Assessment of two different rapid compression tests for the evaluation of texture differences in osmo-air-dried apple rings

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Abstract

Mechanical properties of dried apples rings were studied through two different rapid compression tests. A bending-snapping test and a modified compression-relaxation test were performed in order to differentiate between osmo-air-dried apple rings as a function of variety (*Golden Delicious* and *Pink Lady*®) and drying temperature (70°C, 80°C, 90°C). Elastic modulus during bending, fracturability indices, peaks density, and relaxation coefficient during compression were taken into consideration. The obtained results reflect primarily the effect of the drying process on the moisture content of both varieties, but also the different changes in the tissues structure related to both the different solid-liquid exchanges during the osmotic pre-treatment and the drying process. Undergoing the same drying treatment, Pink Lady® rings showed a more rigid and stiff texture than Golden Delicious, which in contrast had a more brittle texture. The obtained results described satisfactorily structural changes of apple tissues, giving the possibility to discriminate, in a rapid way, between different categories of dried apples.

Keywords: Apple rings; Drying; Texture; Compression test; Fracturability

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Nomenclature

b	relative preponderance of low intensity vs. high intensity fractures
C	number of fractures below a minimum observable non-zero stress reduction
d	diameter (mm)
E	elastic modulus, slope (kNmm^{-2})
F	force (kN)
Fc	cumulative fracturability
Lv	support separation (mm)
h	height of sample (m)
R^2	determination coefficient
S	cross-section area perpendicular to force (mm^2)
XH	end of E-modulus determination (kN)
XL	beginning of E-modulus determination (kN)
y	frequency
p	probability value
Pd	peaks density

Greek

ε	true deformation
σ	stress (kPa)
$\Delta_{xi} = x_i - x_{i-1}$	incremental changes in stress during compression
ΔL	flexure between X_H and X_L (mm)

Subscripts

0	initial
i	inner
o	outer
r	relative
τ	final

1. Introduction

Apples are the fourth most important tree fruit crop worldwide after all citrus, grapes and banana. The world production of apples is more than 45 million tons (http://www.fao.org/es/ess/top/commodity.html). China is the world's largest apple producer (25.006.500 T), followed by the U.S. in second place (4.254.290 T); Turkey, Iran, Italy, France, Poland and Russian Federation produce each more than 2 million tons. Americans eat about 8.9 kg of fresh apples annually, compared to about 20.9 kg consumed annually by residents of European Countries. In addition to the primary consumption as fresh fruit, apples can be canned, juiced and fermented to produce apple juice, cider, vinegar, and pectin. Apples are an important ingredient in many desserts.

Recently new interest has arisen in the field of dehydrated apple products, used mainly as snack food (Lewicki and Jakubczyk, 2004; Velic et al., 2004). However, air drying of vegetable tissues is characterized by extensive shrinkage and microstructural changes (Aguilera and Stanley, 1999; Bai et al., 2002). This phenomenon affects the rate of drying as well as physical and functional properties of the dehydrated products. Maximal shrinkage during drying of a fruit material decreases as its solids increase and structural collapse was shown to decrease when fruit was impregnated with sugars prior to air drying (Del Valle et al., 1998; Lerici et al., 1985; Riva et al., 2005; Torreggiani, 1993). Partial dehydration and solute intake can be achieved by immersion in concentrated aqueous solutions, the so called osmotic dehydration process (Torreggiani and Bertolo, 2004). By modifying the extent of the partial dehydration and syrup composition not only can the end product be diversified but chemical, physical and functional properties can be improved. Both osmotic dehydration and air drying could produce great changes in the structure of vegetal tissue, as widely reviewed by Lewicki (Lewicki, 1998; Lewicki et al., 1997; Lewicki and Jakubczyk, 2004). In particular, texture of material moves from elastic-visco-plastic to rigid, becoming fragile and brittle. These changes are welcomed when they have to be transformed into a snack food such as apple chips, in which 'crispy' and 'crunchy' are sensory attributes greatly influencing quality evaluation by the consumers, as demonstrated by Shewfelt (1999).

The interest towards the production and preservation of crispy foods is also showed by the large number of published scientific research dealing with 'crispy/crunchy' attributes, as widely reviewed by Roudaut et al. (2002). Crispness and crunchiness are strongly linked to fracture and breaking characteristics of the product (Vincent, 1998). A crispy and crunchy product should indeed fracture and break into little pieces during biting and chewing as a consequence of a firm and brittle physical structure (Djksterhuis et al., 2007). Different instrumental measurements were assessed to evaluate the texture of apples taking into consideration several attributes such as hardness, crispness, ripeness. Nevertheless, the obtained results are often hard to compare, hence not of general use (Marquina et al., 2001), due to their high dependency from a lot of factors such as cultivar, process conditions, specific drying process method, and presence or absence of pre-treatment (Ratti, 1994; Sjöholm and Gekas, 1995). For that reason, the parameters taken into account were often interpreted in different ways. So, according to Harker et al. (2003), it is necessary to compare specific categories, to strengthen the link between product and quality in the consumer's perception. To this purpose, instrumental tests should be accurately performed in accordance with the specific instance (Marquina et al., 2001).

The aim of this work was to set two different rapid compression tests in order to obtain parameters to use as indices of textural characteristics of osmo-air-dried apple rings obtained using two different cultivars and three different drying temperatures.

2. Materials and Methods

2.1 Apples

Two cultivars of organic apples were used: Golden Delicious and Pink Lady®, both cultivated in the Research Centre for Agriculture and Forestry (Laimburg, BZ, Italy). Apples, harvested at the same maturity stage (Golden

Delicious: dry matter 14.84%, acidity 10.73 meqNaOH/100 g, refractive index 13.05 °Bx; Pink Lady®: dry matter 15.96%, acidity 9.70 meqNaOH/100 g, refractive index 14.10 °Bx), were washed, dried and cored by a spoon soil auger (25.0 mm diameter). Finally, they were mechanically cut (LT INOX, Kronen, Germany) into 5.0 mm thick rings.

2.2. Treatments

2.2.1. Osmotic dehydration

Apple rings were dipped for 60 minutes at 25°C in a maltose solution (Sirtori et al., 2007) (a_w = 0.90; 62.8 % $^w/_w$), which was continuously recirculated through a peristaltic pump. The ratio fruit/solution was 1/3.

