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Cereal food texture evaluation with application of mechanical and acoustical methods

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1. Introduction

The perceived textural attributes of consumed food constitute significant part of eating quality estimation and are usually ranked as second after flavor. The textural attributes are of primal importance for assessment of quality of bakery products.

Food texture could be described as physical and structural properties of the materials, percept from several senses such as vision, hearing and touch and sensed during consumption process [1]. In 1981 the International Standard Organization issued the following definition of a texture: A texture combines all rheological and structural (including geometry and surface) food properties, which are perceived by humans by means of receptors of touch and mechanical feelings, and – if possible – by visual and audible senses. Besides the texture, the rank of taste, odor and other sensory perception aspects is well documented in the literature. Surprisingly, the audible perception is still a matter of a minor concern.

A crunchy bread product, which structure is shown in Fig. 1, is produced in a mass scale throughout the world. It is made from the flour using the extrusion method, i.e., the low moisture substrate is treated by the instant

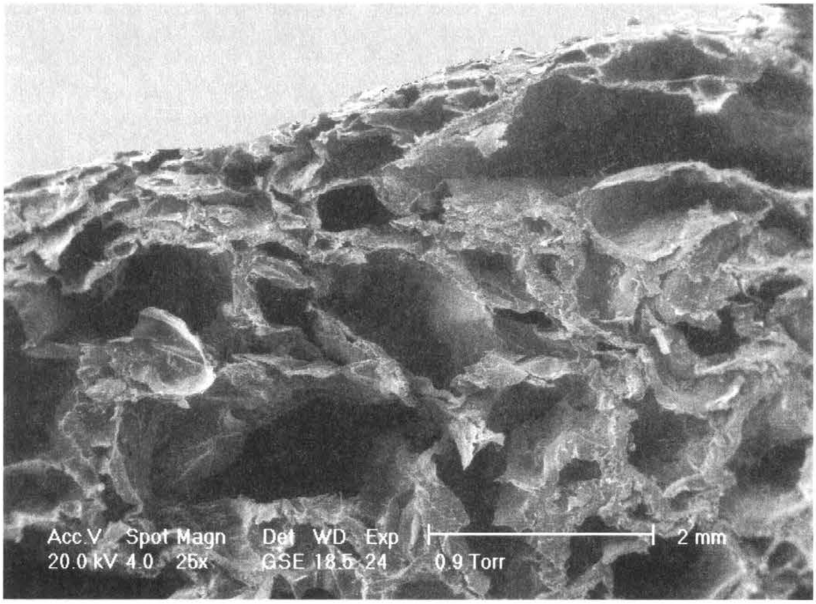


FIGURE 1. Microphotography of a crunchy wheat bread structure.

influence of high temperature (up to 180°C) and high pressure (5-15 MPa) under the load of the shearing force [2].

The variables described above cause an instant expansion of an overheated vapour, in the volume of the processed product, at an outlet of the extruder. The sudden loss of the pressure and water evapouration leads to formation of a porous structure and unique textural properties typical for the extruded food. The product consists mostly of starch (some 70%), proteins (about 9%) and minor quantities of fat and cellulose. From the mechanical point of view the structure can be considered as that of a porous composite with a matrix formed of starch and embedded proteins. Therefore, high temperature – high pressure treated starch is generally responsible for the textural properties of the product [3]. All the structural components listed above are partly elastic and partly plastic polymers and their rheological behaviour highly depends on the amount of adsorbed water.

The quality loss of the extruded products is mainly caused by the changes of their texture and especially by the adsorption of water from the environment. The increase of water content, and especially the change of the state of water expressed by the thermodynamic parameter known as *water activity* a_w, changes hydration of starch-protein matrix and modify its mechanical strength. At a certain water activity level an optimal crunchiness is observed. When a_w exceeds 0.5 the effect of crunchiness vanishes. The effect is investigated using ordinary mechanical tests and rectangular samples. The application of mechanical tests is less useful for non-rectangular or too small specimens.

The aim of this work was to investigate the effect of water activity on acoustic emission generated during breaking wheat and rye extruded bread equilibrated at different water activities. Acoustic emission was also measured on samples of plain wheat bread produced by traditional method.

2. Material and methods

Bread samples were removed from the retail packages and stored in desiccators over solutions with specified water activity (sulfuric acid and saturated solutions of some salts) for 3 months at 25°C. These conditions enabled the specimens to reach the structural moisture equilibrium in the range from 0 up to 75% of relative humidity.

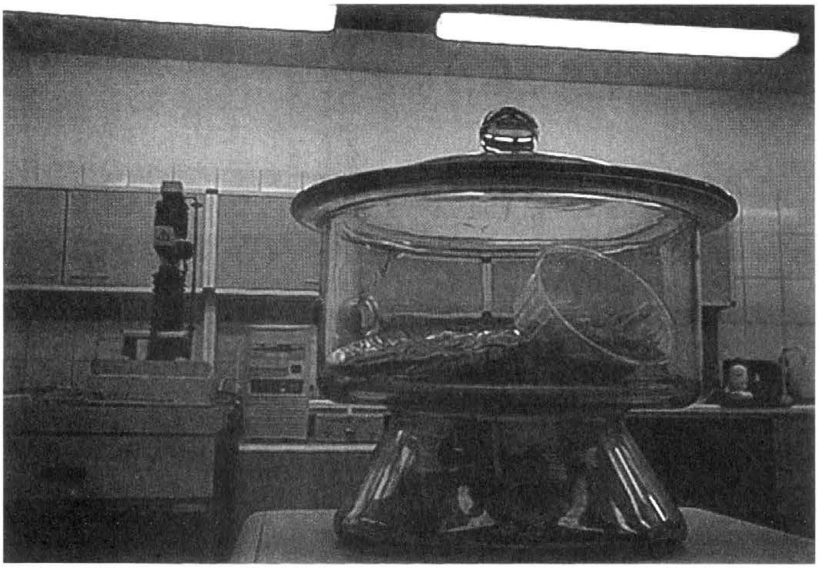


FIGURE 2. Extruded bread specimens stored in desiccator.

