) and the lower the sample height (5 mm), respectively. The increase of sample height causes a decrease of AF_r/A_0, as the higher the sample diameter (25.4 mm). Lubrication causes a significant increase of the AF_r/A_0 average value (1.4723), near 5% with respect to that obtained with non-lubricated friction conditions (1.3964), any the rest of experimental conditions. Additionally, lubrication means a lower significant influence of the deformation rate and of sample height, and on the contrary the influence of sample flatness is higher with lubrication. Apparently low effect of the lubrication on the area expansion ratio is ascribable to the additional role of cell fluids released from potato flesh during testing. In order to minimise the influence of friction conditions, deformation rate and sample dimensions on the AF_r/A_0 average value in compression tests of cylindrical potato samples, the experiment setting can be suggested as follows: the surface of sample has not to be lubricated, deformation rate should be low-intermediate (R_d = 100 mm min^{-1}), and samples have to be made with large diameter (ϕ = 25.4 mm) and intermediate height or flatness (h = 10-15 mm, λ =1.57-2.36). These conditions can pronounce other important parameters as variety effect that is masked by the variability in conditions. Definitely optimum conditions of any compression test with potatoes require effects studied have to be analyzed on other failure parameters in next works.

References

Alvarez, M. D., Canet, W., & Tortosa, M. E. (1997). Effect of freezing rate and programmed freezing on rheological parameters and tissue structure of potato (cv. Monalisa). *Zeitschrift für Lebensmittel Untersuchung und Forschung A, 204*, 356-364.

Alvarez, M. D., & Canet, W. (1997). Effect of pre-cooling and freezing rate on mechanical strength of potato tissues (cv *Monalisa*) at freezing temperatures. *Zeitschrift für Lebensmittel Untersuchung und Forschung A, 205*, 282-289.

Alvarez, M. D., & Canet, W. (1998). Rheological characterization of fresh and cooked potato tissues (cv. *Monalisa*). *Zeitschrift für Lebensmittel Untersuchung und Forschung A, 207*, 55-65.

Alvarez, M. D., Canet, W., & López, M. E. (2002). Influence of deformation rate and degree of compression on textural parameters of potato and apple tissues in texture profile analysis (TPA). *European Food Research and Technology, 215*, 13-20.

Atkin, G., & Sherman, P. (1984). The influence of surface friction on firmness evaluation by compression tests. Proceedings of the IXth International Congress of Rheology, 4. Applications pp.123-144.

Canet, W., & Sherman, P. (1988). Influence of friction, sample dimensions and deformatiom rate on the uniaxial compression of raw potato flesh. *Journal of Texture Studies, 19*, 275-287.

Canet, W., & Sherman, P. (1990). Effect of friction, sample dimensions, and deformation rates on the uniaxial compression behaviour of potato tissues. In W. E. L. Spiess, & H. Schubert (Eds.), *Engineering and food physical properties and process control* (Vol. I) (pp. 159-168). London: Elsevier Applied Science.

Charalambides, M. N., Goh, S. M., Lim, S. L., & Williams, J. G. (2001). The analysis of the frictional effect on stress-strain data from uniaxial compression of cheese. *Journal of Materials Science, 36,* 2313-2321.

Charalambides, M. N., Goh, S. M., Wanigasooriya, L., Williams, J. G., & Xiao, W. (2005). Effect of friction on uniaxial compression of bread dough. *Journal of Materials Science, 40,* 3375-3381.

Chu, C. F., & Peleg, M. (1985). The compressive behaviour of solid food specimens with small height to diameter ratios. *Journal of Texture Studies, 16*, 451-464.

Culioli, J., & Sherman, P. (1976). Evaluation of Gouda cheese firmness by compression tests. *Journal of Texture Studies, 7*, 353-372.

Diehl, K. C., Hamann, D. D., & Whitfields, J. K. (1979) Structural failure in selected raw fruits and vegetables. *Journal of Texture Studies, 10*, 371-400.