Soluble solids gain (SG) and water loss (WL) were calculated according to Giangiacomo et al. (1987), and are expressed as g/100 g of initial fresh fruit weight.

2.2.2. Air drying

Air drying was performed at 70°, 80° and 90°C, up to a constant weight, using a pilot alternate upward-downward air circulated drier (Thermolab, Codogno, Italy) operating at an air speed of 1.5 m/s. For all samples, the equilibrium weight (i.e. the constant weight) was achieved when the difference in weight was less than 1 mg/g solids after 90 additional minutes of drying.

2.3. Chemical analyses

Raw apple dry matter and total titratable acidity were determined according to AOAC methods (1985); refractive index (°Bx) using a Multiscale automatic refractometer (mod. RFM91, BS, UK).

Osmo-air-dried apple rings water activity (a_w) was measured by an electronic hygrometer (Aqua Lab. CX-2 – Decagon Devices, Pullman, USA), based on the determination of the dew point and previously calibrated with a standard solution of LiCl of known activity (prepared by High-Purity Standards for Decagon Devices). Results are the mean of 6 determinations. Moisture content was determined according to Karl Fischer method after extraction in anhydrous methanol (ASTM D 6304-2004 a, 1-procedure A). Results are the mean of 3 determinations and are expressed as g H_2O/100 g solids.

2.4. Mechanical analyses

2.4.1. Stress-Relaxation test (modified)

A 40 ± 2.0 mm pile of apple slices one upon the other was put into a steel cylinder placed between a lower (150 mm diameter) and an upper plate (80 mm diameter). The latter was connected with a Zwick Machine (mod. Z005, Zwick Roell, Germany) fitted with a 100 N load cell. Apple slices were compressed by the upper plate at a speed of 10 mm/min. This slow speed was set to allow a better observation of each compression step rather than at higher speed, in order to carry out the next quantification of fracturability. At 20% deformation, the crosshead surface was stopped and the pile was allowed to relax for 20 s, which is a shorter time than a typical compression-relaxation test. The relaxation time selected in this work is due to the fact that stiff material is able to accumulate stress and to relax fast and brittle material shows a very small relaxation because most of stress accumulated during compression is consumed in the breaking work. Hence, apple rings analyzed in this work were able to relax within 20 s (i.e. the specified interval of time for relaxation) at least 70% of the total stress developed during compression. Therefore, the obtained curves will show only two of the three typical zones described by Bhattacharya and Narasimha (1997): the first characterized by a sharp decrease of the stress and the second showing a reduction of the rate of decrease. Both the stress-strain and the stress-time profile were continuously recorded and the following parameters were calculated directly by the software (TestXpert V10.11 Master):

- *True deformation:*

$$\varepsilon = -\ln\left(1 - \frac{h_0 - h_\tau}{h_0}\right) \qquad (1)$$

- *Stress:*

$$\sigma = \frac{F}{S} \qquad (2)$$

- *Relative relaxation stress:*

$$\sigma_r = \frac{\sigma_\tau}{\sigma_0} \qquad (3)$$

Relative relaxation stress represents a part of the total stress that the material accumulated during compression and is not relaxed after a given relaxation time (Lewicki and Jakubczyk, 2004). Furthermore, according to the method for quantifying fracturability by Barrett et al. (1994), the distribution of fracture intensities occurring during compression in the 4-20% strain region was quantitatively described through the following exponential function:

$$y = Ce^{(b\Delta_{xi})} \quad (4)$$

Decreases in stress (i.e. fractures) are given by negative Δ_{xi} values; in contrast, positive values involve increases in stress due to compression. Only negative Δ_{xi} values were taken into consideration to obtain the frequency distribution of fracture intensity. Parameters derived from the equation (4), C and b, were used as fracturability indices. Cumulative fracturability (Fc) was used as further index. It was obtained by summing the fracture intensity of frequencies of each distribution. Finally, the density of peaks, Pd (number of peaks / deformation in mm) was used as a measure of brittleness of apple rings in the investigated region (4-20% strain).
All measurements were carried out on 10 different apple piles for each temperature condition and for each cultivar.

2.4.2. Bending-Snapping test

Tests were carried out using a Zwick Machine (mod. Z005, Zwick Roell, Germany) fitted with a 100 N load cell. Slices were 72.0 ± 2.0 mm in diameter and 3.5 ± 0.3 mm thick after drying. So, the length of the specimen was at least 16.2 times greater than thickness, to avoid shearing and compression effects, compromising the final results (Bourne, 2002). In addition, to limit negative effects by shape and surface imperfections, discs as flat and regular as possible were selected. One apple disc at a time was placed on two supports separated by a distance of 45.0 mm, each one equipped with a 8.0 mm diameter horizontal rod at the tip. A third compressing bar, also a 8.0 mm diameter horizontal rod at the tip, was driven down between the two supports at a speed of 10 mm/min, bending each specimen until it snapped. The slope (i.e. the elastic modulus, E) before the first fracturability peak of highest magnitude was calculated from the force-displacement curves as the index of crispness (Jackson et al., 1996; Konopacka et al., 2002) of the dried apple rings, in accordance with the following equation which takes into consideration the actual surface area of the rings in contact with the upper bar (i.e. without the central part of 25.0 mm diameter):

$$E = \frac{\left[8 \times Lv^3 \times \left(XH - XL\right)\right]}{\left[6 \times \Delta L \times \pi \times \left(d_o^4 - d_i^4\right)\right]} \quad (\text{kNmm}^{-2}) \qquad (5)$$

Ten replicates for each air temperature and for each cultivar condition were made.

2.5. Statistical analysis

The effect of temperature conditions and cultivar was statistically assessed using a two-way analysis of variance. The mean values, when appropriate, were compared by LSD (least significant difference) multiple range test at $p \leq 0.05$ (or 95% confidence interval) using Statgraphics Plus 4.0 software (STSC Inc, Rockville, USA). Intensity distributions were fitted by an exponential model with two constants using a nonlinear curve-fitting package (Tablecurve 4.0, Jandel Scientific, San Rafael, USA).