Determination of moisture content of bread specimens

Moisture content of the extruded bread specimens was measured before and after the storage period according to Polish Standard PN-84/A-86361 [4].

Determination of water activity

Determination of water activity (a_w) was done using the Higroscope DT 2 (Rotronic AG) of accuracy ±0.001 of a_w unit at 25°C.

The idea of water activity

The potential influence of the moisture sorption processes on food quality degradation caused by chemical and enzymatic reactions, and especially by the activity and proliferation of microorganisms, is possible to assess on the basis of water activity parameter (a_w). It is a thermodynamic measure of the state of the water in food and expressed as the ratio of the water vapour pressure over the product to the water vapour pressure over the pure water at constant temperature and total pressure [5, 6, 7]. Under that equilibrium state the water activity of a food product corresponds with the 1/100 of the surrounding air relative humidity [8, 9]. In diluted solutions the water activity, according to the Raoult Law, can be calculated as the molar fraction of water in solution [10].

3. Experimental setup

Acoustic Emission (AE) signals were generated by the 120 × 55 × 7 mm slices of flat rye bread during a 3-point breaking process done with a silent Zwick 1445 loading machine. An accelerometric sensor, Brüel & Kjaer 4381V was mounted near the lower end of the upper head of loading machine to achieve an acoustic contact with the bread sample. The loading was performed at the constant head speed of 20 mm/min. Each AE signal registering session lasted ca. 10 seconds. The AE sensor was capable to register the acoustic signal at the frequency range from 0.1 Hz to 14 kHz. AE signal was transmitted from the sensor to a 20 dB low – noise amplifier and finally registered using a 44.1 kHz sampling sound card placed in a PC computer. A special uniformity test, including 0.5 mm pencil HB break, was applied to keep the sensitivity control of AE signal.

4. Processing of recorded acoustic emission

A population of specimens included extruded rye and wheat bread with the water activity in the range from 0.037 to 0.750.

Since the population was examined under the same conditions, it was possible to compare the recorded "AE signal energy" of bread specimens in relation to their moisture content. The recorded time – depended AE signal,

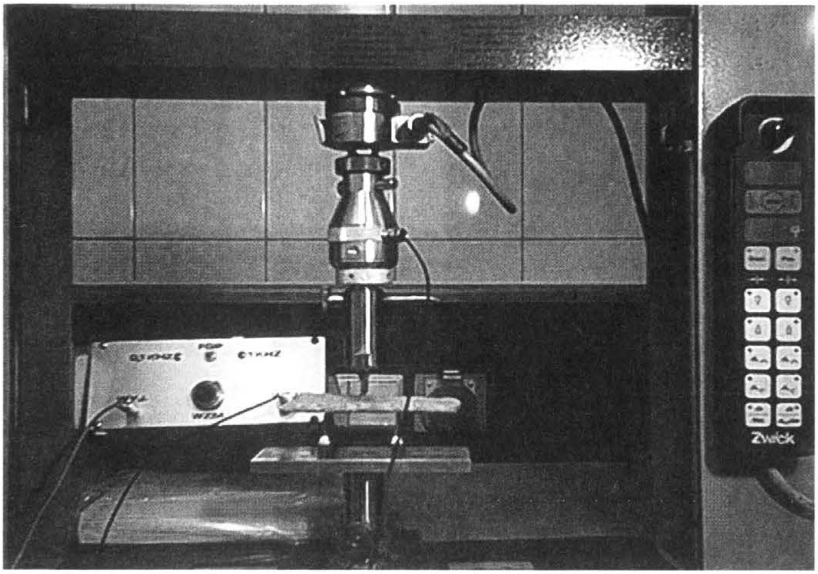


FIGURE 3. A flat bread sample placed in the loading machine.

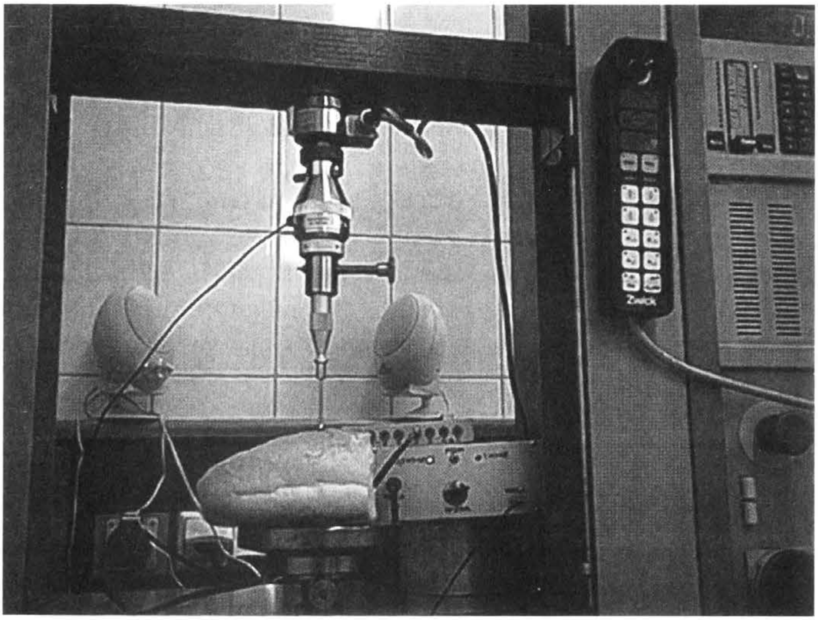


FIGURE 4. Investigation of acoustic emission of traditionally baked wheat bread.

