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María Dolores Alvarez · Wenceslao Canet · María Elvira López

Influence of deformation rate and degree of compression on textural parameters of potato and apple tissues in texture profile analysis (TPA)

M.D. Alvarez (✉) · W. Canet · M.E. López
Instituto del Frío-CSIC, c/ José de Novais nº 10
E-28040 Madrid, Spain
e-mail: ifrat44@if.csic.es

Abstract The influence of the degree of compression, at deformation rates of 50, 250 and 500 mm min^{-1}, on the textural parameters in the Texture Profile Analysis (TPA) of cylindrical samples of potato and apple tissues was examined. The tests were performed at up to eight different deformation levels ranging from 10 % to 80 %. The values of all the parameters measured in the samples of both tissues were influenced more by the degree of compression than by the deformation rate. Degrees of compression >40 % and >20 % caused the rupture of potato and apple specimens, respectively. Regression models were fitted to express the variation of cohesiveness and chewiness with deformation rate and degree of compression. In apple and potato tissues the degree of compression had a quadratic effect on the cohesiveness while the effect of the deformation rate was only linear. Cohesiveness was the most appropriate textural parameter for detecting effects of deformation rate and degree of compression in TPA tests of potato and apple tissues. Recoverable instantaneous springiness offers a high potential to differentiate the structural natures of different tissues.

Key words Cohesiveness· Fruits· Regression· Texture· Vegetables

Introduction

Compression testing has been widely applied to assess the mechanical behaviour of potato and apple tissues [1-3]. This test has also been used to study deformation rate and degree effects on rheological parameters. Shama and Sherman [4] were the first to show that, as deformation rate increases, the force required to achieve a particular compression also increases in different foods. However, deformation rate did not exert a significant effect on the failure stress of raw potatoes, although the values tended to decrease slightly with increasing rate in standard and lubricated compression [5]. Deformation rates much less than those typical of mastication can be used to characterize the firmness of UF-Feta cheese from compression test [6].

Texture Profile Analysis (TPA) was developed about 35 years ago and adapted to a universal texturometer, providing a useful means of analyzing a series of textural parameters in a single test by means of a double compression of the sample [7-9]. TPA was performed on apple, carrot, frankfurter, cream cheese and pretzels with the Instron and the effect of the degree of compression on TPA parameters measured at a fixed deformation rate [10]. However, the use of TPA became widespread with the appearance of versatile computer-assisted texturometers such as the TA.HD (Stable Micro Systems, UK) or the QTS (Stevens, UK). This type of instrument can be used to perform a TPA test and obtain all the TPA parameters directly by means of software.

Nevertheless, TPA is often used without knowledge of the correct definition of its parameters or selection of suitable experimental conditions. Since TPA parameters vary with sample size and shape, ratio of compressing probe size versus sample, degree of compression, deformation rate, number of bites, and replicates per mean value [11], all the TPA measurements should clearly state in reports what conditions were used. In TPA tests the choice of the degree of compression will depend upon the purpose of the test. An imitation of the highly destructive process of mastication in the mouth, deformation values that will fracture the specimen are required. However, some parameters such as springiness or cohesiveness can become physically meaningless, since the second compression cycle does not usually find a weakened sample with just the first internal cracks, but portions or small pieces of the initial sample [12, 13].

Current instruments such as the TA.HD (Stable Micro Systems-SMS) give the option of selecting a variable time period to elapse between bites. The amount of time between bites clearly determines TPA parameters such as springiness, cohesiveness, gumminess and chewiness, mainly in systems with a high viscous component [14]. One of the parameters which has undergone most modifications is springiness, initially called elasticity. Pons and Fiszman [11] measured two different springiness-related parameters in the same test: “instantaneous recoverable springiness”, derived from the first compression cycle, and “retarded recoverable springiness”, which corresponds to the springiness parameter normally measured by instrumental TPA and defined by Bourne [15].

TPA software for some texturometers automatically gives results for the adhesiveness parameter, although it is not worth measuring adhesiveness in all cases [16]. For some kinds of food the measurement of adhesiveness by this method is not appropriate [11]. Hoseney and Smewing [13] stated that in order to study adhesive properties it is imperative to have a procedure that forces a clean separation at the probe-material interface. Besides, gumminess and chewiness are parameters mutually exclusive and should not both be reported for the same product [17, 18].

The aim of the present work was to test the validity and reproducibility of the textural parameters calculated automatically from the TA-HD Texture Analyzer (SMS). This was investigated by measuring texture in potato and apple tissues over a wide range of deformation rates and degrees of compression in order to address the broad spectrum of experimental conditions in which this test may be used. Raw potatoes were studied and considered as a model vegetable for comparisons. Regression models were fitted to express the variation of the most appropriate textural parameters with deformation rate and degree of compression, and correlations between parameters were studied in order to find redundant parameters.

Materials and methods

Sample preparation. The produce used in this study were potato tubers (cv. *Kennebec*) and apple (cv. *Golden Delicious*). These were purchased locally and stored in the dark in polythene bags at 4 °C prior to testing. All experiments were completed within four days of purchase. Potato tubers and apples were conditioned at room temperature (≈ 20-22 °C) first (with their skin), and then cut immediately before testing. Cylindrical specimens were obtained using a stainless-steel cork borer, nominally 19.1 mm in diameter. Each cylinder was subsequently trimmed to a length of 10.0 mm using a mechanically guided razor blade. From potato tuber, cylindrical specimens were taken from the center part of slices cut perpendicular to the long axis of the tuber to avoid the large textural differences reported to exist between the cortex and pith tissues [19]. Three specimens were obtained of each tuber. From apple flesh, cylindrical specimens were taken from the outer cortex of slices cut perpendicular to the core of the fruit, taking care to avoid the core. Three specimens were obtained of each piece.

TPA tests. TPA tests were performed with a TA.HD texturometer (Stable Micro Systems, Godalming, UK) using a 2500 N load cell and the application program provided with the apparatus (Texture Expert for Windows™, version 2.03). A flat 75-mm diameter aluminum plunger (SMS P/75) was used in the TPA tests. The texturometer was programmed so that the downward movement began at a point 5 mm above the surface of the sample. The following experimental conditions were selected for each TPA test: three different deformation rates (50 mm min^{-1}, 250 mm min^{-1} and 500 mm min^{-1}), eight compression levels (10, 20, 30, 40, 50, 60, 70 and 80 %), and a rest period of 3 s between cycles. The position to which the probe returned after the first compression cycle cannot be selected: the probe always returned to the trigger point before beginning the second cycle. After the second cycle, the probe returned to its initial position. There were five replicates for each experimental unit.

From the curve generated by such a test, according to the program User Guide [20], the textural parameters are automatically calculated by the software as follows: *hardness* is given as the first force peak if there are only two peaks found, or the second peak if there are three peaks found on the TPA curve. *Cohesiveness* is calculated as the ratio of the positive force area during the second compression portion to that during the first compression. *Springiness* is calculated as the ratio of the distance or time from the start of the second area up to the second probe reversal over the distance or time between the start of the first area and the first probe reversal. *Adhesiveness* is the negative area between the point at which the first curve reaches a zero force value after the first compression and the start of the second curve. *Fracturability* is the force value corresponding to the first peak (only when there are three peaks). *Gumminess* is calculated as *hardness* x *cohesiveness*, c*hewiness* is calculated as *hardness* x *cohesiveness* x *springiness.* The software also gives the peak force corresponding to the second compression cycle, which was designated *force peak 2* throughout this study. A broad survey of the evolution and different definitions of either the current or the original TPA parameters can be found [11].

