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MECHANICAL AND ACOUSTIC PROPERTIES OF DRIED APPLES

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A B S T R A C T

The aim of this research was to analyze mechanical and acoustic properties of apples which were dried using different methods. Apple slices were dried using the following methods: convective, fluidal, microwave-convective and the sublimation. The obtained dried apple material was compressed in a Zwick machine with a velocity of 20 mm/min and with a simultaneous recording of the acoustic emission (AE) generated during sample destruction. Brüel&Kjær accelerometer type 4381 was used for sound recording. Dried fruit porosity was also determined.

Analyses conducted proved that drying methods significantly influence mechanical and acoustic properties of dried apples. Mechanical parameters: apparent Young's modulus, work and compression force were the highest for the fluidal dried apples, and the lowest for apples dried by the sublimation method. The latter group of dried apples was also most porous in structure.

The obtained dried apple material differed in the number of events, the acoustic energy and in the range of emitted frequencies. There were negative correlations between mechanical and acoustic parameters of dried apples. The porosity of material correlated with the compression force, as well as the acoustic energy and the number of events.

Key words: dried apples, mechanical properties, acoustic properties, porosity

INTRODUCTION

Drying is one of many methods aimed at food preservation and creation of food products with specific physicochemical and organoleptic properties. According to Lewicki (1998), during the drying process of fruit and vegetables one can observe various changes. The changes are in cell shape and size while stress occurring within the fruit and vegetable material causes tearing of its internal structure, breaking, and formation of cracks. Additionally the amount of inflicted damage increases from the expanding air present within intercellular spaces. This air destroys cells during its migration into the atmosphere. Contraction, semi-perme--ability of cellular membranes and change of rheological properties of plant material, occur, as the result of water disappearance from this material (Lewicki, 1998; 2006).

Different drying methods implemented for fruit and vegetables, i.e. convective, radiation, microwave or sublimation produce products with brittle/crispy properties. Consumers evaluate the organoleptic factors of dried fruits, i.e. taste, odour, colour, as well as crunchiness and texture when biting into the fruit. Colour is the first and the main property of food that gets evaluated. Mechanical properties, as well, are evaluated at first bite. The conditions during the drying process obviously influence a product's quality. Mechanical tests and acoustic tests in the case of dry products, form basic instrumental texture measuring methods. Acoustic tests are important because of the high correlations which take place between the acoustic/textural properties and the sensory analysis of products (Harker et al., 2006). Sound frequency emitted during deformation depends mainly on the kind of material being deformed (Wavers, 1997). In the case of dried fruit the internal structure remains responsible for the acoustic emissions during their simulated consumption. Differences in the structure of dried fruit may be caused by different techniques of drying the material. Pasik (2007) demonstrated that the acoustic spectrum emitted by apples dried using the sublimation method was nearly identical to the spectrum emitted by carrots dried using the same method. According to available literature, higher amplitude and frequency were emitted during consumption of more brittle products while lower amplitudes and sound frequency accompanied chewing of more brittle food products (Drake, 1965; Dacremont, 1995).

MATERIAL AND METHODS

'Idared' apples were cut into slices, 5 mm in height and 20 mm in diameter, and then immersed in a 1% citric acid solution to avoid enzymeatic browning. Two hundred grams of samples were dried.

Four drying methods were used in the experiment:

1. The convective method at 70°C with an air flow of 2 m/s.
2. The convective-microwave method at 40°C with an air flow of 1.7 m/s and the microwave set at 200 W.

The convective and convective--microwave drying experiments were continued until a constant mass was obtained. Weight of samples was controlled during drying by computer program ,,Pomiar".

3. The fluidal method at 70°C with an air flow of 7m/s. Apple slices were dried for 190 min.
4. Sublimation (frozen at –21°C, apple slices were dried for 24 h at

pressure 63 Pa and shelf temperature of 20°C).

After drying, products were stored for 2 weeks under controlled conditions (temperature 25°C, relative humidity of air 0%) in order to equalize as well as to lower their water activity.