$v(t)$ of each session is presented as a series of its digital samples where T_1 is time delay between the consecutive execution of taking a sample. Hence, $v(m\,T_1)$ is here understood as an amplitude of voltage registered on the AE sensor. An independent variable m represents the consecutive number of a signal sample. Total session time T (equalled 10 seconds) includes N digital AE signal samples. If a 44.1 kilosamples/sec recording speed was used, it gives 441 kilosamples. Thus the "AE signal energy" can be calculated in arbitrary units as:

$$E = \sum_{m=1}^{n} v(m\,T_1).$$

The authors proposed another acoustic parameter, not dependent on the specimen cross-section area – as it was observed calculating "AE signal energy". The idea was to consider a specific attribute of emitted sound – a shape of its power spectrum. Continuous AE signal can be, in the frequency domain f, characterized by its power spectrum function $A(\omega)$ where w is a linear analogue of frequency f, $\omega = 2\pi f$. A computer procedure was used to derive a discrete image of $A(\omega)$. The procedure analysed recorded AE signal samples in sections of 0.25-second length. To reject the influence of background noise one dominant AE burst was detected (if any was present) in each section. All the bursts were processed to obtain its power spectrum function keeping the same phase of each burst at the transformation process. This algorithm is sometimes called "event filtering" enabling to suppress the random noise accompanying the recorded signal. As a result, for each time section the procedure produced a series of coefficients c_n and each of them represented the AE signal power in the frequency range of 11 Hz. The whole series of c_n covered the desired spectral range of 100-1500 Hz. The algorithm performing the $v(m\,T_1) \rightarrow c_n(w)$ transform is based on the following approximation formula:

$$c_n \approx \frac{1}{N} \sum_{m=0}^{N-1} v(m\,T_1) \cdot \mathrm{mod}\left(e^{j\,n\,2\pi\,m/N}\right).$$

It was found experimentally that in rye and wheat samples there are two regions in the frequency domain where the high level of the power spectrum function is measured. These regions are 1-3 kHz and 7-15 kHz. This led the authors to propose the AE signal practical descriptor independent of the sample volume. This coefficient is called *partition power spectrum slope* (β) and is calculated as a ratio of AE signal power spectrum registered in the frequency range 7-15 kHz, labelled as $P_{7\text{-}15}$, and the AE signal power registered in the frequency range 1-3 kHz, labelled as $P_{1\text{-}3}$,

$$P_{7\text{-}15} = \sum_{n\mapsto 7\,\mathrm{kHz}}^{n\mapsto 15\,\mathrm{kHz}} c_n, \qquad P_{1\text{-}3} = \sum_{n\mapsto 1\,\mathrm{kHz}}^{n\mapsto 3\,\mathrm{kHz}} c_n, \qquad (\beta) = \frac{P_{7\text{-}15}}{P_{1\text{-}3}}.$$

5. Investigation of acoustic emission in traditionally baked wheat bread

The following investigation was undertaken on wheat bread baked by traditional method. Its aim was to investigate the effect of moisture sorption on the thickness of the crunchy layer on the bread surface. This was made by crushing this layer by a standard penetrating tool shown in Fig. 4, moving with the speed of 1 mm/s. The registered AE bursts of short duration were analyzed in time and frequency domain using the wavelet signal analysis. According to the theory presented in [12], the registered signal can be represented by a series of coefficients. These coefficients summarize the whole signal information. The series can be derived using a family of wavelet functions:

$$\Psi_{mn}(t) = a_0^{-m/2}\Psi(a - m_0\,t - n\,b_0),$$

where $\Psi(t)$ denotes a wavelet mother function of oscillating shape and of short duration. This function generates the family $\Psi_{mn}(t)$ covering the entire time-frequency domain, a_0 – scale factor, b_0 – translation factor, m, n – integer numbers.

The idea of discrete waveform decomposition applied by us was realized by the determination of scalar products of the set of signal samples $f(k\,t_0)$ and the family Ψ_{mn}. The parameter m denotes the current moment of the signal processing, while the parameter n represents the current frequency band of the signal processing. The determined set of values constitutes the discrete wavelet transform of the analyzed signal. So wavelet decomposition process can be understood as digital filtering in frequency domain. Typical outlook of the wavelet function *symlet8* [13] is shown in Fig. 5, while its filtering properties are presented in Fig. 6. For practical reasons (to make decomposition algorithm faster in execution), we applied the simplified form of the wavelet function. Its base form consisted of two harmonic components, 8 elements in each one. To perform the filtering using the sine and cosine functions both components were phase shifted by $\pi/2$. Both components, generated in form of third order (i.e. of 20 elements), are shown in Fig. 7.

The following assumptions were taken for the software applied for the investigation: $a_0 = 1.5$, the signal sampling frequency $f_0 = 44.1\,\mathrm{kHz}$, scale factor a to resample of the stored signal ($f_0 \cdot 3$, thus $a = 3$), time domain

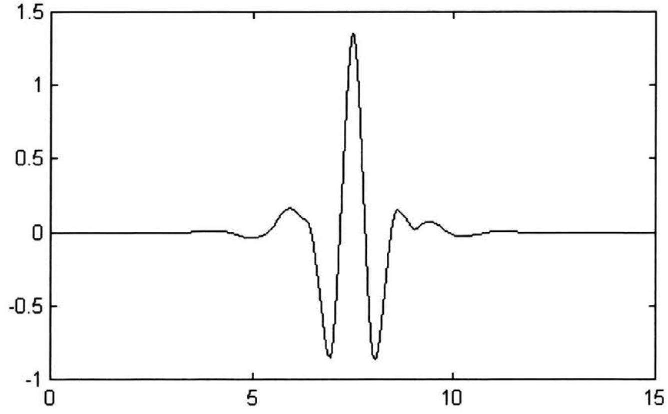


FIGURE 5. The typical view of the wavelet in time domain (symlet8).