Gil, M. J. (1991). *Estudio del efecto de la fricción, dimensión de las muestras y velocidades de deformación en ensayos de compresión uniaxial de alimentos sólidos. PhD Thesis,* Universidad Politécnica de Madrid.

Goh, H. C., & Sherman, P. (1987). The influence of surface friction on the stress relaxation of Gouda cheese. *Journal of Texture Studies, 18,* 389-404.

Hamann, D. D. (1983). Structural failure in solid foods. In M. Peleg & E. B. Bagley (Eds.), *Physical properties of foods* (pp. 351-383). New York: Van Nostrand Reingold/AVI Co.

Khan, A. A., & Vincent, J. F. V. (1993). Compressive stiffness and fracture properties of apple and potato parenchyma. *Journal of Texture Studies, 24*, 423-435.

Konstance, R. P. (1991). Axial compression properties of kamaboko. *Journal of Food Science, 56*, 1287-1291.

Luyten, H., Van Vliet, T., & Walstra, P. (1992). Comparison of various methods to evaluate fracture phenomena in food material. *Journal of Texture Studies, 23*, 245-266.

Olkku, J., & Sherman, P. (1979). Compression testing of cylindrical samples with an Instron Universal Testing machine. In P. Sherman (Ed.), *Food texture and rheology*) (pp. 157-175). London: Academic Press.

Scanlon, M.G., & Long, A. E. (1995). Fracture strengths of potato tissue under compression and tension at two rates of loading. *Food Research International, 28*, 397-402.

Schoorl, D., & Holt, J. E. (1983). Cracking in potatoes. *Journal of Texture Studies, 14*, 61-70.

Smith, O. (1987). Transport and storage of potatoes. In W. F. Talburt & O. Smith (Eds.), *Potato processing* (pp. 203-285). New York: Van Nostrand Reinnold.

Acknowledgements

The authors wish to thank the CICyT for financial support (AGL2004-01780/ALI). This work has been prepared *in memory of* Dr M. J. Gil recently deceased, based on results of his PhD carried out under direction of Dr W. Canet at the Instituto del Frío-CSIC, Spain.

Figure legends

Fig. 1. Effects of friction condition and deformation rate on the variation with the level of deformation of the real surface in contact with the loading –platens. (a) cylindrical potato sample with flatness, λ = 1.05 ($\varnothing$= 19.05 mm, h = 5 mm); (b) cylindrical potato sample with flatness, λ = 4.20 ($\varnothing$= 19.05 mm, h = 20 mm); (c) cylindrical potato sample with flatness, λ = 0.79 ($\varnothing$= 25.4 mm, h = 5 mm); (d) cylindrical potato sample with flatness, λ = 3.15 ($\varnothing$= 25.4 mm, h = 20 mm).

Fig. 2. Ideal area expansion of cylindrical potato sample.

Fig. 3. Three dimensional plots of failure area expansion ratio in function of factors flatness and deformation rate. (a) lubricated friction condition; (b) non-lubricated friction condition.

Nomenclature

AF actual maximum area of the deformed sample in contact with the loading platens (cm^2)

AF_r actual maximum area of the deformed sample in contact with the loading platens at failure (cm^2)

A_0 original area of the non-deformed sample in contact with the loading platens (cm^2)

AF/A_0 dimensionless area expansion ratio (actual maximum area of the deformed sample in contact with the loading platens/original area of the non-deformed sample)

AF_r/A_0 dimensionless area expansion ratio at failure (actual maximum area of the deformed sample in contact with the loading platens at failure/original area of the non-deformed sample)

b_0, b_1, b'_0, b'_1 dimensionless constants in regression equations

b_0, b_1, b_2, b_{11}, b_{22}, b_{12} dimensionless constants in second order polynomial equations

F_0 F-ratio

h sample height (mm)

R_d Deformation rate (mm min^{-1})

R^2 Determination coefficient

X_1, X_2 Independent variables in second order polynomial equations (flatness and deformation rate, respectively)