Preliminary tests of compression to failure for the potato and apple specimens were conducted to assess the value of deformation at rupture, measured as a percentage of the original sample height. Potato specimens required a much higher deformation (40-50 %) than apple specimens (15-25 %) to rupture, confirming previous studies [1-3, 5].

Statistical analysis. The effects of deformation rate and degree of compression were statistically tested using a two-way analysis of variance, and the means were compared by least significant difference (99 %). The data were subjected to backward stepwise regression, and the best model for each textural parameter was chosen by maximizing r^2 (determination coefficient), while maintaining a significant F-*ratio* for each independent variable in the model selected. Statgraphics software version 5.0 (STSC Inc, Rockville, MD, USA) was used in the multiple regression involved in the modeling [21]. Three dimensional plots were drawn to highlight the main effects of deformation rate and degree of compression on textural parameters.

Results and discussion

TPA curves

Force/time curves of the double cycle for potato and apple tissues at deformation rates (50, 250 and 500 mm min^{-1}) and degrees of compression (10–80 %) were plotted. Figures 1 and 2 show curves for potato and apple tissues respectively, corresponding to 50 mm min^{-1}. Curves similar in shape were plotted at the other two deformation rates.

Figure 1 shows that for degrees of compression between 10 % and 40 % of the initial height of the potato specimens, i.e. below the rupturing deformation range (40-50 %), the TPA curves had only two force peaks, the first peak corresponding to hardness and the second peak corresponding to force designated as force peak 2. As specimens did not fracture under these degrees of compression, the resulting hardness value was always lower than the required rupture force of the specimens. However, at deformation levels greater than deformation at failure, i.e. compression between 50 % and 80 %, the specimens ruptured and three force peaks were then found on TPA curves. The first peak of the first compression cycle corresponds to the rupture force of the specimens, the second to hardness, also lower than rupture force at such high degrees of compression, and the third corresponds to force peak 2 (Fig. 1).

In apple specimens, which ruptured at lower percentages of deformation (15-25 % as indicated above), there were three force peaks on the TPA curves at degrees of compression greater than 10 % or 20 % (Fig. 2). As in the potato specimens, the first peak corresponds to rupture force, the second peak corresponds to hardness, which is again lower than rupture force, and the third peak represents force peak 2. Given that the height of the first significant break in the TPA curve peak, at 50-80 % deformation levels in potato tissue and at 20-80 % deformation levels in apple tissue, corresponded exactly to the rupture force of each specimen, this value was not considered as the fracturability of the sample. This parameter was originally defined as a change in the inflection of the curve whose magnitude would be expected to be lower than that of hardness. There are examples in the literature where fracturability is referred to as the bioyield point [22]. In fruits and vegetables, the fracturability value coincides in most cases with the rupturing of the external peel of the fruit or vegetable [9].

Figures 1 and 2 also show that at 10 % deformation, the curve for the upstroke of the plunger was almost symmetrical with respect to the downstroke portion. This indicates that there was instantaneous recovery of potato and apple specimens at so low a deformation level. Similar results have been reported in cylindrical samples of different gels subjected to two successive cycles of compression at deformation levels corresponding to 25 % of their respective degrees of compression at failure [14]. As the applied degree of deformation increased, curves did not show this symmetry, implying that the deformation was not followed by a rapid recovery. This is due to the fact that at higher compression levels, but below deformation at failure, the potential damage to the structure is greater and recovery is less likely, indicating that deformation causes structural weakening, which augments with the degree of compression. The weak internal structure is then incapable of storing the energy received. When the applied degree of deformation caused rupture of the specimens, curves showed total asymmetry, with the curve for the upstroke of the plunger much greater than the curve for the downstroke (Figs. 1 and 2).

Figure 2 shows slight adhesiveness in TPA curves corresponding to 10 % and 20 % deformation levels for apple tissue. Since only two samples showed adhesiveness at 10 % and 20 % degrees of compression, this parameter was also discarded.

TPA parameters

Of the TPA parameters supplied automatically by the software provided with the TA.HD texturometer, hardness, force peak 2, cohesiveness, springiness and chewiness were chosen as the parameters for determining the influence of deformation rate and degree of compression. Potato and apple tissues should be considered as solid samples; therefore, since both gumminess and chewiness cannot be determined in the same food, gumminess was discarded as a parameter [17, 18].

Table 1 shows that both effects and their interactions influenced the values of the textural parameters in both tissues. From the F-*ratio* values for both effects, it seems clear that the degree of compression influenced the parameters measured in the samples of both tissues more than did the deformation rate. The deformation rate had no significant effect on the hardness of either potato or apple tissue (Figs 3 and 4). However, the degree of compression significantly ($P \leq 0.01$) affected the hardness values of both tissues. In potato, hardness increased with the degree of compression up to 40 % (Fig. 3) and decreased when the deformation level passed the deformation at failure. When sample-breaking degrees of compression (>40 %) were applied, there were no significant differences in the hardness values of the potato specimens. Only for 80 % deformation was hardness significantly greater than at 70 %. This could be due to compaction of the remnants of the collapsed structure at high degree of compression [23]. In apple tissue, hardness increased up to 20 % (Fig. 4) and decreased when the deformation level surpassed the level of deformation for failure. There were no significant differences in the hardness values of apple specimens at 30-60 % deformation. For deformation levels of 70 % and 80 %, hardness increased significantly with respect to the values obtained at 60 %, again possibly due to increasing compaction of the collapsed structure.

Both the deformation rate and the degree of compression significantly affected force peak 2 ($P \leq 0.01$) in potato and apple tissues. In potato, force peak 2 decreased when the deformation rate increased, although the only significant differences were between the slowest and the fastest rates. In potato, the interaction between both effects did not affect this parameter. In apple, force peak 2 increased when the deformation rate increased, with significant differences between the slowest rate and the two fastest. This parameter behaved similarly to hardness when the level of deformation changed. For this reason, plots of force peak 2 are not included in Figures 3 and 4. However, the deformation level in potato influenced this parameter (F-*ratios*) much less than hardness. This may be because at deformation levels that rupture the sample in the first compression cycle, the second compression cycle finds portions or small pieces of the initial sample, so that the reliability of this parameter at breaking deformation levels is questionable. Comparison of means by two-sample analysis showed that hardness and force peak 2 in apple were significantly lower than in potato at the various combinations of the studied factors.