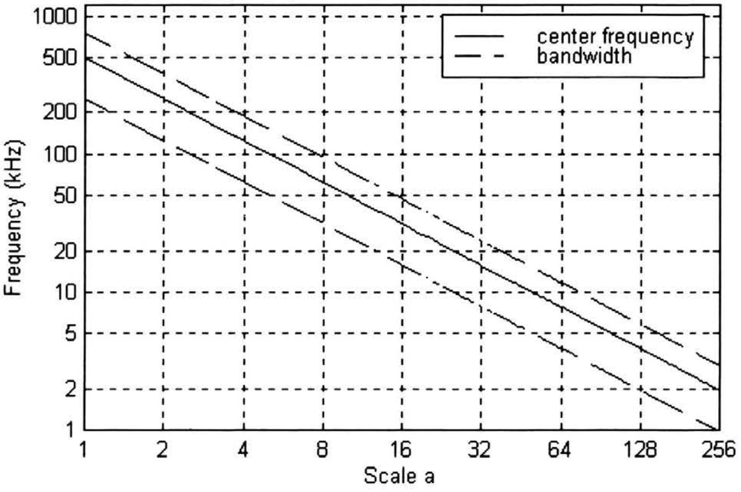


FIGURE 6. The filtering properties of the wavelet symlet8 shown in frequency domain.

resolution of the performed decomposition $m = 12.5\,\mathrm{ms}$, number of decomposition levels $\sum n = 300$, total number of analyzed moments $\sum m = 1600$.

Statistical analysis. Data presented in this paper was analyzed statistically. The analysis of variance and parametric tests (t-Student, Tukey's test) were used at the probability level 95%. Software Excel v.7 and SPSS v.10.1 for Windows were used in the statistical analysis.

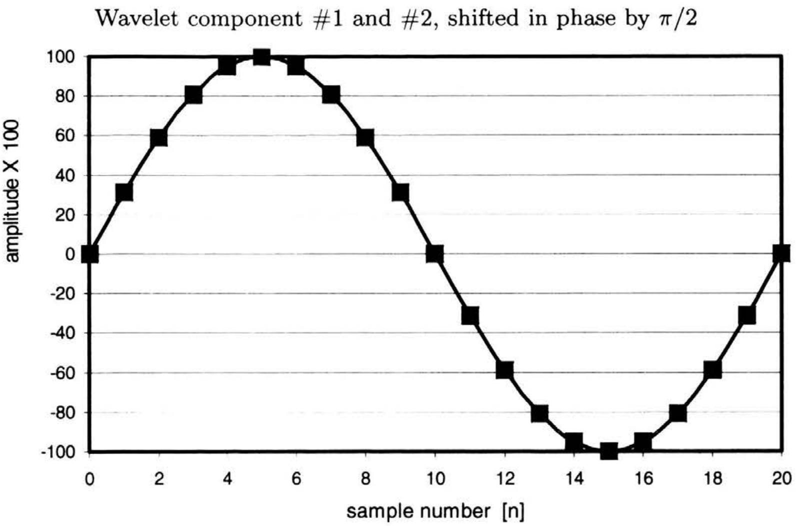


FIGURE 7. Wavelet components used to decompose signals, shown as generated at the order $o = 3$ (i.e. consisting of $n = 20$ elements; $n = 8 + o \cdot 4$).

6. Results and discussion

Extruded flat bread. The water activity influence on the AE signal energy was registered during breaking of samples made of wheat and rye bread. Breaking test was done in 10 replicates and spread of points did not exceed 5% of measured average value. The results (Fig. 8) show that the water activity strongly affects registered AE signal. The higher the water activity the lower the AE signal energy is observed. The relationship is not significantly dependent on the kind of extruded bread tested.

At the water activity 0.037 of the wheat bread the AE signal was equal to 3520 units and the increase of a_w to 0.530 caused 3.3-fold decrease of the signal. For the rye bread the AE signal decreased, in the same water activity range, 4-fold starting from 3392 units. At $a_w = 0.75$ the AE signal was weak and for the wheat bread was equal to 839 units. For the rye bread the signal was 4 times as low as that for the wheat bread.

The water activity affects significantly the amplitude – time relationship. Both rye and wheat extruded bread showed the largest amplitude at the lowest water activity investigated. The amplitude for wheat bread was 1.92 mV, and for the rye bread it was 1.36 mV. The increase of water activity resulted in the decrease of the amplitude (Figs. 9 and 10), and at $a_w = 0.75$ both the rye and wheat breads were "silent".

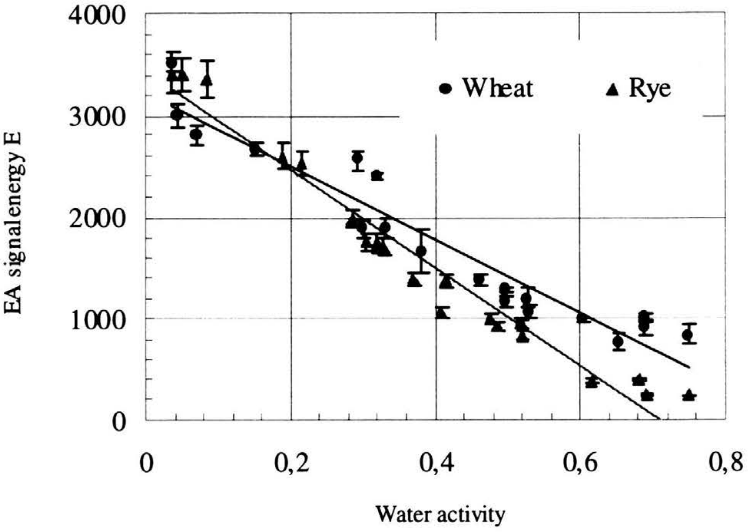


FIGURE 8. Relationship between AE signal energy and water activity.