Water activity (a_w) of dried apples was measured with precision ±0,001 using Hygroscope DT2 (Rotronic AG, Switzerland) as well as their real density (ρ) and apparent density (ρ_L) using a helium peak flow meter (Stereopicnometer, Quantachrome Instruments). Porosity of dried apples was calculated according to the correlation: $\varepsilon = 1-(\rho_L \cdot \rho^{-1})$. where: ρ_L – apparent density, ρ – real density.

The mechanical properties were investigated in a compression test. Apple slices were stacked 20 mm high in a plastic cylinder. A piston 15 mm in diameter was connected to a Zwick Machine 1445 (ZWICK GmbH, Germany) and used to compress the samples in the cylinder. The compression was done with a piston velocity of 20 mm/min.

An accelerometric sensor, Brüel &Kjær 4381 V was mounted near the lower end of the upper head of the loading machine to achieve an acoustic contact with the dried apple samples. The acoustic emission signal was amplified (40 dB) in the low--noise amplifier and digitalized using Adlink Technology Inc. type 9112 analogue-digital conversion sound card with the sampling frequency of 44.1 kHz. This card enabled recording of the force overloading the analyzed sample, along with recording of the acoustic emission. The acoustic emission signal was analyzed from 1 kHz to 15 kHz.

The following mechanical parameters were calculated: relative strain (ε_0), true strain (ε_t), compressive stress (σ), work. Compression work was calculated as the area under the deformation curve of slices of dried apples (Marzec et al., 2007). Apparent Young's modulus E was determined as the slope of the initial segment of the curve (to $\varepsilon_0 = 0.125$) in a compressive stress and strain relative.

Special computer programs were used to determine the acoustic parameters of dried apples: sound amplitude, number of events, acoustic energy and power spectrum (Ranachowski, 2005). The partition power spectrum slope (β) was calculated as a quotient of sound energy of high frequency in the range from 10 kHz to 15 kHz and sound energy of low frequency in the range from 1 kHz to 7 kHz.

The recorded time-depended AE signal, v(t), of each session was presented as a series of its digital samples, where T_1 was a time delay between the consecutive executions of taking a sample. Hence, $v(mT_1)$ was here understood as amplitude of voltage registered on the AE sensor. An independent variable m represented the consecutive number of a signal sample. Total session time T included N digital AE signal samples. When a 44.1 ksamples/s recording speed was used, it gave 44.1 T kilosamples. Thus ‘‘AE signal energy'' was calculated in arbitrary units as:

$$E = \sum_{m=1}^{N} v(mT_1) \quad (1)$$

Tests were conducted in 20 replications and then 20 s of force and acoustic emission recording were chosen for further analysis. Mechanical and acoustic parameters forming averages from the 20 replications were calculated statistically with the analysis of variance (Anova) using Statistica 8 program. The significance of differences between means was determined using the Tukey's test at $p = 0.05$. A correlation analysis was conducted between mechanical and acoustic properties.

RESULTS AND DISCUSSION

Analyzed dried apple samples were characterized by similar water activity properties (Tab. 1). Porosity of apples dried using sublimation was significantly higher than of apples dried with other methods. Differences between porosity of dried apples obtained with fluidal, convective and microwave-convective methods turned out to be insignificant (Tab. 1). The differences were probably the result of large material contraction while drying. The available literature proves that all drying methods except for sublimation cause a decrease in the cell area in relation to fresh material which is most probably connected with material contraction (Lewicki and Pawlak, 2003).

Mechanical properties of the dried apple material depended on the drying methods (Fig. 1, Tab. 1). Many shreds and peaks were observed proving that the analyzed dried apple material had a complex structure.

The statistical analysis proved that observed differences between compression curves of apples dried with convective and microwave--convective methods were insignificant. However, fluidal and sublimation drying significantly influenced the aforementioned compression curves. The fluidal drying compression curve was the highest and was characterized by the highest value of compression stress (Fig. 1). At a true strain of 0.5 the average compression stress of apples from fluidal drying equalled to 276.1 kPa (± 80.1 kPa), and 162.8 kPa (±36.1 kPa) for apples dried by sublimation.