Of the textural parameters, cohesiveness was the one most significantly influenced ($P \leq 0.01$) by deformation rate and deformation degree in potato and apple tissues. The interaction between both effects was also significant. Moreover, there were no significant differences in the cohesiveness values of either tissue as calculated directly by the software. In both potato and apple, the faster deformation the higher the cohesiveness. Cohesiveness values in potato and apple tissues were higher at 500 mm min^{-1} than at slower rates up to the degrees of deformation at which either specimen broke (Figs 3 and 4). Potato and apple tissues are known to be viscoelastic [24], and one of their prominent characteristics is that the stress they develop in compression is a function not only of the deformation level, but also of the rate at which is applied. The exact nature of the rate dependency is a characteristic of each material. It has been stated that at high rates, the response of a viscoelastic material converges to what is equivalent to the behaviour of an elastic material [25]. The more solid or elastic it is, the less is the rate effect in compressive and tensile tests [23]. The deformation rate affected cohesiveness more in apple than in potato (Table 1), which is consistent with those findings. Potato tissue is in fact a more solid material than apple tissue due partially to its higher dry matter content. Cohesiveness decreased when the deformation level increased, with significant differences between 10 % and 40 % compression in both samples (Figs 3 and 4). There were no significant differences between deformation levels of 60 %, 70 % and 80 %; nor were there significant differences between deformation levels of 50 % and 60 % in potato tissue or 50 % and 80 % in apple tissue.

Again, there were no significant differences in the springiness values of potato and apple, and both factors significantly affected springiness in both samples ($P \leq 0.01$). Springiness also increased with increase in deformation rate, although the effect in potato tissue was minor. The deformation rate effect on springiness was more significant in apples than in potatoes (F-*ratios*). Also, the effect of degree of compression was more significant in apple tissue, with values decreasing with increased deformation level. Springiness was close to 1 at 10 % deformation (Figs. 3 and 4). This was to be expected since the curve for the plunger upstroke was almost symmetrical with respect to the downstroke part at such a low deformation level. For *k*-carrageenan/locust bean gum and gellan gels the values of recoverable instantaneous springiness and recoverable retarded springiness were quite different, indicating that recovery of their initial heights was retarded [14]. Recoverable instantaneous springiness was derived from the first compression cycle, and retarded recoverable springiness corresponds to the springiness parameter normally measured for instrumental TPA and considered throughout this study. By considering these two springiness parameters separately, a viscous component can be detected which causes recovery of the initial height of the sample to be delayed. In this way, if the calculation is made only from the curve for the first cycle, the viscous element does not intervene and what is considered is principally the elastic element [11]. These parameters seem to be a good index of the relative magnitude of elastic and viscous components of foods. Recoverable instantaneous springiness is not calculated automatically from Stable Micro Systems software and has to be derived manually from each TPA curve. Since it is not directly readable, instantaneous springiness was not considered as a TPA parameter. However, in order to ascertain the relative magnitude of elastic and viscous components in these tissues, the values of recoverable instantaneous springiness at 250 mm min^{-1} were derived from the corresponding double-compression curves. The instantaneous and retarded recoveries of the initial height of the samples were compared and the effect on these of the degree of compression was analyzed (Table 2). Proposed parameters should be measured and compared over a deformation range without fracture of the sample [11, 14]. The values of the two parameters were significantly different in both potato and apple. The value of retarded springiness was always greater than instantaneous springiness for a specific percentage of compression, since the value of retarded springiness included instantaneous springiness plus the recovery achieved by the sample during the waiting time. The effect of the percentage of compression was even more significant on instantaneous springiness (F-*ratio,* Table 2) than on retarded springiness in potato. As the degree of compression increased, significantly lower values ($P \leq 0.01$) were recorded for the two springiness parameters of both tissues. There were similar differences between the values of the two parameters in the deformation range for no fracture of the sample. The differences between the values of the two parameters were greater in potato tissue, indicating a more perceptible viscous component in this tissue. The degree of compression did not influence the viscous component of potato tissue, reflecting the presence of a considerable viscous component in this tissue as found for *k*-carrageenan/LBG and gellan systems [14]. On the other hand, the degree of compression did influence the viscous component of apple tissue, which was higher at 20 % than at 10 % deformation. At both these compression levels, the values for the different tissues can be compared since there was no fracture of the samples. The difference between springiness parameters was greater in potato than in apple at the lowest compression level; the potato samples presented a higher initial rate of relaxation and more pronounced viscous characteristics as has been found in previous rheological studies [2, 24]. It must be emphasized than the measurement of the retarded springiness normally calculated in TPA, did not indicate differences in the elastic response of the two tissues. This means that the proposed parameter differentiates products more than does the traditional retarded springiness parameter.

Deformation rate, compression degree and the interaction between both effects significantly affected chewiness (Table 1). Chewiness increased with the deformation rate; there were significant differences between the three deformation rates used in potato tissue and between 50 mm min^{-1} and the two fastest rates in apple tissue. In potato, chewiness increased with deformation level up to 30 %. Chewiness decreased for higher deformation levels, and there were no significant differences in the 50-80 % deformation range. In apple, chewiness decreased with increasing degree of compression in all cases, although the differences were not significant between 40-80% (Figs. 3 and 4).

Regression models

Table 3 shows models fitted to express the variation of cohesiveness and chewiness with deformation rate and degree of compression. Polynomial models did not usefully express the variation of hardness, force peak 2 and springiness under both effects. Figure 5 (a,b) highlights the effect of the deformation rate and the degree of compression on cohesiveness of potato and apple tissues. In both tissues the degree of compression had a quadratic effect on cohesiveness, while the deformation rate had only a linear effect on this parameter. Interaction between both effects was significant for cohesiveness in both tissues as evidenced previously in Table 1. Models fitted for cohesiveness presented high percentages of explained variability (r^2) and could be consider sufficiently accurate to make predictions in the ranges of deformation rate and degree of compression studied. Both effects had a linear influence on chewiness in potato tissue. Although the model fitted was significant, the r^2 found was lower than 0.75, so that this model should only be used to analyze trends, not to predict [26]. Plots for chewiness are not included. However, the model fitted for chewiness of apple tissue was similar to the model fitted for cohesiveness of the same tissue. It offered a high percentage of explained variability and can be suitable for making predictions. The similarity of the last models mentioned was to be expected since these parameters are highly correlated. Table 4 shows correlation coefficients between textural parameters of both tissues. Hardness and force peak 2 are significantly and positively correlated specially in apple tissue, suggesting that there could be redundancy between the two parameters. Cohesiveness shows a negative but significant correlation with hardness in potato tissue. Cohesiveness, springiness and chewiness are significantly and positively correlated in both potato and apple, the highest correlations being found between cohesiveness and chewiness in apple tissue. This findings could be due to the definition of the parameters, since chewiness is calculated as hardness x cohesiveness x springiness. The correlations found weaken the relevance of calculation all the parameters given automatically by the software.

The results of this study show that in TPA tests on potato and apple tissues, the cohesiveness parameter was most affected by deformation rate and deformation degree. Significant polynomial models can be used to predict cohesiveness at deformation rates ranging from 50 to 500 mm min^{-1} and degrees of compression ranging from 10 % to 80 %. As calculated automatically from the software, cohesiveness seemed to be the most suitable textural parameter for detecting deformation rate and degree of compression effects in potato and apple tissues. Springiness can also offer some more information of relevance, although the proposed recoverable instantaneous springiness has a higher potential to differentiate the structural natures of different tissues. By contrary, the calculation of parameters highly correlated, such as hardness and peak force 2 seems to be unnecessary. Besides, results show that a 50 % compression in potato and 30 % in apple are enough to fracture specimens and significantly reduce the duration of tests with respect to the application of higher compression percentages. This time saving is worth considering in application to quality control of these and other fruit and vegetable tissues.