Effect of water activity on the AE signal is probably related to the spatial distribution of the mechanical stress in investigated samples. In dry samples the walls of pores are stiff and under large mechanical stress, which was incurred to the material during the extrusion and expansion process. Increase in content of water enables macromolecule mobility and relaxation of the stress. Hence, during the bending process the walls of pores break with low acoustic emission because most of the stress was already relaxed.

Spectral density of emitted AE signals, regardless of the type of investigated bread, was strongly affected by the water activity. Figures 11 and 12 illustrate the calculated spectral density function for wheat and rye bread specimens tested at low and high level of the water activity. The power spectrum density is presented in the logarithmic scale (decibels), referred to 1 mV standard source signal. The regions of high power level (1-3 kHz and 10-15 kHz) of AE signal can be noticed here. This can be caused by the resonant abilities of vibrating system, including a specimen, and loading machine traverse and AE sensor. However, it is worth noting that during the loading of specimens containing more water the power spectrum function includes significant increase of high frequency components. It is possible that the specimen with higher water activity represents the AE source less powerful as the dry specimen but propagation of high frequencies is less damped when the water content is increased. Such effect could explain the increase of partition power spectrum slope – β coefficient in accordance with sample

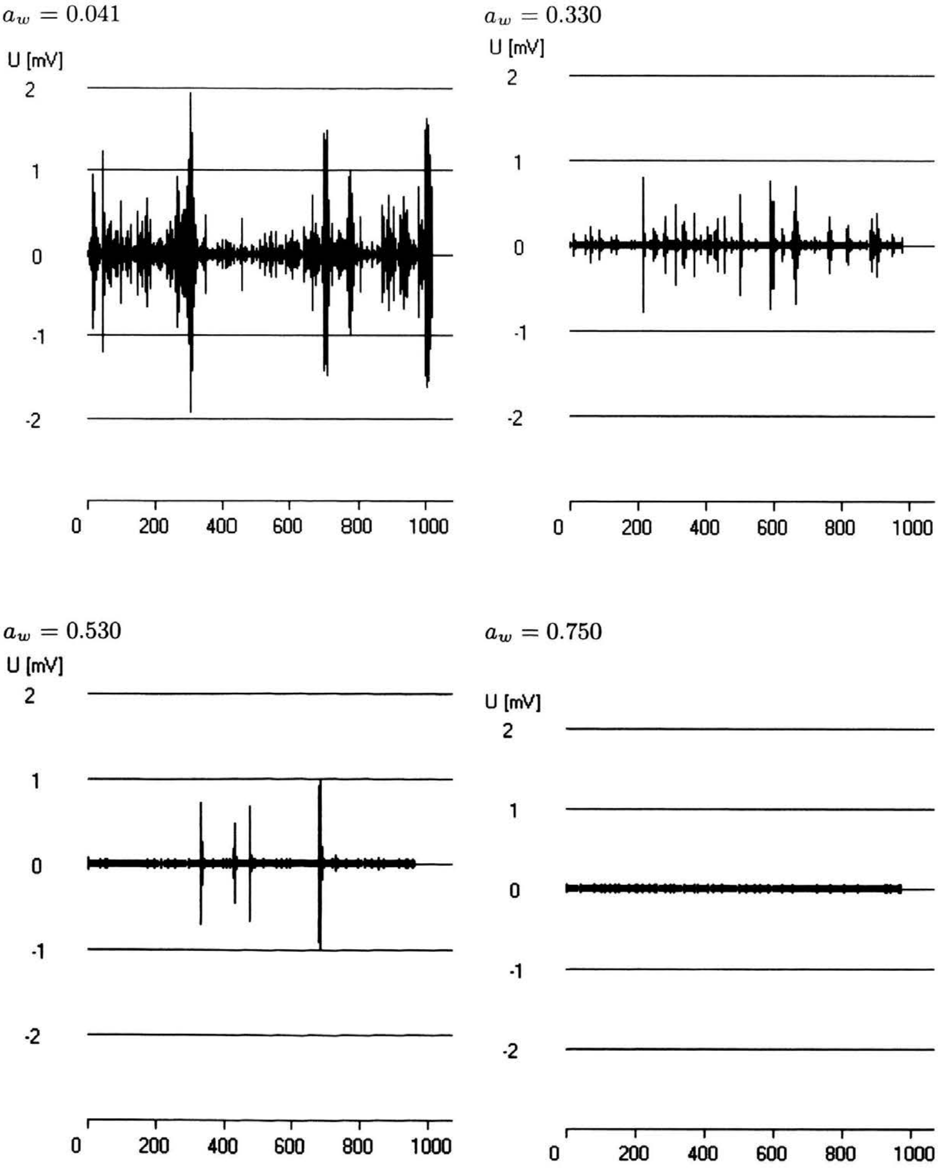


FIGURE 9. Relationship between amplitude and time for extruded wheat bread broken at different water activities shown in fragments of acoustic signal records (all horizontal axes – time in milliseconds).