Determined values of mechanical parameters of dried apples were characterized by large standard deviations up to around 35% (Tab. 1). This clearly portrays diversity in the obtained products regardless of the drying method.

The analysis of compression work and of the apparent Young's modulus demonstrated that apples from fluidal drying were characterized by having the highest durability while apples from sublimation drying by the lowest. However, no significant differences were observed between parameters determined for convective drying apples and microwave-convective ones (Tab. 1).

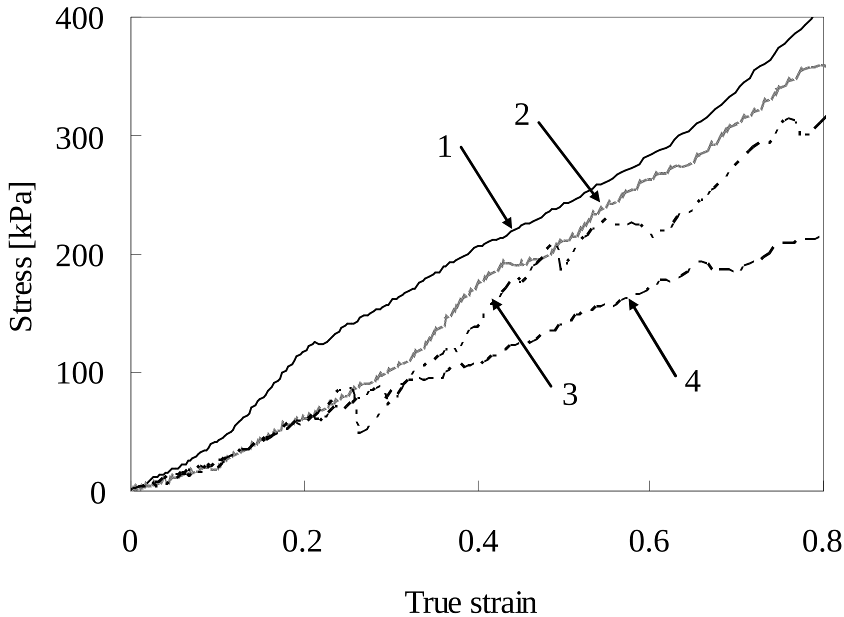

Figure 1. Compression curves of apples dried by the following methods: fluidal (1), convective (2), microwave (3) and sublimation (4)

Hardness of material can be determined on the basis of the compression force. Tests proved that the apples dried by fluidal method were the hardest (Tab. 1). The compression force determined both at a true strain of 0.8 as well as of 0.3 reached the highest values for dried apples obtained by the fluidal method. It was significantly higher than values of force noted for the remaining dried material (Tab. 1). The reaction of the materials was probably caused by different drying times. Moreover, the faster the product dries the higher the probability of a crystallized state formation. A long drying process results in a rubbery product and is characterized by low resistance.

Acoustic properties were analyzed on the basis of amplitude-time characteristics and it was found that apples dried with the fluidal method emitted the lowest number of sound impulses during compression (the number of events). The highest number of events was found in apples dried using the sublimation method (Tab. 2). Similar dependencies were observed in the case of sound energy analysis (Tab. 2). No influence of drying method on sound amplitude and energy of one event was ever observed (Tab. 2).