3. Results and discussion

3.1. Stress-Relaxation test

The three different curves (each one as a mean of ten replicates) resulting from the compression-relaxation test of the Golden Delicious cultivar reported in Fig. 1 show the effect of air temperature on the relaxation characteristics of apple rings. The curve profile (similar for the three lots) is characterized by three observable parts: an initial rising tract, culminating in a first fracture, that represents the deformability prior to rupture of the structure; a halfway jagged-oscillating zone, depending on the brittleness of the samples, indicating the deformation and destruction of internal structure; a final descending smooth tract (after about the first 2/3 of each curve), along which part of the stress accumulated during compression is relaxed. This shape is typical for foods characterized by a crunchy or crispy texture, like breakfast cereals and snacks. Relative relaxation stress values (σ_r) (Table 1) indicate that the three different drying temperatures were able to produce significant effects on apple rings. In fact, after a relaxation time of 20 s, the amount of not relaxed stress increased from about 65% (70°C) to almost 90% (90°C). Moreover, a significant difference was observed between the two varieties. In particular, the number of cavities and voids formed by drying could play an important role in defining the compression-relaxation curves (Lewicki and Jakubczyk, 2004). These changes are strongly related to the tight relationship between temperature and moisture content in the biopolymer matrices, as can be seen in Table 1. Moisture content of osmo-air-dried apple rings decreased for both varieties as the drying temperature increased (60% approximately from 70°C to 90°C). At all the tested temperatures, Pink Lady® osmo-air-dried rings had a significantly lower moisture content than the Golden Delicious ones, probably due to intrinsic factors (e.g. composition, cellular shape and tissue structure), together with the diverse solid-liquid exchanges during the osmotic pre-treatment. Soluble solid gain and water loss were 4.913 and 11.013, respectively for Golden Delicious, and 3.651 and 6.903 respectively for Pink Lady®, leading to a dry matter content of 21.358 for Golden Delicious and 21.192 for Pink Lady®. As a consequence of the decrease in moisture content, a_w decreased moving from 70°C to 90°C for both cultivar, even if a statistical significant difference was assessed only within but not between each group (i.e. variety).

Considering that the higher the drying temperature the lower the moisture content and water activity values, the different trend of the curves reported in Fig. 1 can be better interpreted. At 70°C the material maintained fairly elastic-plastic behaviour (as shown by the smooth ascent part of the curve) and it relaxes approximately 35% of the developed stress. As temperature increased, the texture profile of apple rings changed, as confirmed by the ruggedness of the curves. As ascertained by several researchers, these results are related to the removal of water during drying. In fact, the convective flux of hot air yielded an almost total loss of the plasticizing effect of water, affecting the rheological properties of apple tissues and promoting some main physical phenomena (e.g. shrinkage, moisture gradients) especially in the first step of drying (Lewicki and Lukaszuk, 2000).

The overall relationship between moisture content, water activity and relative relaxation stress is shown in Fig. 2. Moving from 70°C to 90°C both water activity and moisture content decreased drastically, causing an increase of relative relaxation stress as a consequence of rigidity gained by apple tissues, which are unable to relax most of the induced stress. Indeed, the majority of the stress developed during the compression phase is relaxed abruptly by simultaneous failures. At any of the drying temperatures moisture content and water activity values of Pink Lady® rings were lower than those of Golden Delicious, whereas RRS values were significantly higher. These results evidenced that the original structure and composition, together with the different solid-liquid exchanges during the osmotic pre-treatment could play an important role in determining the extent of heat-induced micro-structural modification, such as cell separation, cellular collapse and, in general, damage to cell walls and membranes.

3.2. Fractures quantification

A further measure of the brittleness of apple rings is the degree of jaggedness of their stress-strain curve. It can be assessed in different ways, for example, by the power spectrum of the Fast Fourier Transform and the Natural Fractal dimension of normalized compression curves (Peleg, 1997). In the present study, the distribution of fracture intensities occurring during the first step of compression-relaxation test was quantitatively described by an exponential function. By using mathematical procedures 'easy-to-use' by the common statistical programs, main parameters used as fracturability indices were obtained. In a first step, a frequency distribution of changes in stress during compression was constructed as described by Barrett et al. (1994) for each air temperature condition and for both varieties (Fig. 3 a, b, c). Here, descent negative lines indicate fractures, whereas positive tracts are for increases in stress due to compression. Moving from the lowest to the highest temperatures, graphs result in more evident noise due to an increase of fractures and ruptures of specimen. Furthermore, a substantial difference exists between the two varieties: for each drying temperature, Golden Delicious graphs show the greatest number of failures over the whole strain path, whereas Pink Lady® led to graphs with the longest negative lines (i.e. the greatest fracture intensities).

In a second phase, each average intensity distribution was fitted to the Eq. (4) and coefficient *C* and *b* were calculated to be used as fracturability indices. Fracture intensity distributions for both varieties are presented in Fig. 4, whereas the corresponding *b* and *C* indices are reported in Table 1. At each temperature the highest number of breaks (high frequency values) corresponds to the lowest fracture intensity values (on the right of the x-axis) for both apple varieties. Still, a significant difference is observed between the two varieties. At 70°C and 80°C the number of low intensity fractures was higher for Pink Lady® (45 and 109 frequencies, respectively) than for Golden Delicious (17 and 74 frequencies, respectively). At 90°C, the low intensity fractures number for Golden Delicious was about twice as high (241, as a sum of the two values around -0.1 kPa indicated by the letter A and B in Fig. 4) as Pink Lady® (122, indicated by the C letter in Fig. 4). The latter showed a higher number of high intensity fractures, i.e. a larger number of data points at the highest negative values of stress, corresponding to the largest fracture intensities. These results were confirmed by the *b* and *C* coefficients, highlighting the effect of drying temperature on moisture content. High values of *b* were calculated for Pink Lady® only at 70°C and 80°C (61.288 and 14.003, respectively, vs. 60.711 and 9.279 for Golden Delicious). At the highest temperature (90°C) the two cultivars behaved in an opposite way, in that the highest value of *b* index was for Golden Delicious (4.724) rather than for Pink Lady® (3.328). With respect to *C* coefficient, Pink Lady® rings yielded the highest values at 70°C and

80°C air temperature, whereas at 90°C the maximum was for Golden Delicious. This means that the number of fractures below a minimum observable non-zero stress reduction is greater for Golden Delicious only at the highest drying temperature. This is in agreement with the *Fc* index, as reported in Table 1. In fact, values of this coefficient confirmed that the total number of breaks was greater for Pink Lady® (58 vs. 29) at 70°C and for Golden Delicious (360 vs. 265) at 90°C. Nevertheless, in contrast to *C* index values at 80°C, the total number of failures were higher for Golden Delicious (166 vs. 135) at this drying temperature.