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Legend

Fig 1 TPA curves from the TA.HD texturometer for potato specimens at 50 mm min^{-1} at degrees of compression varying between 10 % and 80 % of their initial heights.

Fig 2 TPA curves from the TA.HD texturometer for apple specimens at 50 mm min^{-1} at degrees of compression varying between 10 % and 80 % of their initial heights.

Fig 3 Values of four TPA parameters of potato tissue at the three deformation rates and the eight degrees of compression studied.

Fig 4 Values of four TPA parameters of apple tissue at the three deformation rates and the eight degrees of compression studied.

Fig 5

a. Three dimensional plot of cohesiveness, deformation rate (mm min^{-1}) and degree of compression (%) in potato tissue. **b.** Three dimensional plot of cohesiveness, deformation rate (mm min^{-1}) and degree of compression (%) in apple tissue.

Table 1 Effect of deformation rate, degree of compression and interaction between the two effects analysed on textural parameters in potato and apple tissues

Mechanical parameter	Hardness (N)		Force peak 2 (N)		Cohesiveness		Springiness		Chewiness (N)	
	Potato	Apple	Potato	Apple	Potato	Apple	Potato	Apple	Potato	Apple
Main effects										
A: *Deformation rate*										
F-*ratio*	3.97^{ns}	2.12^{ns}	7.09*	33.10*	111.64*	142.32*	5.03*	18.16*	51.74*	29.25*
B: *Degree of compression*										
F-*ratio*	257.12*	33.14*	43.88*	38.78*	521.57*	879.82*	73.98*	124.00*	162.79*	139.45*
Interactions										
AB										
F-*ratio*	2.97*	4.29*	1.48^{ns}	14.52*	14.04*	21.45*	1.12^{ns}	3.32*	7.09*	4.80*

ns non significant;* significant difference at the level of 0.01

Table 2 Effect of the degree of compression on instantaneous recoverable springiness and retarded recoverable springiness in potato and apple tissues at 250 mmmin^{-1}

Degree of compression	*Retarded springiness*	*Instantaneous Springiness*	*Retarded Springiness*	*Instantaneous Springiness*
	Potato tissue	Potato tissue	Apple tissue	Apple tissue
10 (%)	0.866 *a*	0.628 *a*	0.885 *a*	0.739 *a*
20 (%)	0.706 *b*	0.464 *b*	0.750 *b*	0.514 *b*
30 (%)	0.622 *b*	0.400 *b*	-	-
40 (%)	0.625 *b*	0.382 *b*	-	-
F-*ratio*	10.03	16.58	22.28	14.77

Different letters in the same column indicate significant differences at 1%

Table 3 Regression coefficients and analysis of variance of the polynomials

Coefficients	Cohesiveness		Chewiness	
	Potato	Apple	Potato	Apple
b_0	0.712**	0.765**	34.227**	12.342**
b_1	0.000687**	0.000628**	0.0218*	0.012**
b_2	-0.0212**	-0.02843**	-0.496**	-0.473**
b_{11}	-	-	-	-
b_{22}	0.000166**	0.000257**	-	0.004272**
b_{12}	-9.133×10^{-6}**	-8.536×10^{-6}*	-	0.000166**
R-squared (r^2)	0.967	0.920	0.665	0.930
F-*ratio*	138.675	54.437	20.832	77.781

Models in which X_1 = deformation rate, X_2 = degree of compression

b_0: constant; b_1, b_2: parameter estimates for linear terms; b_{11}, b_{22}: parameter estimates for quadratic terms; b_{12}: parameter estimate for interaction terms

**significant at 1%. * significant at 5%

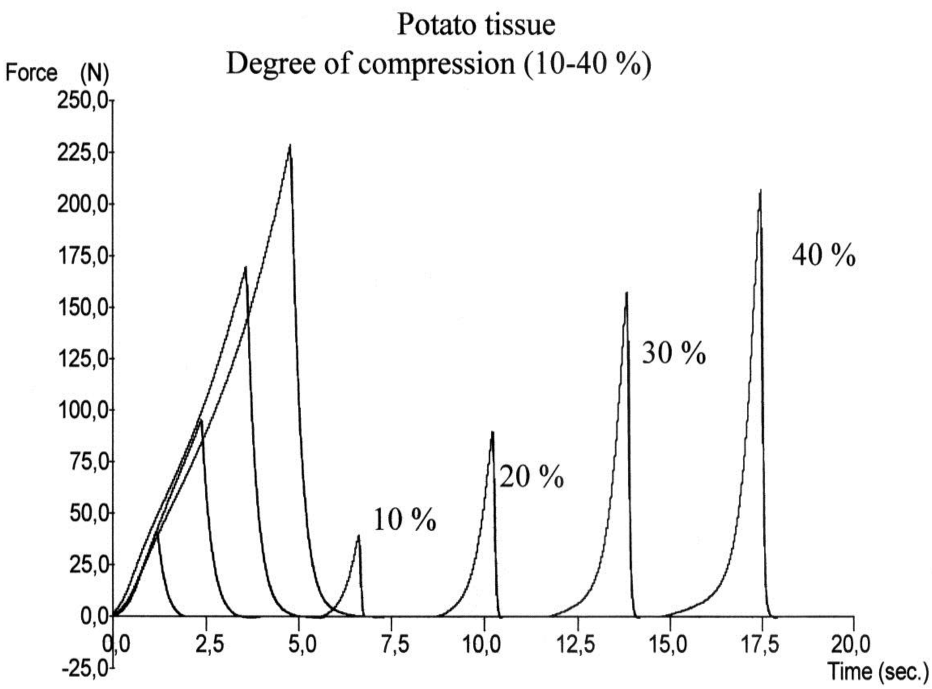
Table 4 Correlation matrix between textural parameters of potato and apple tissues