Acoustic emission descriptors were characterized by high diversity (high values of standard deviation) (Tab. 2) similarly to mechanical par-

T a b l e 1 . Porosity and the mechanical parameters of dried apples

Drying method	Drying time [min]	Water activity in dried and stored apples	Porosity	Apparent Young's modulus [kPa]	Compression work [J]	Compression force at $\varepsilon_t = 0.3$ [N]	Compression force at $\varepsilon_t = 0.8$ [N]
Fluidal	190	0.105	0.825[a]	447.9±58.8[a]	0.460±0.133 [a]	48.3±11.7[a]	148.6±50.9[a]
Convective	240	0.090	0.822[a]	277.5±39.9[b]	0.260±0.072 [b]	38.4±10.6[b]	116.8±33.6[b]
Microwave-convective	150	0.098	0.830[a]	254.4±41.2[b]	0.259±0.083[b]	31.7±8.7[b]	115.6±27.4[b]
Sublimation	-	0.085	0.854[b]	286.1±48.9[b]	0.225±0.048[c]	24.8±5.5[c]	81.1±14.7[c]

a, b, c – homogeneous groups

T a b l e 2 . Descriptors of acoustic emission parameters of dried apples

Drying method	Amplitude [mV]	"Energy" of the AE event [μV]	Number of events	"Acoustic energy" [V]	Partition power spectrum slope
Fluidal	125.8±1.3[a]	481.6±36.5[a]	49±23[a]	23.7±10.5[a]	0.01±0.02[a]
Convective	125.3±0.5[a]	465.5±6.8[a]	139±35 [b]	64.6±16.3[b]	0.96±0.19[b]
Microwave-convective	126.7±0.6[a]	489.0±18.5[a]	293±51[c]	145.3±19.9[c]	1.36±0.30[b]
Sublimation	125.3±0.5[a]	478.6±18.9[a]	344±47[c]	164.6±23.0[c]	1.00±0.33[b]

a, b, c – homogeneous groups

ameters (Tab. 1). All analyzed dried apple products were porous and this was the probable cause for the lack of differences in the sound amplitude. On the other hand, defects caused by the drying method and time, could cause differentiation in the number of events and acoustic energy. Kowalski and Mielniczuk (2005) demonstrated that thermal stress causes damage in the internal structure which results in cracks and geometry change in the dried material.

The fluidal drying lasts longer than the microwave drying and these processes differ significantly in term of the way they evaporate water from material. During fluidal drying water is first evaporated from the material's surface and subsequently from its interior. High temperature and velocity of air flow cause the surface layer to close up forming a barrier which suppresses water diffusion from the inside towards the outside of the dried material (Janowicz and Lenart, 2007). When drying by microwave, the microwave energy gets absorbed by the dried material. The effect of this strong absorption allows water to heat up quickly in entire volume of the dried material. This causes shortening in the drying time, smaller contraction and structure defects, and bigger porosity of the material. Because of this, apples dried using the microwave-convective method are characterized as having lower endurance along with a higher acoustic activity than apples dried using the fluidal method.

The partition power spectrum slope shows proportions between the amount of sound emitted in high and low frequency ranges. It was much higher than 1 for apples dried using the microwave convective method. This means that the dried apple material emitted more high than low frequency sounds. Apples dried with the sublimation method were characterized by values of this partition power spectrum slope. β at the level of 1. The values of partition power spectrum for fluidal and microwave-convective dried material were lower than 1 which means that the share of lower frequency sounds in the acoustic emission was higher. Probably such acoustic emissions are mainly due to the stresses and defects formed in apples during drying using different methods. The frequency of the sound depends on the elastic properties of the material and of the kind sound source. It depends also on the natural defects of raw material (Luyten and Van Vliet, 2006) or defects acquired during drying process (Kowalski and Mielniczuk, 2005).

Research of the acoustic characteristics proved that products made from grains like: crunchy bread, cookies and bread are characterized by an individual spectrum slope. Technology of product processing also significantly influenced the range of emitted frequencies (Marzec et al., 2005). Drying method significantly influenced frequencies of sound emitted by the dried carrot (Pasik, 2007).