The last criteria considered to measure the extent of fracturability of differently dried apple rings is the peaks density, *Pd*. As shown in Table 1, this index was determined considering peaks of magnitude both equal and greater than 0.5% and 5.0% the maximum force (i.e. the highest peak) registered during compression. In the first case (peaks ≥ 0.5% maximum force) ruptures of small and large intensity were simultaneously measured, whereas in the second (peaks ≥ 5.0% maximum force) only the largest ones were taken into consideration. Both at 0.5% and 5.0%, and also for both varieties, this index increased along with drying temperature, though a difference was observed between Golden Delicious and Pink Lady®, mainly at 80°C and 90°C. For peaks ≥ 0.5% the maximum force, the Golden Delicious had *Pd* values greater (80°C) and fairly similar (90°C) to those of Pink Lady®. In contrast, for peaks ≥ 5.0% the maximum force (i.e. only peaks of large intensity), Pink Lady® had the highest *Pd* values both at 80°C and 90°C. This behaviour indicates that during compression Golden Delicious originated fractures to a smaller extent than Pink Lady® at 80° and 90°C. On the contrary, Pink Lady® evidenced abrupt breaks during compression, causing ruptures of higher intensity. At 70°C, the density of peaks during the deformation range 4-20% was always greater for Pink Lady®, implying that when Golden Delicious rings are dried at this temperature they still keep their visco-elastic properties, whereas Pink Lady® rings start to acquire a more brittle texture.

Once again, the results relating to fractures quantification highlighted the significant difference between the two cultivars. After the same drying treatment, Pink Lady® rings acquire a stiffer and more rigid texture than Golden Delicious, which appear, in contrast, more brittle. From a practical point of view this fact may be important because Golden Delicious could be able to produce a more appreciable crispness and crunchiness sensation than Pink Lady®. This different behaviour can be attributed to the different impact of the drying treatment on the moisture content of the two different matrices as well as to the specific intrinsic characteristics of apple tissues. Furthermore, Pink Lady® apple rings have lower solid-liquid exchanges than Golden Delicious ones, therefore during drying their structure could be less protected from shrinkage (Riva et al., 2005). A further factor affecting the different behaviour between the two cultivars is their firmness, due to the ripening stage. Even though Pink Lady® and Golden Delicious were used at the same maturity stage, it is known from the horticulture practice that Pink Lady cultivar loses its firmness slower than Golden Delicious. That would explain why Golden Delicious tissues are characterized by a lower strength (before and after drying) and also responded differently to osmotic treatment.

3.3. Bending-Snapping test

Fig. 5 and Fig. 6 show typical deformation curves obtained applying the bending-snapping test to Pink Lady® and Golden Delicious osmo-air-dried rings, respectively. The shape of each curve is strictly related to the specific temperature of the drying process, and thus to moisture content and water activity values. At 70°C, the curves show an initial rising tract, characterized by an almost linear relationship between force and deformation. After approximately 1.8 mm deformation, a first inflection of the curve indicates that this relationship becomes non-proportional. At 80°C the obtained curves show a profile similar to the 70°C curves during the initial displacement-path. However, after the first steep linear tract, the curve brakes abruptly, lacking the final descending part. This behaviour is more evident in the sharp curves obtained from apple rings dried at 90°C. In this case, the initial quick, steep and linear tract is immediately (after about 0.5 mm deformation) followed by two subsequent spiky peaks, relating to violent ruptures. As mentioned previously, the steepness of the slope at the beginning of each curve is defined as crispness (Jackson et al., 1996; Konopacka et al., 2002) and it is involved in the resistance of the specimen to bending. In accordance with the results reported in Table 1, a decrease in moisture content, as a result of each drying treatment, leads to increases in crispness. Curves derived from apple rings dried at 70°C had the lowest crispness coefficient, approximately 1.6 times (Pink Lady®) and 2 times (Golden Delicious) less than those obtained at 80°C. Drying at 90°C yields apple rings with the highest crispness values (50% and 30% more than those observed in Pink Lady® and Golden Delicious rings dried at 80°C, respectively), as evidenced by the steepest slope of the initial linear line of the curve. Drying temperatures of 90°C produced the crispiest dried apple rings, having a greater resistance to bending (Jackson et al., 1996). A statistically significant difference between apple varieties was observed. For all temperature-settings, Pink Lady® showed the highest crispness values, acquiring more stiffness and resistance to deformation than Golden Delicious, in accordance with moisture content values (higher for Golden Delicious), as shown in Table 1.

As shown in Fig. 2, the relationship between water activity and moisture content and crispness is inversely proportional: crispness increased as a_w and moisture content decreased. The effect of water can also be highlighted by the shape of the curves obtained at different temperatures. In general, the left-shifted bell-shaped curves obtained at 70°C (i.e. at the highest a_w and moisture content) were wide and smooth, reflecting the plasticizing effect of the remaining water. Moreover, the area under the curve was large (data not shown), indicating that a fair amount of energy is needed to promote the final failure of the specimen. At 80°C the obtained curves showed the increasing effect of drying temperature. The gain of crispness/crunchiness is also manifested in a more jagged relationship, indicating failures and ruptures, due to changes in the structure with the formation, for example, of cavities, voids and local damage (Lewicki and Jakubczyk, 2004). Finally, at 90°C (i.e. at the lowest a_w and moisture content), apple slices broke abruptly, like a brittle and fragile body. Furthermore, the area under the curve was small (data not shown), reflecting the low quantity of energy required to break the dried rings.

All the obtained results indicate that by increasing air temperature, the rheological characteristics strongly change for both variety, but differently. While Golden Delicious acquires rigidity but remains brittle and fragile (and hence develops small fractures in comparison to the other cultivar), Pink Lady® becomes rigid, but harder and stiffer, with abrupt failures of major intensity. It can be inferred that, besides chemical composition and moisture content, an important role may be played by the extent of dried apple rings porosity. This parameter in its turn is strictly linked both to intrinsic tissue characteristics of the cultivar and to the effect on the dried apple structure of the different soluble solids enrichment and water loss achieved through the osmotic pre-treatment. After drying, Golden Delicious may acquire an internal structure characterized by a greater number of cavities and voids than Pink Lady® that lead to a major brittleness during compression.