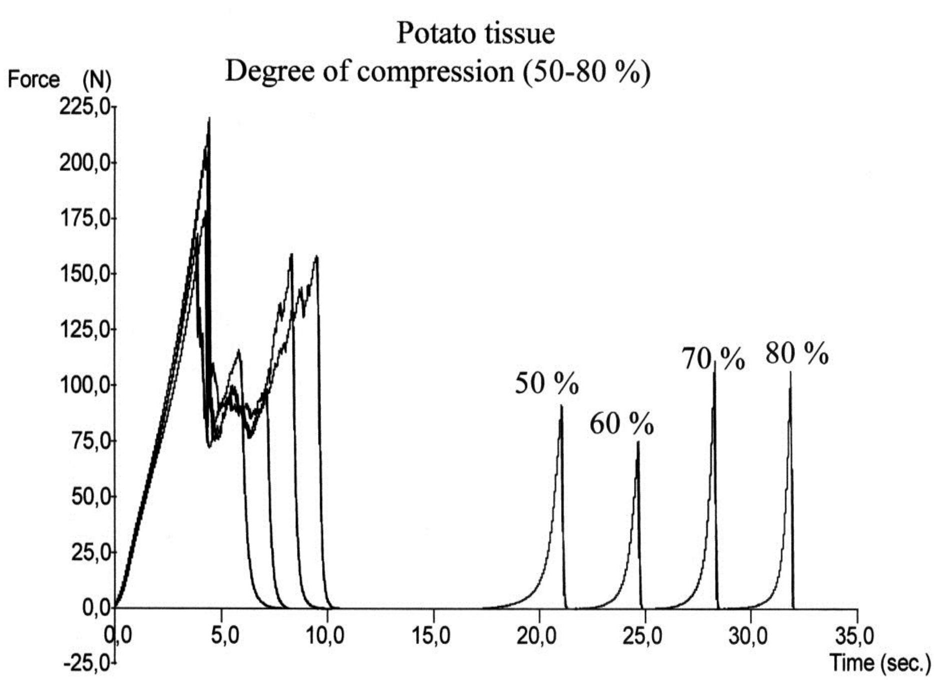
	Hardness	Force peak 2	Cohesiveness	Springiness	Chewiness
Hardness	1				
	1				
Force peak 2	0.4412**	1			
	0.8433**	1			
Cohesiveness	**-0.7630****	-0.0843	1		
	-0.1514	0.0911	1		
Springiness	-0.6096**	-0.2088*	**0.7994****	1	
	-0.2801**	-0.0711	**0.7476****	1	
Chewiness	-0.2517**	0.4454**	**0.7438** **	0.6167**	1
	-0.0365	0.1714	**0.9510** **	**0.7669****	1

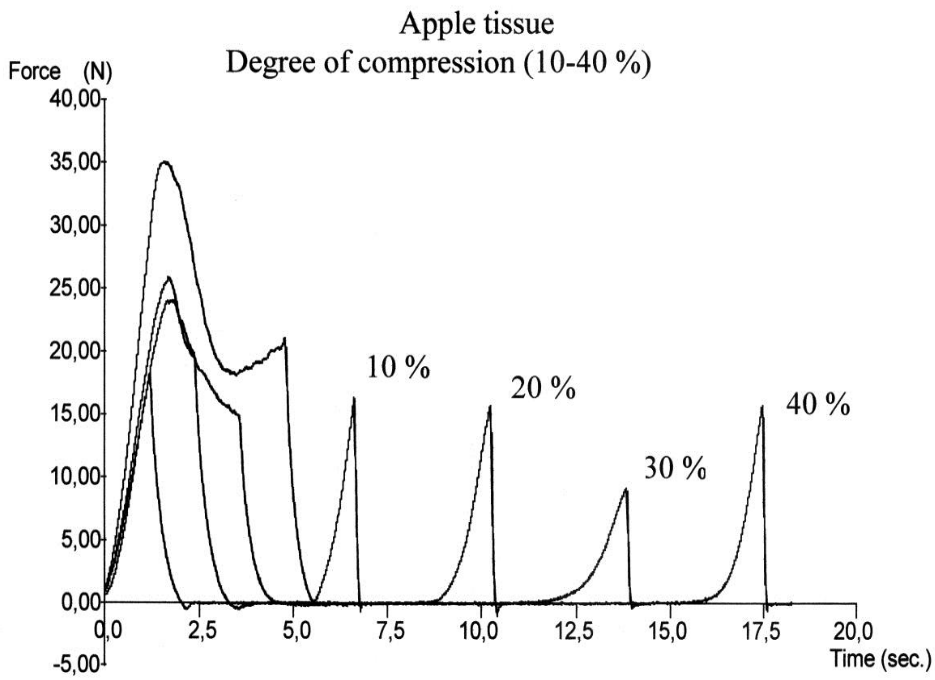
**significant at 1%. * significant at 5%

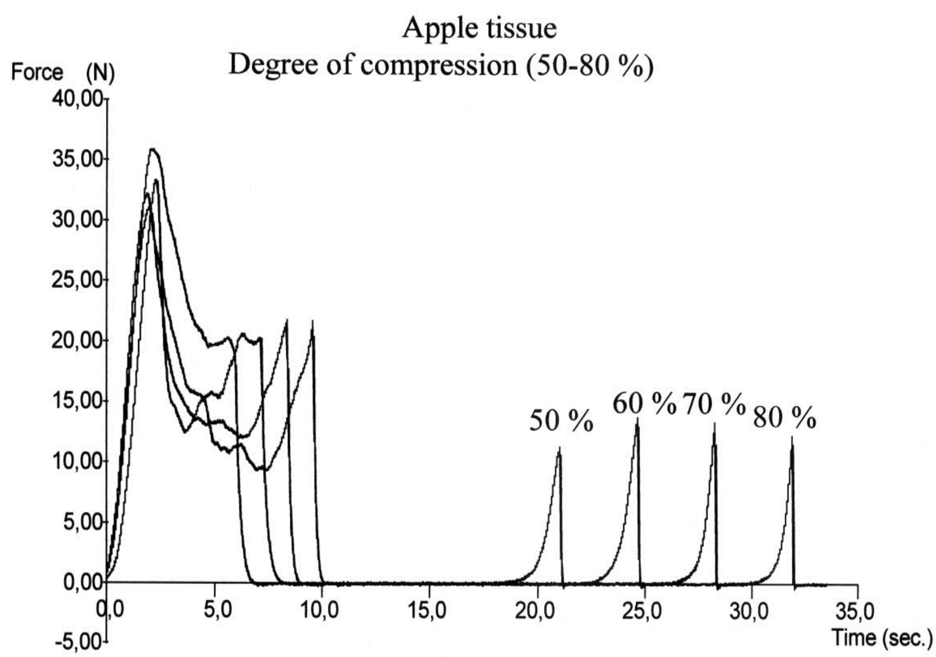
Values in first row are for potato tissue. Values in second row are for apple tissue