Y Dependent variable in second order polynomial equations (area expansion ratio at failure)

ε deformation level (%)

ε_r failure strain (%)

λ dimensionless sample flatness (force free area/loaded area)

$\varnothing$ sample diameter (mm)

Subscripts

r *failure*

Table 1

Regression equations for lubricated friction condition of the loaded area adjusted with respect to the level of deformation, $AF = f(\varepsilon)$: $AF = b_0 + b_1\varepsilon/(100-\varepsilon)$

R_d (mm min^{-1}) [a]	λ [b]	b_0	b_1	R^2 [c]	ε_r (%)	AF_r (cm^2)
50	1.05	2.96	1.09	0.99	46.67	3.91
	2.10	3.09	1.29	0.99	41.45	4.01
	3.15	3.08	1.37	0.99	38.80	3.95
	4.20	3.07	1.35	0.99	38.46	3.91
	0.79	5.59	1.97	0.98	49.76	7.54
	1.57	5.50	2.43	0.99	41.54	7.23
	2.36	5.56	2.62	0.99	39.70	7.29
	3.15	5.47	3.00	1.00	37.64	7.28
100	1.05	2.98	1.31	0.99	43.46	3.99
	2.10	3.09	1.35	0.99	41.64	4.06
	3.15	3.14	1.42	0.99	39.03	4.05
	4.20	3.09	1.51	0.99	38.52	4.04
	0.79	5.63	2.12	0.98	49.44	7.71
	1.57	5.52	2.70	0.99	41.52	7.44
	2.36	5.57	2.73	0.99	39.71	7.37
	3.15	5.48	3.13	0.99	37.62	7.37
200	1.05	3.06	1.38	0.99	41.92	4.04
	2.10	3.11	1.45	0.99	37.98	3.99
	3.15	3.12	1.55	0.99	37.60	4.05
	4.20	3.10	1.58	0.99	37.44	4.05
	0.79	5.62	2.55	0.99	50.40	8.21
	1.57	5.57	2.95	0.99	41.84	7.69
	2.36	5.60	2.97	0.99	38.72	7.47
	3.15	5.45	3.47	1.00	38.26	7.61
400	1.05	3.11	1.45	0.99	50.96	4.61
	2.10	3.12	1.55	0.99	40.48	4.18
	3.15	3.09	1.87	0.99	38.35	4.26
	4.20	3.05	1.88	1.00	38.90	4.25
	0.79	5.76	2.66	0.98	54.80	8.98
	1.57	5.56	3.17	0.99	44.16	8.07
	2.36	5.63	3.18	0.99	41.81	7.91
	3.15	5.55	3.64	0.99	39.74	7.95

a: Deformation rate; b: Flatness; c: R-squared.

Table 2

Regression equations for non-lubricated friction condition of the loaded area adjusted with respect to the level of deformation, $AF = f(\varepsilon)$: $AF = b_0 + b_1\varepsilon/(100-\varepsilon)$