4. Conclusions

Through the two different compression tests used in the present work numerical indices were obtained able to discriminate between two different cultivars osmo-air-dried at three different temperatures. The modified compression-relaxation stress test quickly supplied five parameters that can be used as fracturability indices, reflecting the brittleness of each specimen in terms of the degree of jaggedness of the stress-strain curve. The bending-snapping test provided a significant index able to discriminate between apples characterized by a different crispness. The ease and the speed of the described methods and the possibility to apply them using conventional statistical software in a timely fashion, make the approach of this research a helpful tool to discriminate between different batches in the scale-up manufacturing of dried apple rings with specific textural characteristics. Furthermore, the applied methodologies appear suitable to be correlated with sensory evaluations concerning texture perception arising from trained panellists, in order to pinpoint the critical crispness values (i.e. the texture acceptance limits).

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Figure captions

Figure 1. Typical compression-relaxation curves of osmo-air-dried apple rings piles (Golden Delicious): effect of drying temperature.

Figure 2. Relationship between moisture content, water activity, relative relaxation stress and crispness of apple rings osmo-air-dried to a constant weight at different temperatures.

Figure 3. Frequency distribution of stress intensities during compression of apple rings osmo-air-dried to a constant weight at 70°C (a), 80°C (b) and 90°C (c): Golden Delicious (left) and Pink Lady® (right). Each graph is the mean of ten replicates.

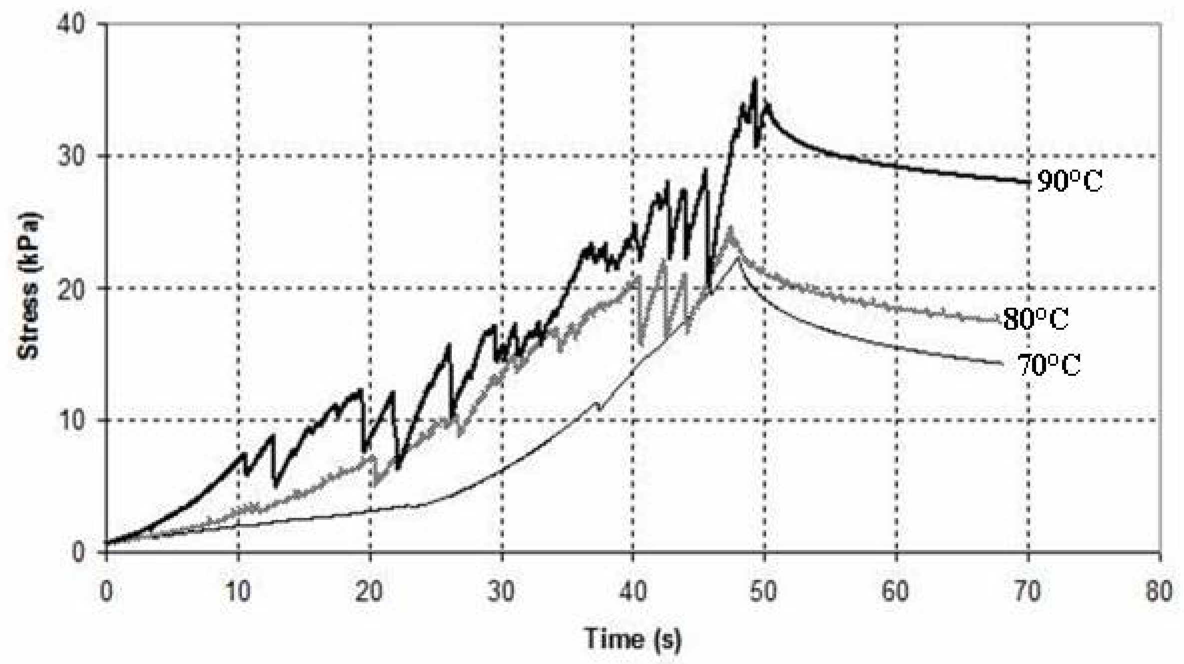
Figure 4. Fracture intensity distributions in apple rings osmo-air-dried to a constant weight at different temperatures: Golden Delicious (up) and Pink Lady® (down). Each graph is the mean of ten replicates.

Figure 5. Force-deformation curve of apple rings (Pink Lady®) osmo-air-dried to a constant weight at different temperatures. The initial slope of each curve is evidenced inside the circle.

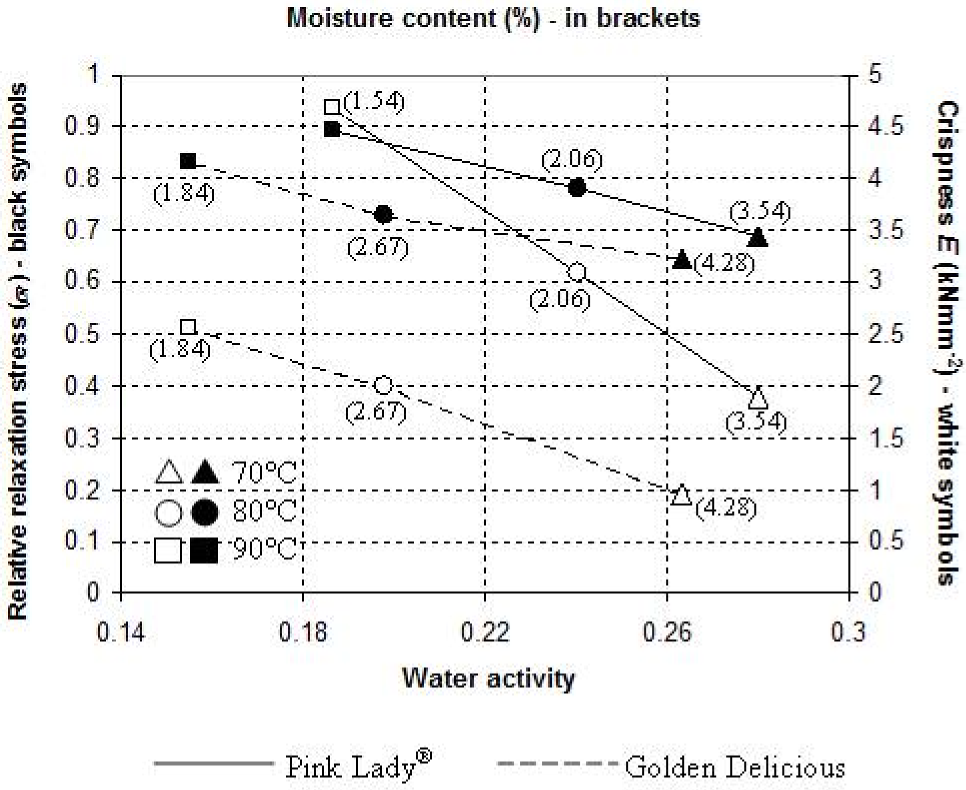
Figure 6. Force-deformation curve of apple rings (Golden Delicious) osmo-air-dried to a constant weight at different temperatures.