Figure 2 shows the spectrum of sound waves emitted by dried apples during compression. There are visible characteristic frequency bands

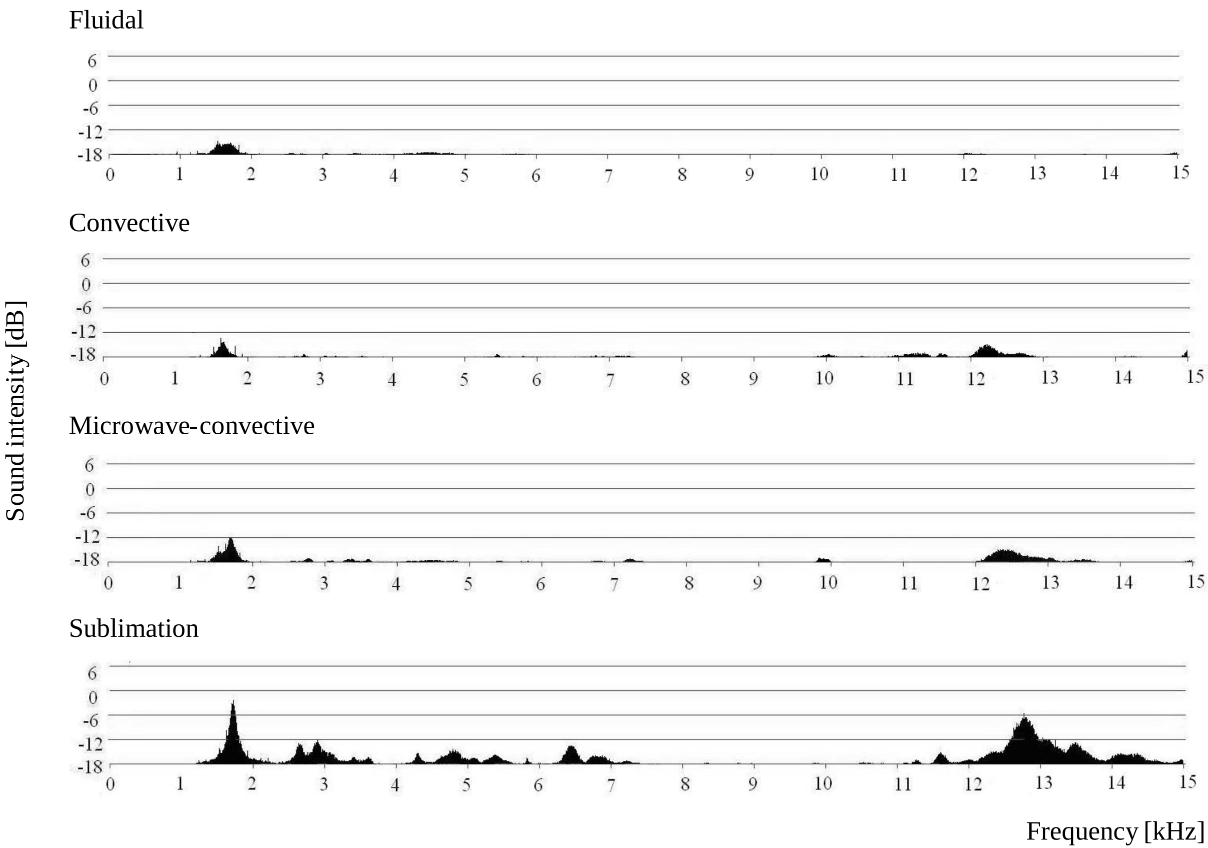

Figure 2. Spectral characteristics of acoustic emission signals of apples dried with different methods

Table 3. The coefficients of linear regress (r^2) between the texture, mechanical parameters, acoustic descriptors and the porosity of dried apples

	Porosity	Apparent Young's modulus [kPa]	Work [J]	Compression force at ε_t = 0.3 [N]	Compression force at ε_t = 0.8 [N]
Porosity	1	-0.278	-0.490	-0.795	-0.833
Amplitude [mV]	-0.297	-0.117	0.106	0.046	0.324
"Energy" of the AE one event [µV]	0.206	0.100	0.184	-0.132	0.104
Number of events	0.779	-0.760	-0.827	-0.979	-0.888
"Acoustic energy" [V]	0.764	-0.758	-0.817	-0.971	-0.870
Partition power spectrum slope	0.282	-0.983	-0.920	-0.805	-0.686

and acoustic signal intensity in the same bands. The spectrum also shows the effect of the drying method's impact upon sound intensity and its frequency. During compression of apples dried using the fluidal method, the strongest sound signal was emitted in low frequencies = 1-2 kHz. Acoustic emission signals of far lower intensity were also registered at a frequency of 5 kHz and very weak at frequency of 14 kHz (Fig. 2).