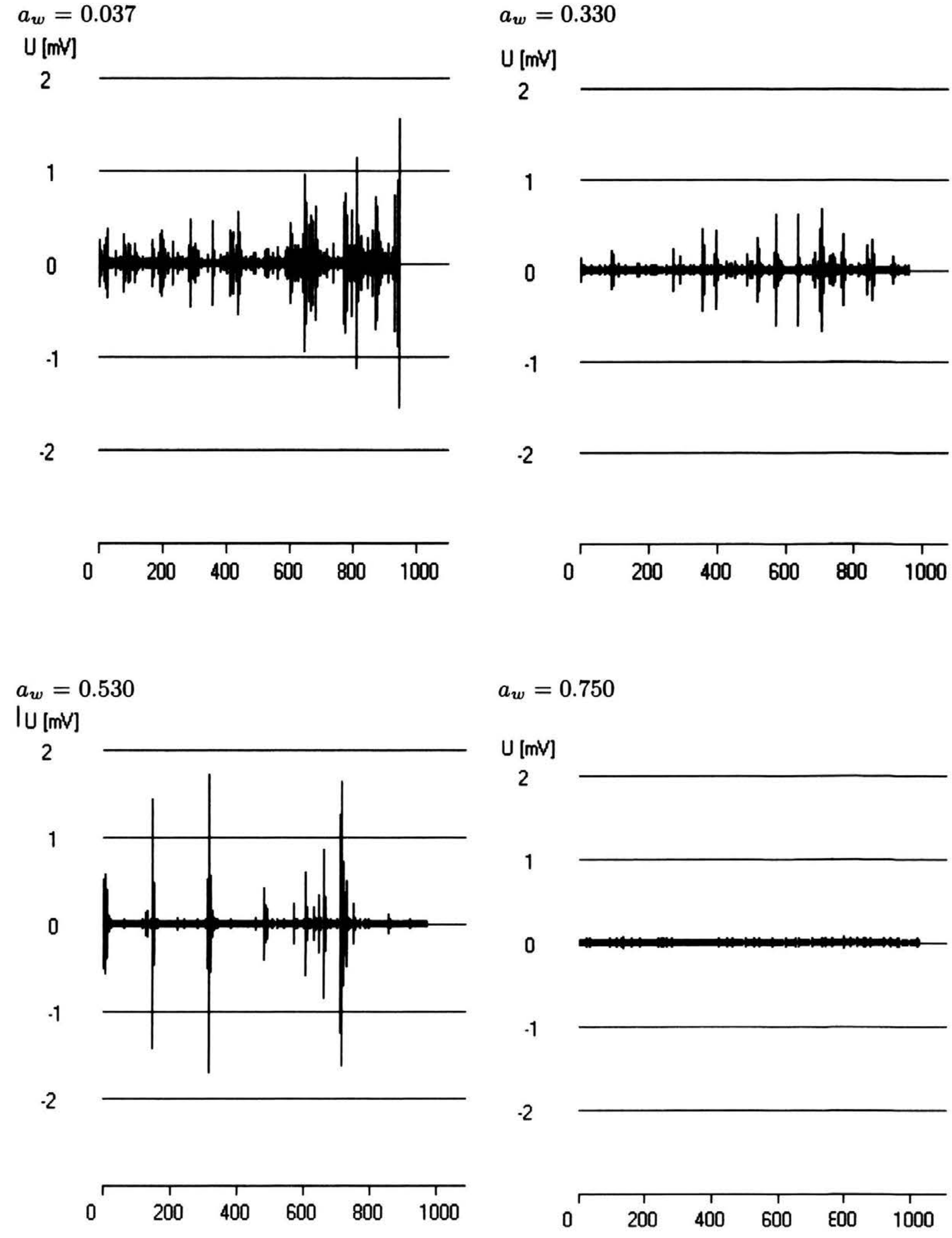


FIGURE 10. Relationship between amplitude and time for extruded rye bread broken at different water activities shown in fragments of acoustic signal records (all horizontal axes – time in milliseconds).

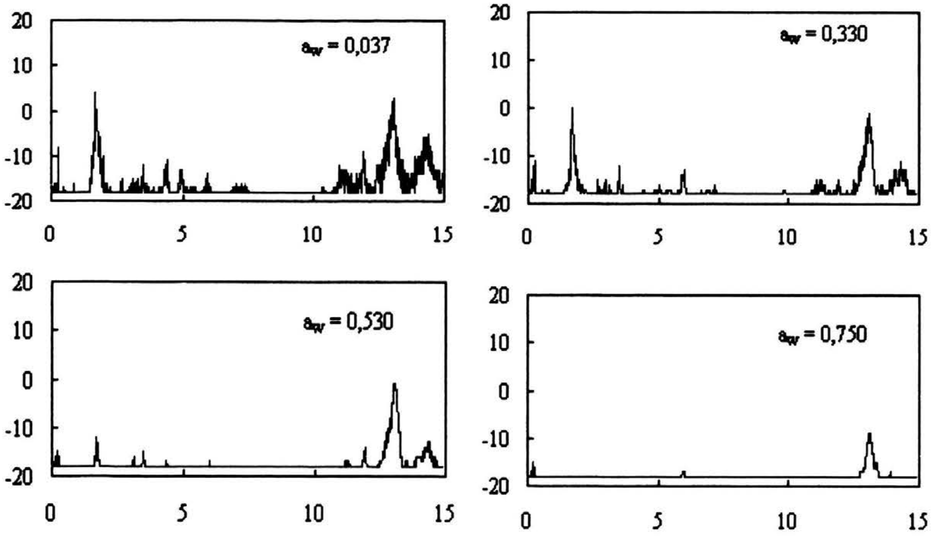


FIGURE 11. Spectral characteristics of emitted AE signal of samples of wheat bread at different a_w (vertical axes – AE signal energy [dB], horizontal axes – frequency [kHz]).