Table caption

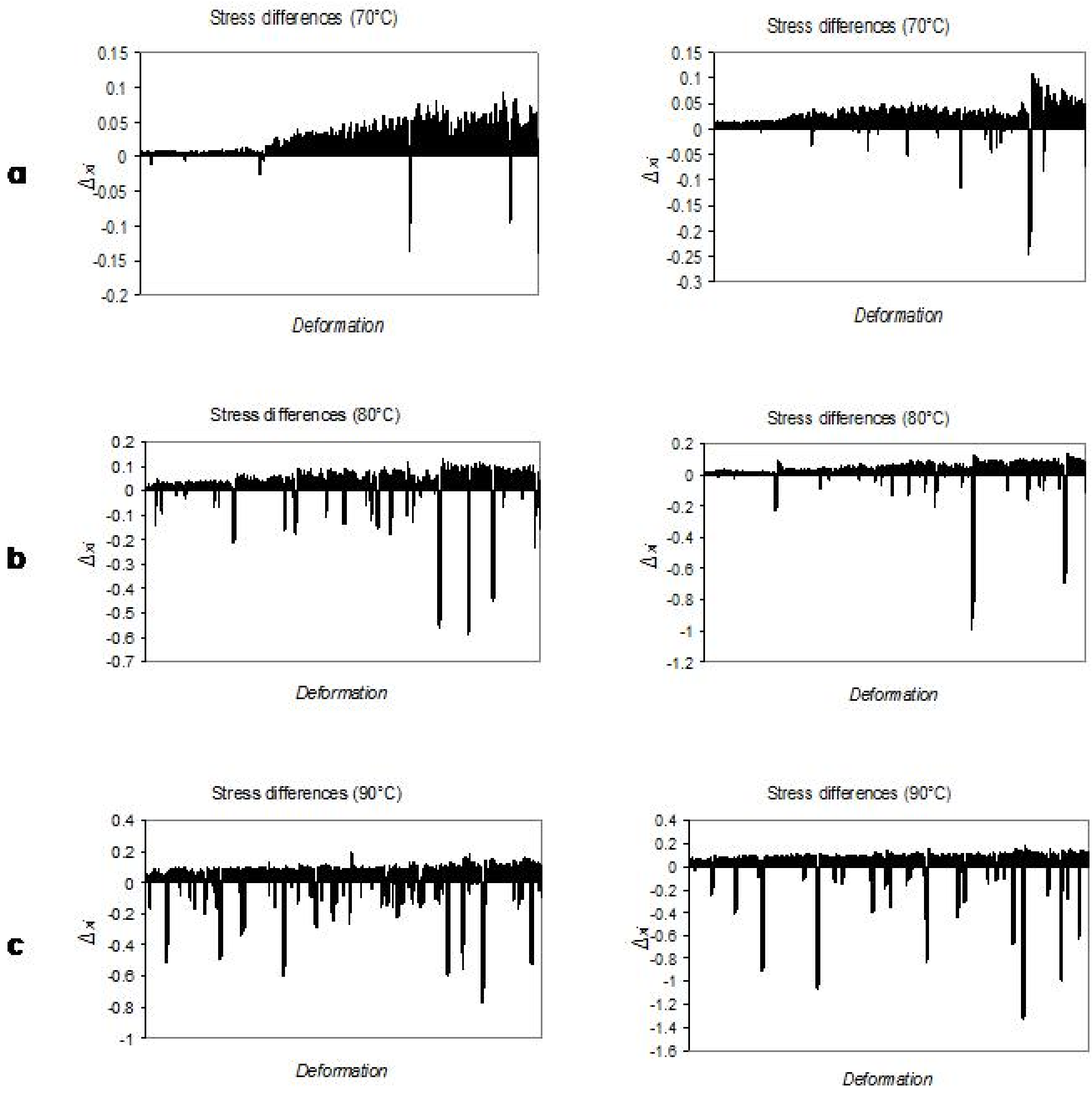
Table 1. Characteristics of apple rings osmo-air-dried to a constant weight at different temperatures.