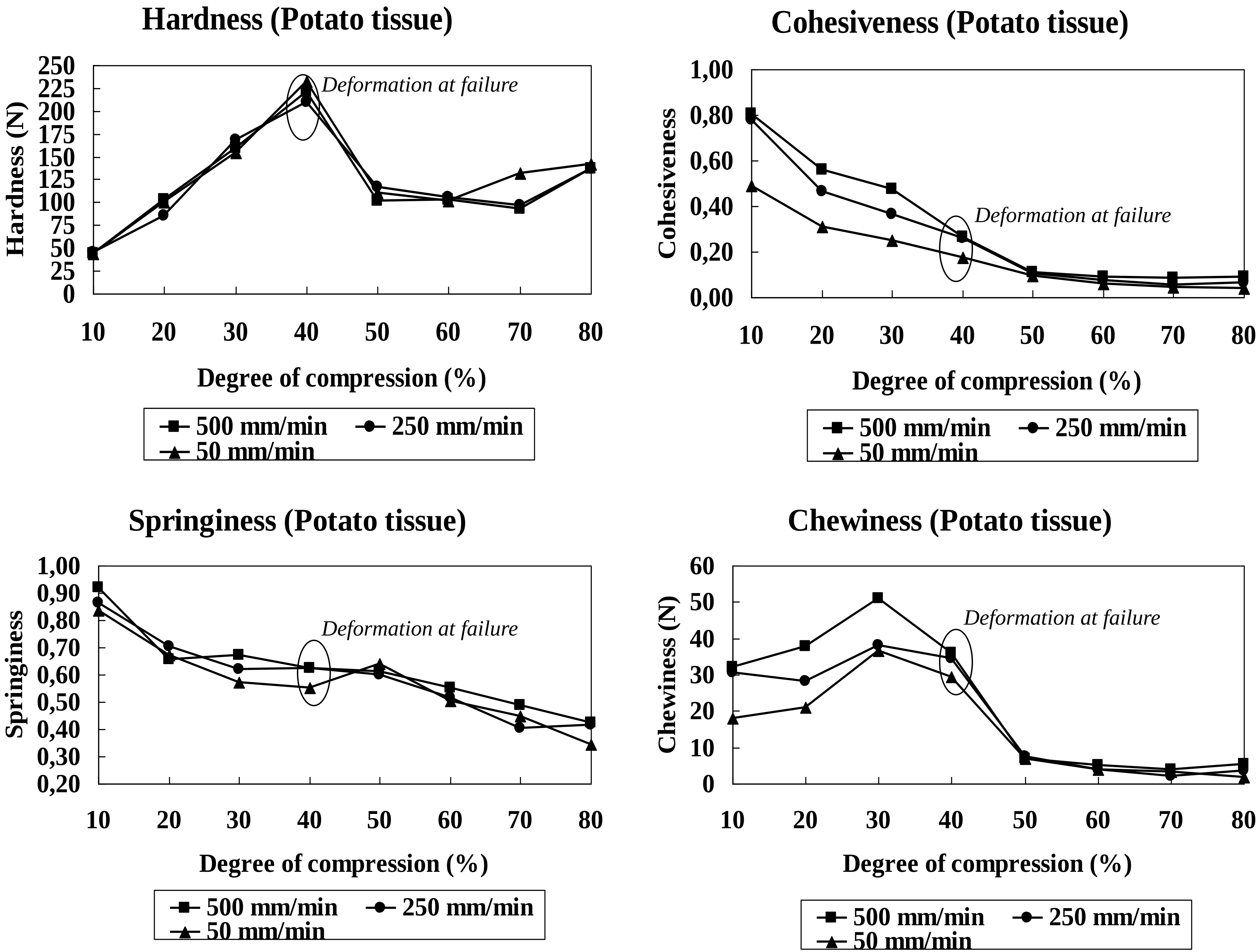
The highest correlations are in boldface


Potato tissue
Degree of compression (10-40 %)
Force (N)
250,0
225,0
200,0
175,0
150,0
125,0
100,0
75,0
50,0
25,0
0,0
-25,0
0,0
2,5
5,0
7,5
10,0
12,5
15,0
17,5
20,0
Time (sec.)
10 %
20 %
30 %
40 %

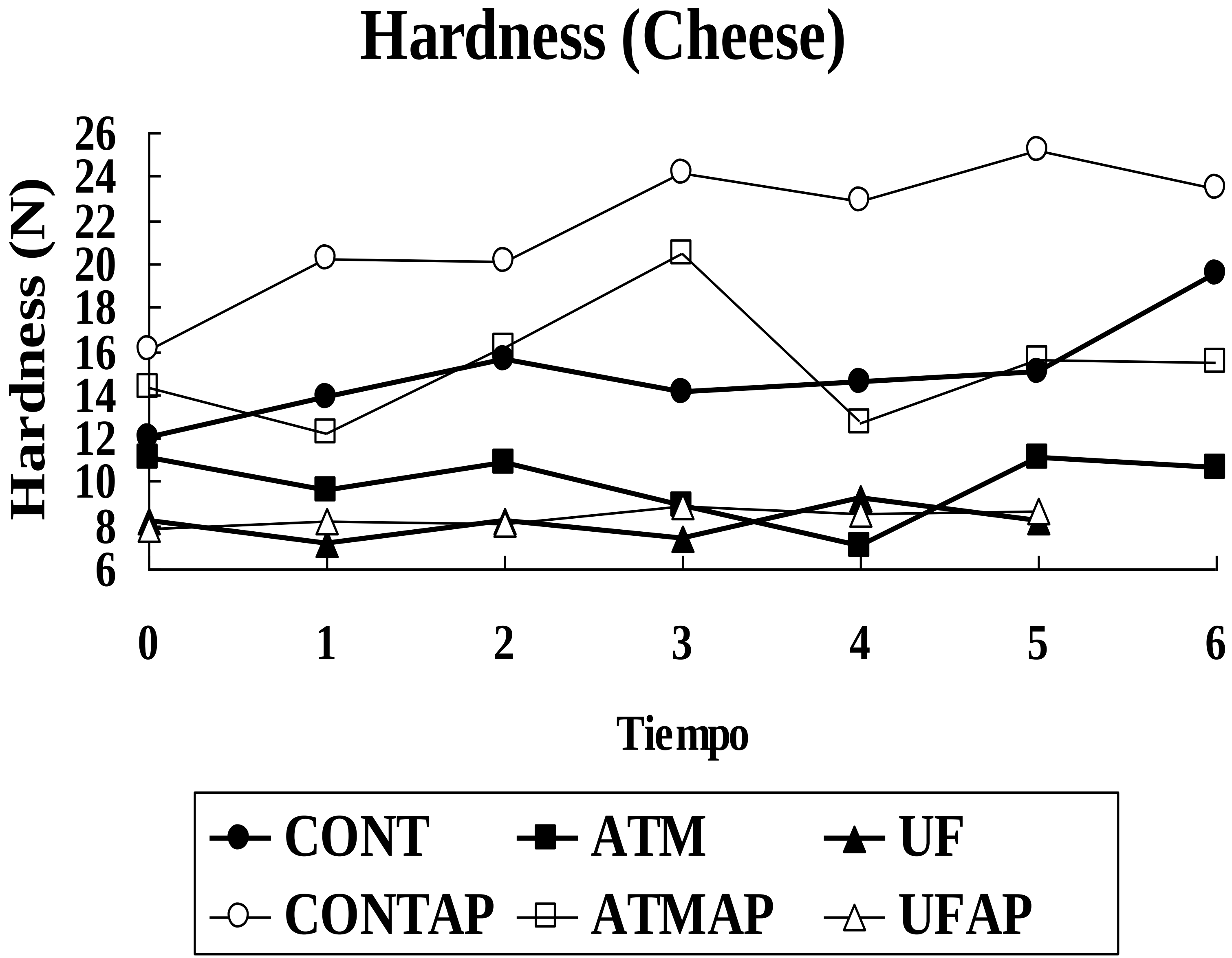

Potato tissue
Degree of compression (50-80 %)
Force (N)
225,0
200,0
175,0
150,0
125,0
100,0
75,0
50,0
25,0
0,0
-25,0
0,0
5,0
10,0
15,0
20,0
25,0
30,0
35,0
Time (sec.)
50 %
60 %
70 %
80 %