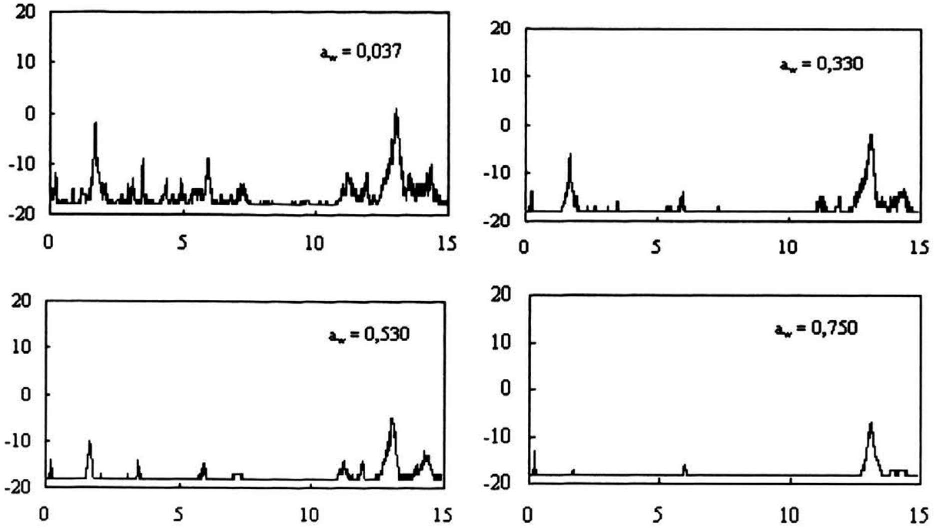


FIGURE 12. Spectral characteristics of emitted AE signal of samples of rye bread at different a_w (vertical axes – AE signal energy [dB], horizontal axes – frequency [kHz]).

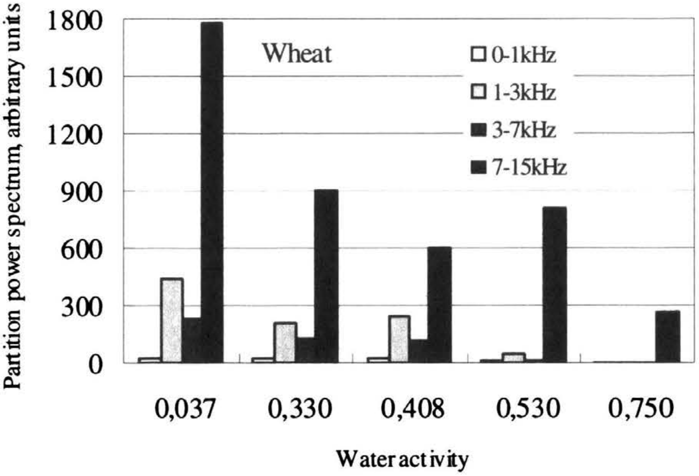


FIGURE 13. Relationship between partition power spectrum and water activity of wheat bread.

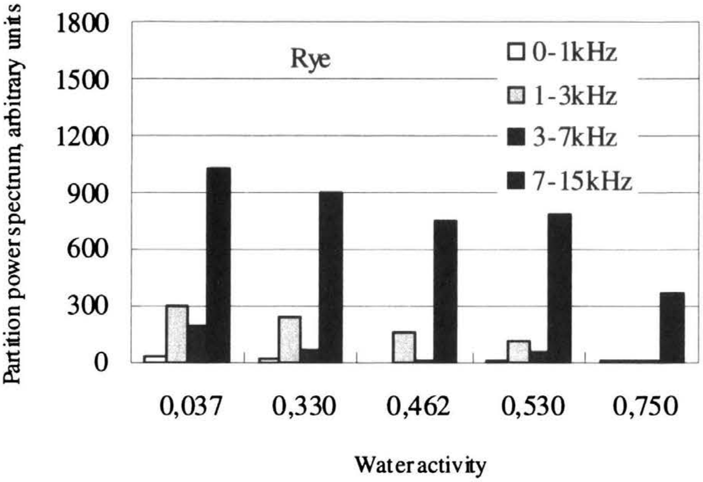
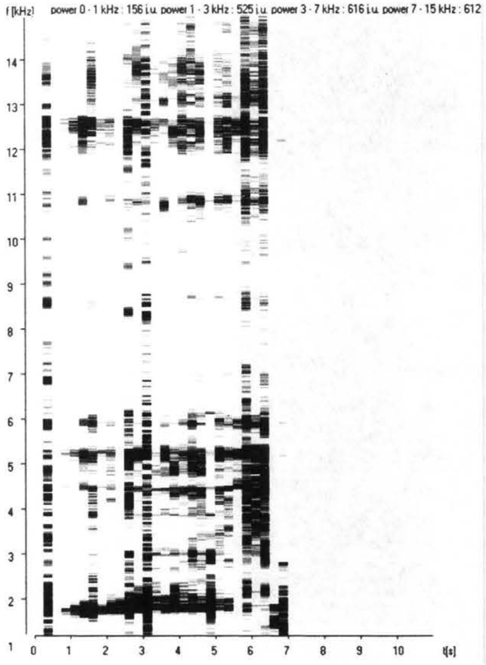


FIGURE 14. Relationship between partition power spectrum and water activity of rye bread.

$a_w = 0.037$



$a_w = 0.750$

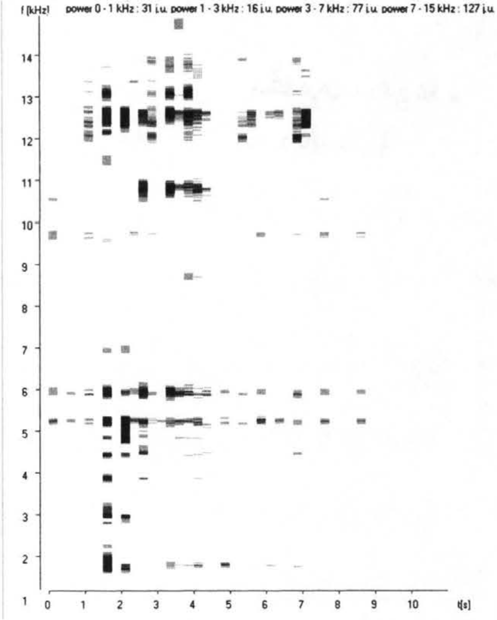
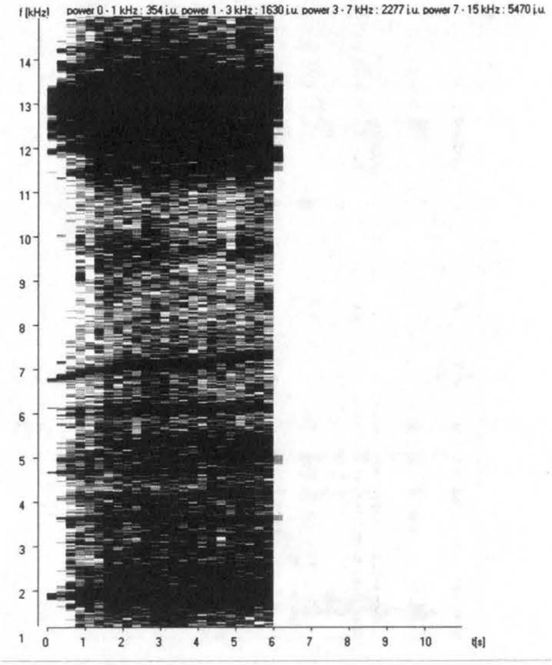