40
30
20
10
0
Stress (kPa)
0
10
20
30
40
50
60
70
80
Time (s)
90°C
80°C
70°C

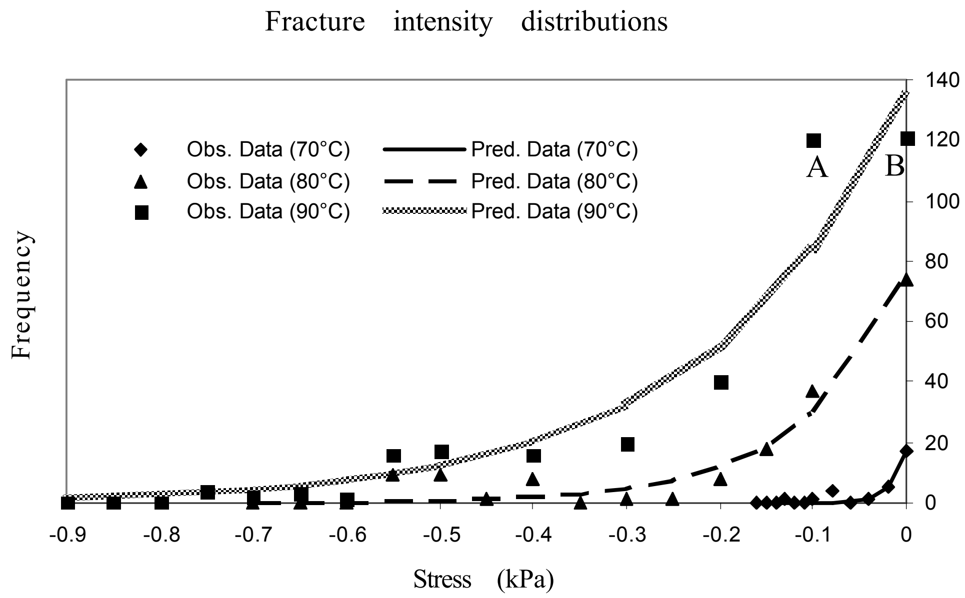


Moisture content (%) - in brackets
Relative relaxation stress (σr) - black symbols
Crispness E (kNmm^-2) - white symbols
Water activity
(1.54)
(1.84)
(2.06)
(2.67)
(3.54)
(4.28)
(2.06)
(1.84)
(2.67)
(3.54)
(4.28)
70°C
80°C
90°C
Pink Lady®
Golden Delicious



a
Stress differences (70°C)
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Δxi
Deformation
Stress differences (70°C)
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
Δxi
Deformation
b
Stress differences (80°C)
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
Δxi
Deformation
Stress differences (80°C)
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
Δxi
Deformation
c
Stress differences (90°C)
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Δxi
Deformation
Stress differences (90°C)
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
Δxi
Deformation

Figure 4


Fracture intensity distributions
Obs. Data (70°C)
Obs. Data (80°C)
Obs. Data (90°C)
Pred. Data (70°C)
Pred. Data (80°C)
Pred. Data (90°C)
A
B
Frequency
Stress (kPa)
140
120
100
80
60
40
20
0
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0

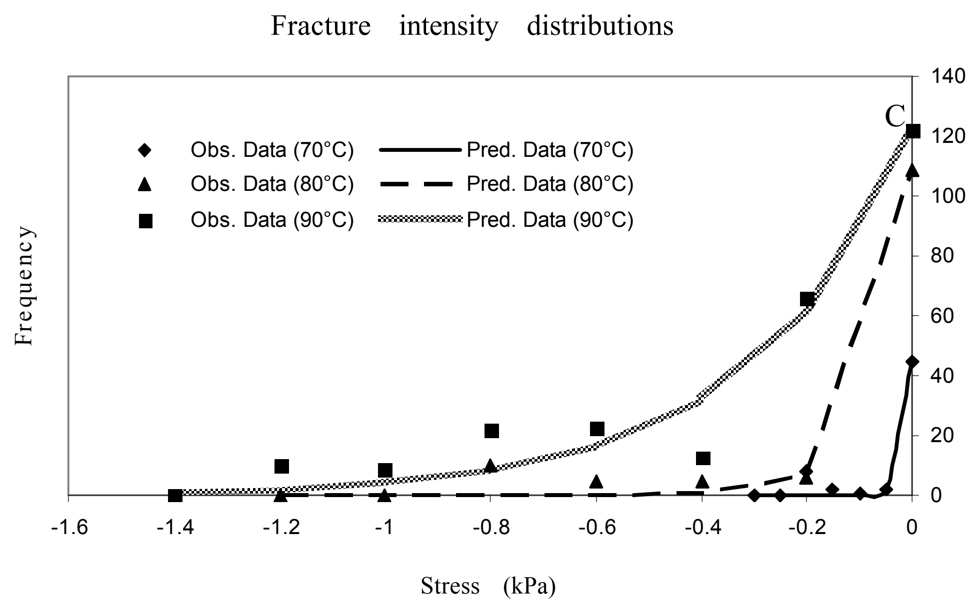

Fracture intensity distributions
Obs. Data (70°C)
Obs. Data (80°C)
Obs. Data (90°C)
Pred. Data (70°C)
Pred. Data (80°C)
Pred. Data (90°C)
C
Frequency
Stress (kPa)
140
120
100
80
60
40
20
0
-1.6
-1.4
-1.2
-1
-0.8
-0.6
-0.4
-0.2
0