R_d (mm min^{-1})[a]	λ[b]	b_0	b_1	R^2[c]	ε_r (%)	AF_r (cm^2)
50	1.05	2.91	0.99	0.99	44.44	3.70
	2.10	2.93	1.27	1.00	40.56	3.80
	3.15	2.97	1.33	0.99	37.78	3.78
	4.20	2.91	1.37	1.00	37.28	3.72
	0.79	5.29	2.01	0.99	48.54	7.19
	1.57	5.27	2.46	0.99	40.66	6.96
	2.36	5.29	2.62	1.00	38.07	6.91
	3.15	5.21	2.90	1.00	37.14	6.92
100	1.05	2.94	1.13	0.99	43.94	3.83
	2.10	2.96	1.34	1.00	37.42	3.76
	3.15	2.99	1.37	0.99	37.14	3.81
	4.20	2.95	1.55	1.00	36.04	3.82
	0.79	5.38	2.07	0.98	46.60	7.19
	1.57	5.28	2.64	0.99	40.54	7.08
	2.36	5.32	2.77	1.00	37.37	6.98
	3.15	5.29	3.00	1.00	35.69	6.96
200	1.05	2.96	1.31	0.99	43.64	3.98
	2.10	2.98	1.43	0.99	37.42	3.83
	3.15	2.99	1.52	0.99	35.43	3.83
	4.20	2.97	1.62	1.00	35.26	3.85
	0.79	5.43	2.34	0.98	46.52	7.46
	1.57	5.29	2.91	1.00	38.24	7.09
	2.36	5.35	2.91	0.99	36.52	7.02
	3.15	5.30	3.32	1.00	36.56	7.21
400	1.05	3.05	1.40	0.98	52.52	4.60
	2.10	3.02	1.52	0.99	40.84	4.07
	3.15	2.99	1.78	0.99	38.56	4.10
	4.20	2.97	1.79	1.00	35.60	3.96
	0.79	5.55	2.50	0.98	54.72	8.57
	1.57	5.36	3.09	0.99	40.56	7.47
	2.36	5.38	3.20	0.99	39.25	7.45
	3.15	5.31	3.55	0.99	37.70	7.45

a: Deformation rate; b: Flatness; c: R-squared.

Table 3

Regression equations for increased friction condition of the loaded area adjusted with respect to the level of deformation, $AF = \mathrm{f}(\varepsilon)$: $AF = b_0 + b_1\varepsilon/(100-\varepsilon)$

R_d (mm min^{-1}) [a]	λ [b]	b_0	b_1	R^2 [c]	ε_r (%)	AF_r (cm^2)
50	1.05	2.47	0.47	0.99	44.28	2.85
	2.10	2.21	1.24	1.00	34.08	2.85
	3.15	1.85	1.85	1.00	35.13	2.85
	4.20	1.74	2.16	1.00	33.93	2.85
	0.79	3.43	1.12	1.00	59.46	5.07
	1.57	3.76	1.99	0.99	39.66	5.07
	2.36	3.35	2.98	1.00	36.57	5.07
	3.15	3.14	3.59	1.00	34.90	5.07
100	1.05	2.45	0.53	1.00	43.16	2.85
	2.10	2.05	1.40	1.00	36.40	2.85
	3.15	1.78	1.96	1.00	35.22	2.85
	4.20	1.76	2.21	1.00	33.07	2.85
	0.79	3.78	1.03	1.00	55.60	5.07
	1.57	3.71	2.07	1.00	39.54	5.07
	2.36	3.29	3.19	1.00	35.78	5.07
	3.15	3.17	3.75	1.00	33.58	5.07
200	1.05	2.25	0.69	0.99	46.72	2.85
	2.10	2.01	1.46	1.00	36.68	2.85
	3.15	1.72	2.07	1.00	35.39	2.85
	4.20	1.64	2.27	1.00	34.77	2.85
	0.79	3.31	1.33	0.99	56.94	5.07
	1.57	3.65	2.32	1.00	37.92	5.07
	2.36	3.16	3.44	1.00	35.72	5.07
	3.15	3.08	3.81	1.00	34.28	5.07
400	1.05	1.56	0.99	0.99	56.72	2.85
	2.10	1.76	1.64	1.00	39.88	2.85
	3.15	1.62	2.14	0.99	36.48	2.85
	4.20	1.45	2.60	1.00	34.90	2.85
	0.79	2.78	1.55	1.00	59.68	5.07
	1.57	3.16	2.83	1.00	40.24	5.07
	2.36	2.84	3.72	1.00	37.44	5.07
	3.15	2.81	4.03	1.00	35.86	5.07

a: Deformation rate; b: Flatness; c: R-squared.