Apples dried using both the convective and microwave-convective method during compression, emitted sounds of the highest intensity at low frequencies 12-14 kHz. Weaker sound signals were registered at a frequency of 7 kHz as well as 10 kHz (Fig. 2). The acoustic activity of apples dried using the sublimation method was much higher than the acoustic activity of apples dried using other methods studied. Acoustic emission signals of low frequency were registered – 1-6 kHz; of middle frequency – 6-7 kHz; and of high frequency – 10-15 kHz (Fig. 2).

Dependencies between acoustic and mechanical parameters of dried apples and their porosity were analyzed. Positive correlations were observed between porosity and the number of events (r^2 = 0.779) and the acoustic energy (r^2 = 0.764). In the case of mechanical parameters, force showed negative interdependencies when compared with porosity (Tab. 3).

Negative correlations took place between mechanical parameters and acoustic descriptors. These included: the number of events, the acoustic energy and the partition power spectrum slope (Tab. 3). The highest interdependencies took place between the apparent Young's modulus and the partition power spectrum slope (r^2 = –0.983) (Tab. 3).

CONCLUSIONS

The conducted research demonstrated that the drying method influences mechanical and acoustic properties of dried apples. All determined parameters had a large diversity.

Mechanical parameters, apparent Young's modulus, and work and force of compression had the highest values for dried apples obtained by fluidal method. Apples died by sublimation were characterized by work and force of compression lowest work and force of compression.

Dried apples differed both with the number of events as well as with the acoustic energy and the range of emitted frequencies. The partition power spectrum slope was the highest for apples dried with the microwave-convective method and was significantly different for apples dried using the fluidal method, convective method and sublimation method.

Negative interdependencies between mechanical and acoustic parameters of dried apples took place.

The porosity of material correlated with the compression force, as well as the acoustic energy and the number of events.

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WŁAŚCIWOŚCI MECHANICZNE I AKUSTYCZNE JABŁEK SUSZONYCH RÓŻNYMI METODAMI

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S T R E S Z C Z E N I E

Celem pracy było badanie właściwości mechanicznych i akustycznych jabłek wysuszonych różnymi metodami oraz analiza korelacji pomiędzy wyznaczonymi parametrami mechanicznymi i akustycznymi suszy. Plasterki jabłek suszono metodami: konwekcyjną, fluidalną, konwekcyjno-mikrofalową i sublimacyjną. Uzyskane susze były ściskane w maszynie wytrzymałościowej Zwick z prędkością 20 mm/min i z jednoczesną rejestracją emisji akustycznej (EA) generowanej podczas niszczenia próbek. Do rejestracji dźwięków wykorzystano akcelerometr typu 4381 firmy Brüel&Kjær. Ponadto wyznaczono porowatość suszy.

Przeprowadzone badania wykazały, że metoda suszenia wpływa na właściwości mechaniczne i akustyczne suszy jabłkowych. Parametry mechaniczne: pozorny moduł Younga, praca i siła ściskania były największe dla suszu fluidalnego, najmniejszą zaś wytrzymałością charakteryzował się susz sublimacyjny. Jabłka suszone sublimacyjnie były również najbardziej porowate.

Susze jabłkowe różniły się zarówno liczbą zdarzeń emisji akustycznej, energią akustyczną, jak i zakresem emitowanych częstotliwości. Wystąpiły ujemne współzależności między parametrami mechanicznymi i akustycznymi suszy. Porowatość materiału korelowała z siłą ściskania oraz z energią akustyczną i liczbą zdarzeń EA.

Słowa kluczowe: suszone jabłka, właściwości mechaniczne, właściwości akustyczne, porowatość