Figure 7

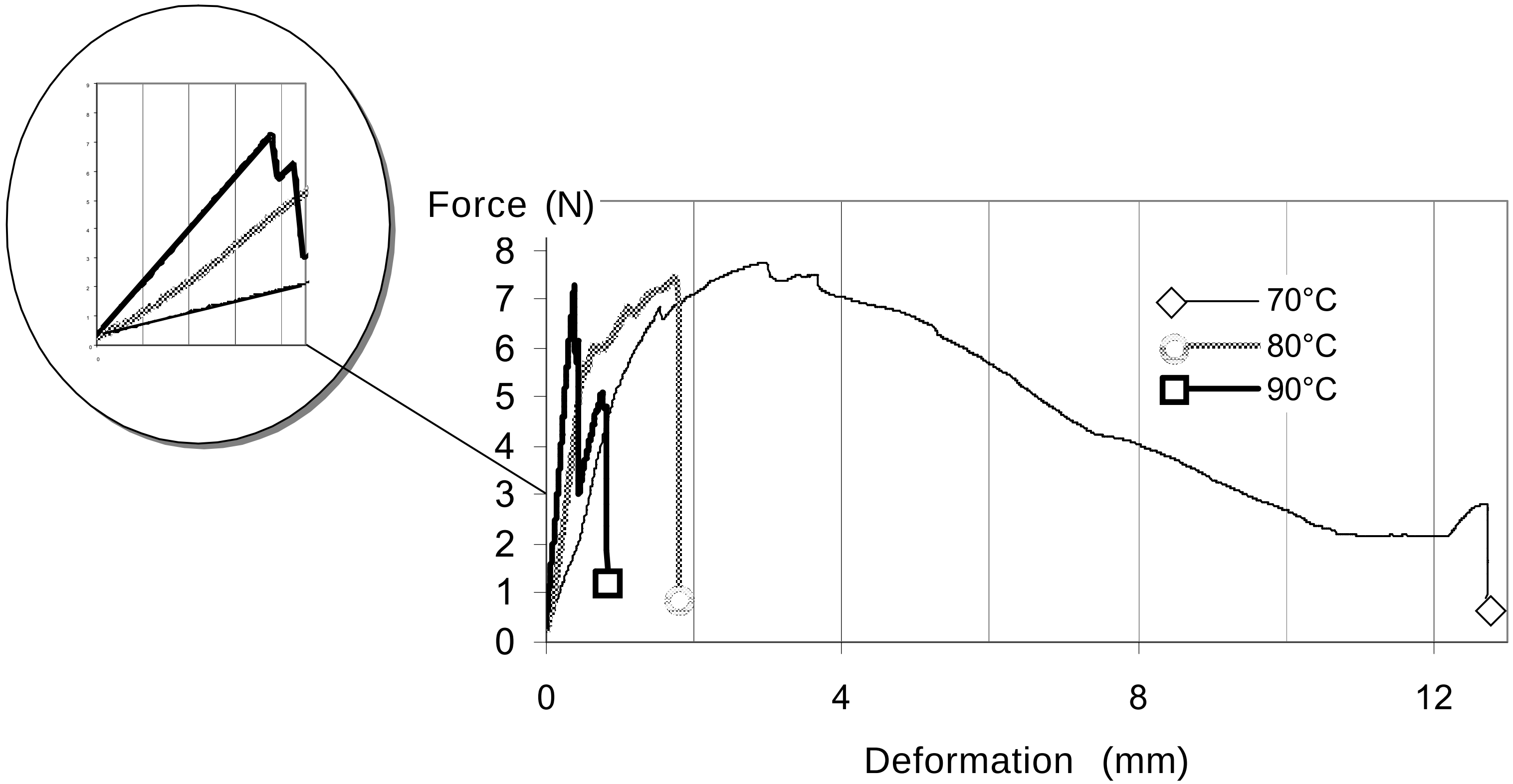
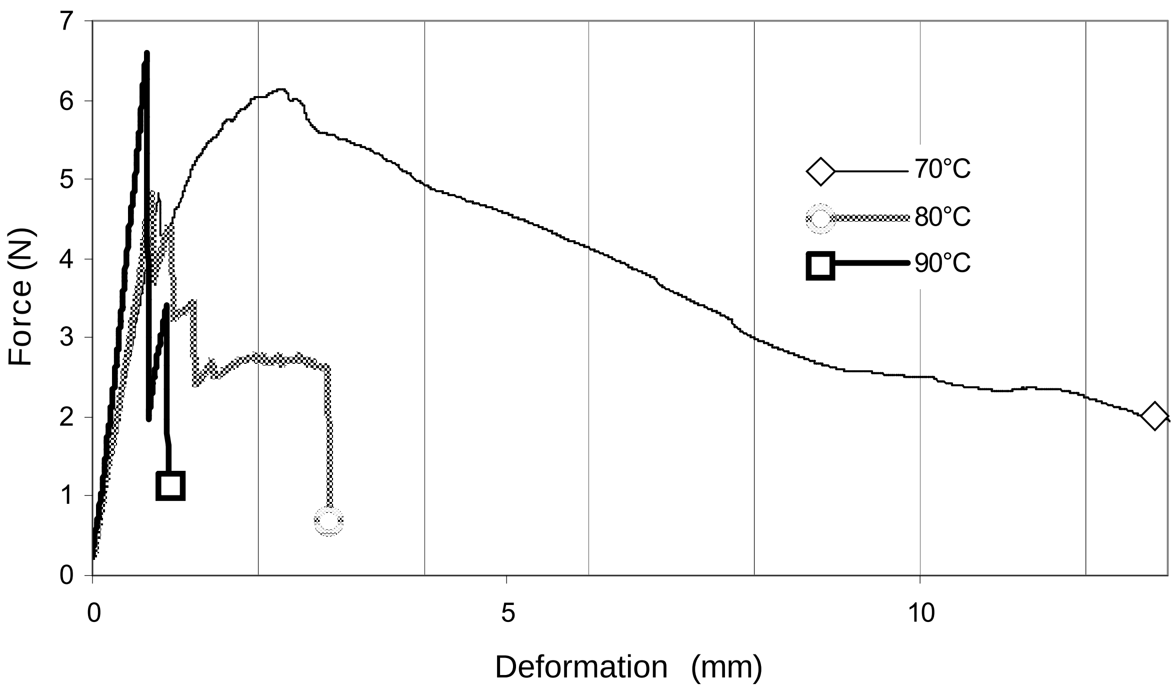


Figure 6



ANALYSIS / TEST TYPE	Pink Lady®			Golden		
	70°C	80°C	90°C	70°C	80°C	90°C
MOISTURE CONTENT (%)	3.541^{a} (±0.44)	2.064^{b} (±0.24)	1.548^{c} (±0.13)	4.282^{d} (± 0.22)	2.671^{e} (±0.14)	1.845^{f} (±0.11)
WATER ACTIVITY	0.280^{g} (±0.0209)	0.240^{h} (±0.0157)	0.186^{i} (±0.0251)	0.263^{g} (±0.0242)	0.197^{h} (±0.0246)	0.155^{i} (±0.0108)
COMPRESSION-RELAXATION (mod.)						
σ_r	0.6875^{j} (± 0.0065)	0.7885^{k} (± 0.03)	0.8905^{l} (± 0.0197)	0.6451^{m} (± 0.0087)	0.7309^{n} (± 0.0330)	0.8312^{o} (± 0.0089)
b	61.288	14.003	3.328	60.711	9.279	4.724
C	16.665	40.363	44.841	6.283	27.917	49.952
r^2	0.967	0.983	0.946	0.937	0.948	0.916
Fc	58	135	265	29	166	360
Pd $\geq$ 0.5% F_{max}	1.476^{p} (± 0.32)	3.532^{q} (± 0.40)	5.433^{r} (± 0.22)	0.848^{s} (± 0.16)	4.031^{qt} (± 0.54)	5.352^{r} (± 0.28)
Pd $\geq$ 5.0% F_{max}	0.508^{u} (± 0.12)	1.825^{p} (± 0.20)	4.046^{t} (± 0.28)	0.321^{u} (± 0.24)	1.665^{p} (± 0.34)	3.517^{q} (± 0.14)
BENDING-SNAPPING						
E ($kNmm^{-2}$)	1.904^{v} (± 0.48)	3.081^{w} (± 0.58)	4.683^{x} (± 0.83)	0.961^{y} (± 0.27)	1.990^{t} (± 0.22)	2.553$^{\text{Ə}}$ (± 0.35)

Standard deviations are reported in brackets. Different letters denote statistically significant differences ($p \leq 0.05$)