Table 4
Multifactor Analysis of Variance (ANOVA Four ways) for the area expansion ratio at failure (AF_r/A_0)

Source of variation	F-ratio	Sig. level
Main effects		
A: Friction	833.61	0.0000*
B: Deformation rate	648.84	0.0000*
C: Diameter	770.68	0.0000*
D: Height	190.45	0.0000*
Interactions		
AB	2.37	0.0695
AC	23.52	0.0000*
BC	6.40	0.0003*
AD	0.84	0.4710
BD	56.49	0.0000*
CD	34.14	0.0000*
ABC	7.33	0.0001*
ABD	1.60	0.1103
ACD	5.50	0.0010
BCD	1.91	0.0478
ABCD	2.49	0.0086

*Significant differences between means at 0.1%; factors and levels: friction (lubricated and non-lubricated); deformation rate (50, 100, 200 and 400 mm min^{-1}); diameter (19.05 and 25.4 mm); height (5, 10, 15 and 20 mm)

Table 5

Multifactor Analyses of Variance (ANOVA Three ways) for the area expansion ratio at failure (AF_r/A_0) under lubricated and non-lubricated friction condition

	Lubricated friction condition		*Non-lubricated friction condition*	
Source of variation	F-ratio	Sig. level	F-ratio	Sig. level
Main effects				
A: Deformation rate	318.06	0.0000*	334.71	0.0000*
B: Diameter	537.66	0.0000*	289.01	0.0000*
C: Height	75.97	0.0000*	101.95	0.0000*
Interactions				
AB	11.32	0.0000*	0.48	0.6936
AC	17.89	0.0000*	32.61	0.0000*
BC	29.60	0.0000*	6.84	0.0002*
ABC	2.84	0.0032	2.33	0.0153

*Significant differences between means at 0.1%; 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)

Table 6

Multifactor Analyses of Variance (ANOVA Two ways) for factors friction and deformation rate, friction and sample diameter, friction and sample height, and sample diameter and height under lubricated and non-lubricated friction conditions respectively

Source of variation	F-ratio	Sig. level	Source of variation	F-ratio	Sig. level	Source of variation	F-ratio	Sig. level
Main effects			*Main effects*			*Main effects*		
A: Friction	218.96	0.0000*	A: Friction	152.83	0.0000*	A: Friction	141.07	0.0000*
B: Deformation rate	159.42	0.0000*	B: Diameter	137.58	0.0000*	B: Height	27.97	0.0000*
Interaction			*Interaction*			*Interaction*		
AB	0.68	0.5628	AB	2.76	0.0974	AB	0.23	0.8741
Lubricated friction condition						*Non-lubricated friction condition*		
Source of variation	F-ratio	Sig. level				Source of variation	F-ratio	Sig. level
Main effects						*Main effects*		
A: Diameter	114.68	0.0000*				A: Diameter	56.08	0.0000*
B: Height	16.20	0.0000*				B: Height	19.78	0.0000*
Interaction						*Interaction*		
AB	6.31	0.0004*				AB	1.33	0.2655

*Significant differences between means at 0.1%; factors: friction (lubricated and non-lubricated); deformation rate (50, 100, 200 and 400 mm min^{-1}); diameter (19.05 and 25.4 mm); height (5, 10, 15 and 20 mm)