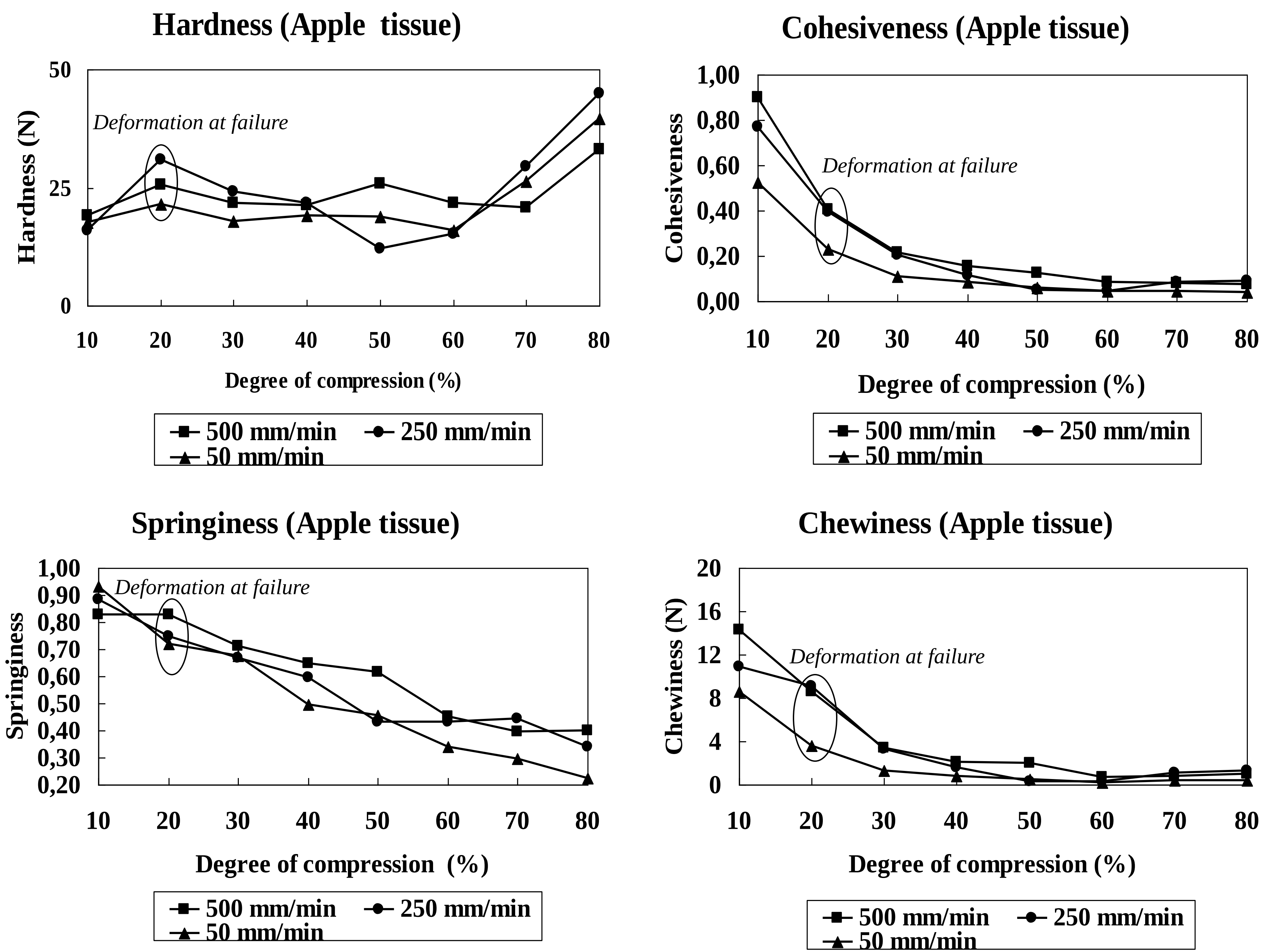

Apple tissue
Degree of compression (10-40 %)
Force (N)
40,00
35,00
30,00
25,00
20,00
15,00
10,00
5,00
0,00
-5,00
0,0
2,5
5,0
7,5
10,0
12,5
15,0
17,5
20,0
Time (sec.)
10 %
20 %
30 %
40 %

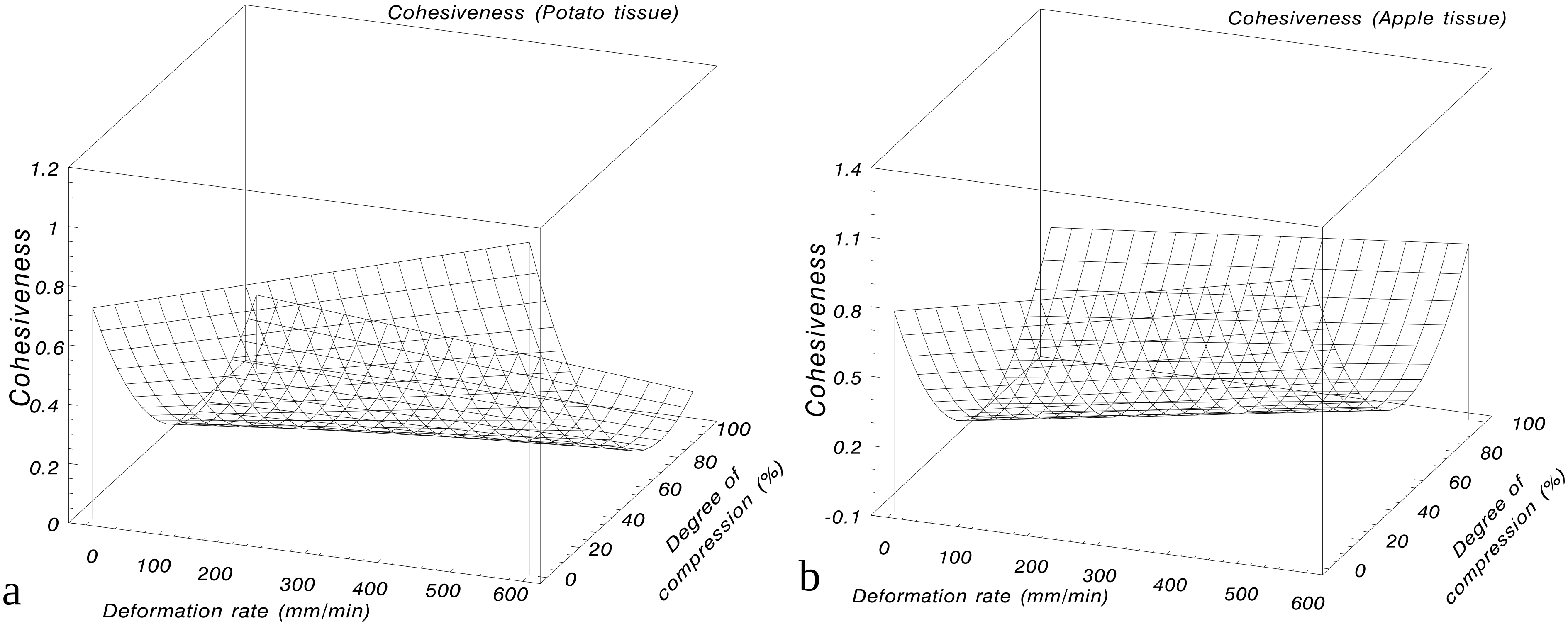

Apple tissue
Degree of compression (50-80 %)
Force (N)
40,00
35,00
30,00
25,00
20,00
15,00
10,00
5,00
0,00
-5,00
0,0
5,0
10,0
15,0
20,0
25,0
30,0
35,0
Time (sec.)
50 %
60 %
70 %
80 %