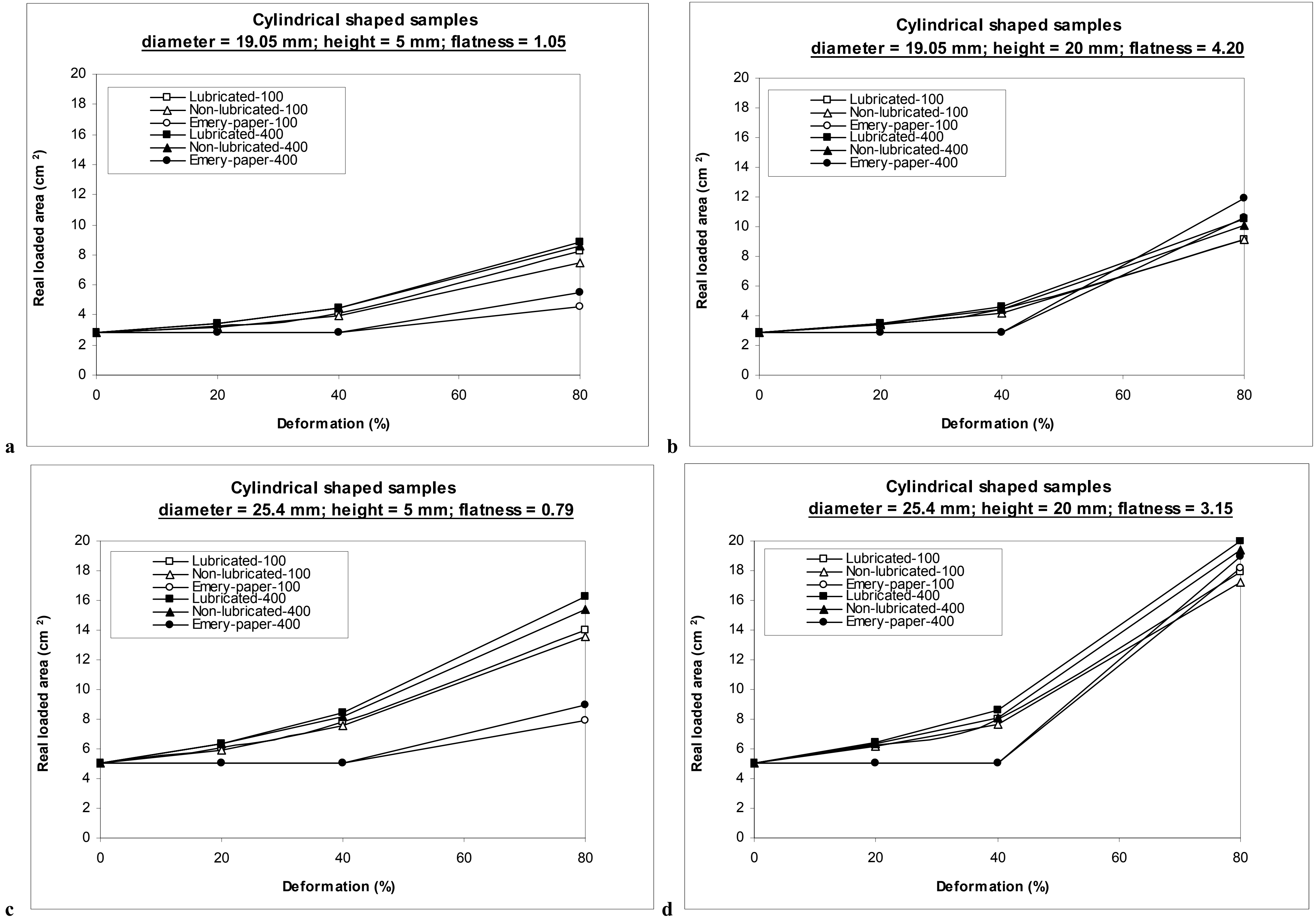
Table 7

Analysis of Variance (ANOVA One way)

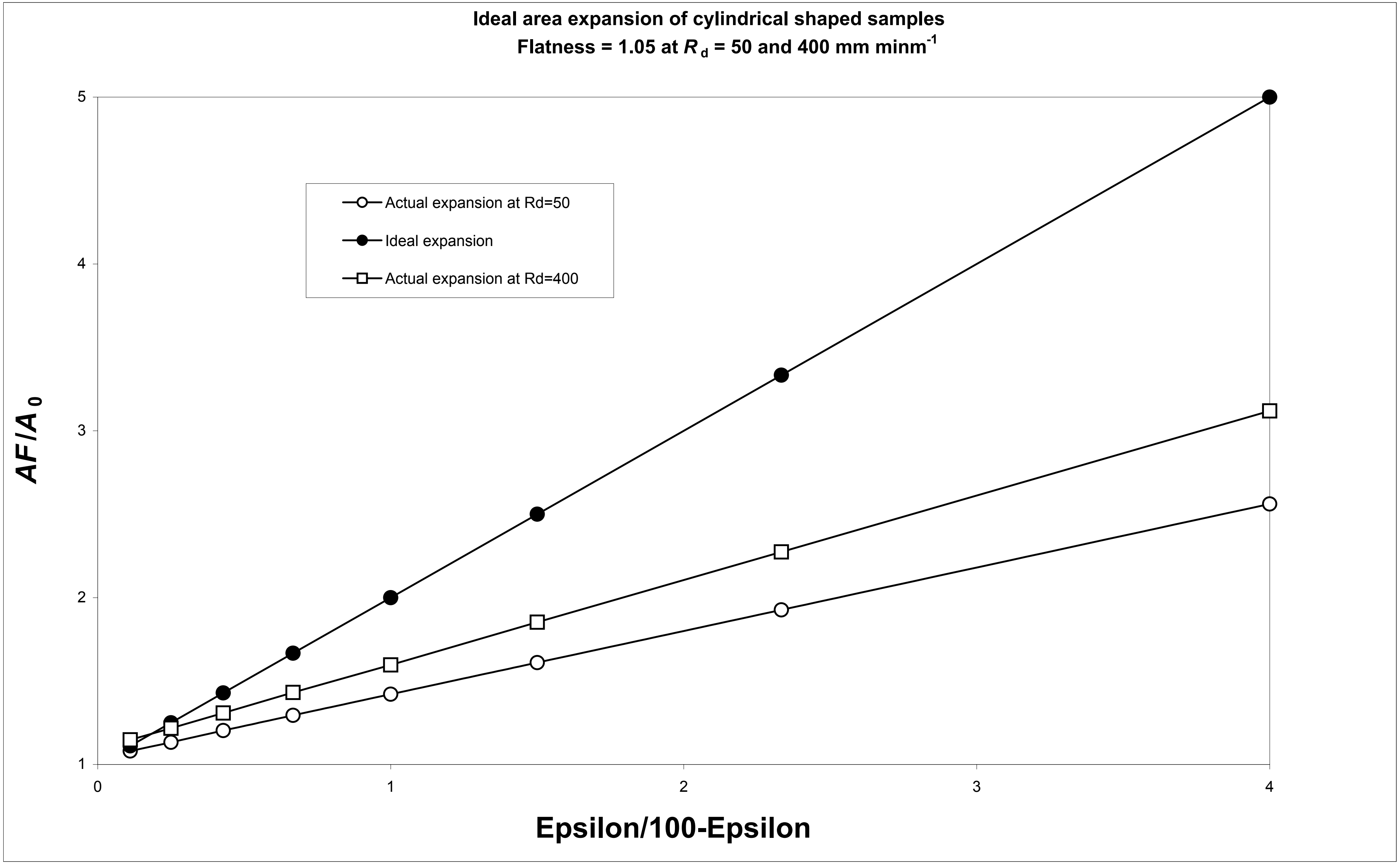
Source of variation	F-ratio	Sig. level
A: Friction	125.59	0.0000*

*Significant differences between means at 0.1%

Factor: friction (lubricated and non-lubricated)



Cylindrical shaped samples
diameter = 19.05 mm; height = 5 mm; flatness = 1.05
Lubricated-100
Non-lubricated-100
Emery-paper-100
Lubricated-400
Non-lubricated-400
Emery-paper-400
Real loaded area (cm 2)
Deformation (%)
a
Cylindrical shaped samples
diameter = 19.05 mm; height = 20 mm; flatness = 4.20
b
Cylindrical shaped samples
diameter = 25.4 mm; height = 5 mm; flatness = 0.79
c
Cylindrical shaped samples
diameter = 25.4 mm; height = 20 mm; flatness = 3.15
d



Ideal area expansion of cylindrical shaped samples
Flatness = 1.05 at R_d = 50 and 400 mm minm^{-1}
Actual expansion at Rd=50
Ideal expansion
Actual expansion at Rd=400
AF/A_0
Epsilon/100-Epsilon
0
1
2
3
4
5