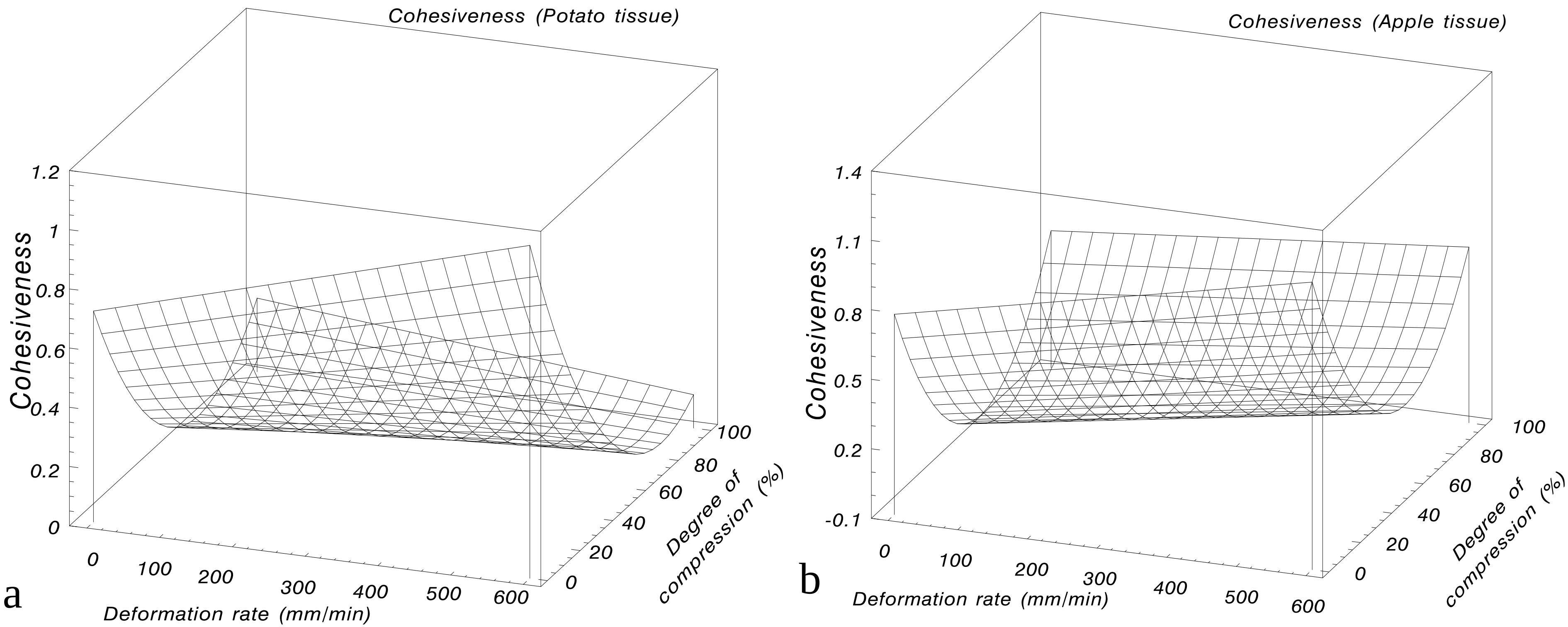
Hardness (Potato tissue)
Hardness (N)
250
225
200
175
150
125
100
75
50
25
0
Deformation at failure
10
20
30
40
50
60
70
80
Degree of compression (%)
500 mm/min
250 mm/min
50 mm/min
Cohesiveness (Potato tissue)
Cohesiveness
1,00
0,80
0,60
0,40
0,20
0,00
Deformation at failure
10
20
30
40
50
60
70
80
Degree of compression (%)
500 mm/min
250 mm/min
50 mm/min
Springiness (Potato tissue)
Springiness
1,00
0,90
0,80
0,70
0,60
0,50
0,40
0,30
0,20
Deformation at failure
10
20
30
40
50
60
70
80
Degree of compression (%)
500 mm/min
250 mm/min
50 mm/min
Chewiness (Potato tissue)
Chewiness (N)
60
50
40
30
20
10
0
Deformation at failure
10
20
30
40
50
60
70
80
Degree of compression (%)
500 mm/min
250 mm/min
50 mm/min


Hardness (Cheese)
Hardness (N)
26
24
22
20
18
16
14
12
10
8
6
0
1
2
3
4
5
6
Tiempo
CONT
ATM
UF
CONTAP
ATMAP
UFAP


Hardness (Apple tissue)
Hardness (N)
50
25
0
Deformation at failure
10
20
30
40
50
60
70
80
Degree of compression (%)
500 mm/min
250 mm/min
50 mm/min
Cohesiveness (Apple tissue)
Cohesiveness
1,00
0,80
0,60
0,40
0,20
0,00
Deformation at failure
10
20
30
40
50
60
70
80
Degree of compression (%)
500 mm/min
250 mm/min
50 mm/min
Springiness (Apple tissue)
Springiness
1,00
0,90
0,80
0,70
0,60
0,50
0,40
0,30
0,20
Deformation at failure
10
20
30
40
50
60
70
80
Degree of compression (%)
500 mm/min
250 mm/min
50 mm/min
Chewiness (Apple tissue)
Chewiness (N)
20
16
12
8
4
0
Deformation at failure
10
20
30
40
50
60
70
80
Degree of compression (%)
500 mm/min
250 mm/min
50 mm/min



Cohesiveness (Potato tissue)
Cohesiveness
1.2
1
0.8
0.6
0.4
0.2
0
0
100
200
300
400
500
600
Deformation rate (mm/min)
0
20
40
60
80
100
Degree of compression (%)
a
Cohesiveness (Apple tissue)
Cohesiveness
1.4
1.1
0.8
0.5
0.2
-0.1
0
100
200
300
400
500
600
Deformation rate (mm/min)
0
20
40
60
80
100
Degree of compression (%)
b


Cohesiveness (Potato tissue)
Cohesiveness
1.2
1
0.8
0.6
0.4
0.2
0
0
100
200
300
400
500
600
Deformation rate (mm/min)
0
20
40
60
80
100
Degree of compression (%)
a
Cohesiveness (Apple tissue)
Cohesiveness
1.4
1.1
0.8
0.5
0.2
-0.1
0
100
200
300
400
500
600
Deformation rate (mm/min)
0
20
40
60
80
100
Degree of compression (%)
b