FIGURE 15. Acoustic activity of wheat bread sample recorded during bending-breaking test.

$a_w = 0.037$



$a_w = 0.750$

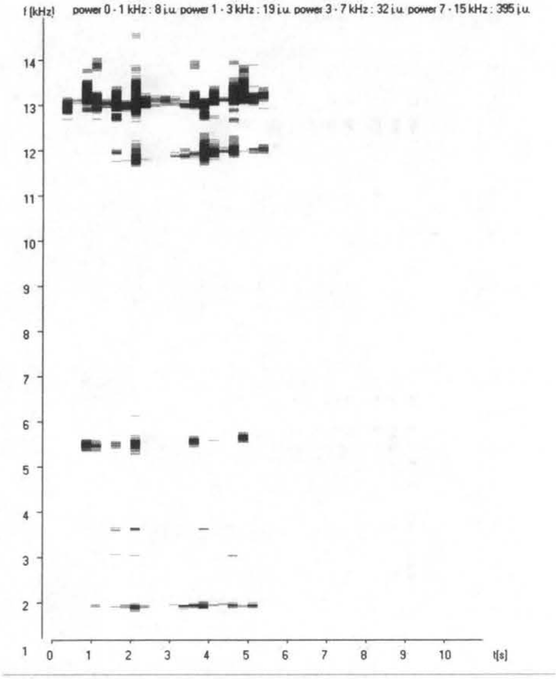


FIGURE 16. Acoustic activity of wheat bread sample recorded during compression test.

moisture content increase. This trend can be more precisely seen in Figs. 13 and 14 where the AE signal spectral power is shown in relation to both the water activity and chosen frequency region.

TABLE 1. Partition power spectrum slope versus water activity measured for wheat and rye bread samples.

	Dry samples ($a_w = 0.037$)	Moist samples ($a_w = 0.750$)
Bending	3 ± 2	35 ± 10
Compression	4 ± 2	48 ± 5

It is interesting to compare the spectral characteristics of the AE signal generated during bending-breaking test and compression of flat bread. The partition power spectrum slope (Table 1) is statistically not dependent on the applied test, however it was strongly related to the water activity. At the water activities lower than 0.5 the coefficient β was not dependent on the moisture content of the sample. Above $a_w = 0.5$ the β coefficient increases with the increase of the water activity.

Figures 15 and 16 present the acoustograms of wheat and rye samples under compression and bending tests. It is evident that the acoustic emission occurs in two frequency regions. The high frequency region is more active than the low frequencies one.

Besides, the samples undergoing compression are more active than the samples bent and broken.

7. Investigation on fresh wheat traditionally baked bread

Penetration and breaking of the surface of the loaf of bread emitted acoustic signal bursts with a maximum at the frequency of 250 Hz. The wavelet decomposition of the AE signal showed that the surface layer which emits acoustic signal has the thickness of 200 μm (Fig. 17). Negligible AE signals were generated when the penetrating tool entered the breadcrumb. Bread stored at the relative humidity of 20% and 40% for 7 days was staled. Its surface crunchy layer was lost and the breadcrumb became acoustically active when stored at dry conditions (Fig. 19a). Thickness of the remaining crunchy surface layer was about 70 μm thick when bread was stored at moist conditions (Fig. 19b).

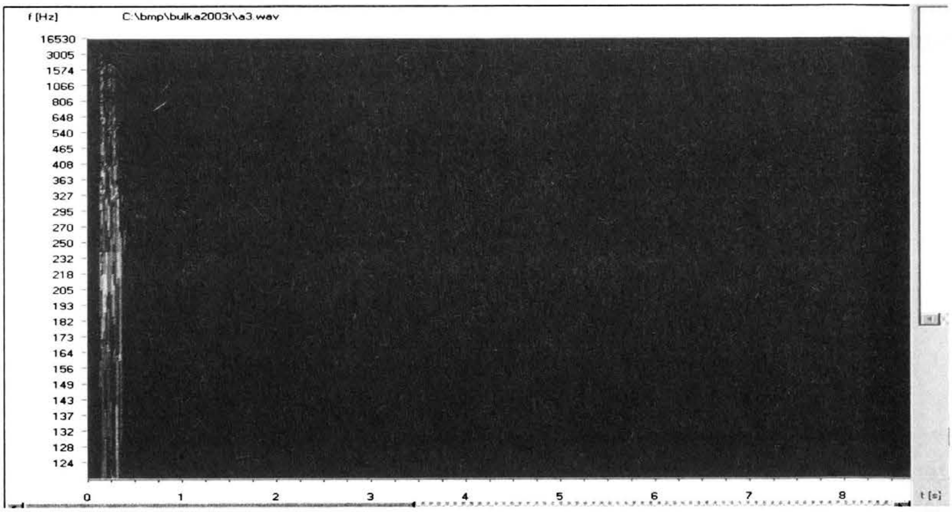


FIGURE 17. Wavelet decomposition of the AE signal recorded during penetration of fresh wheat bread.

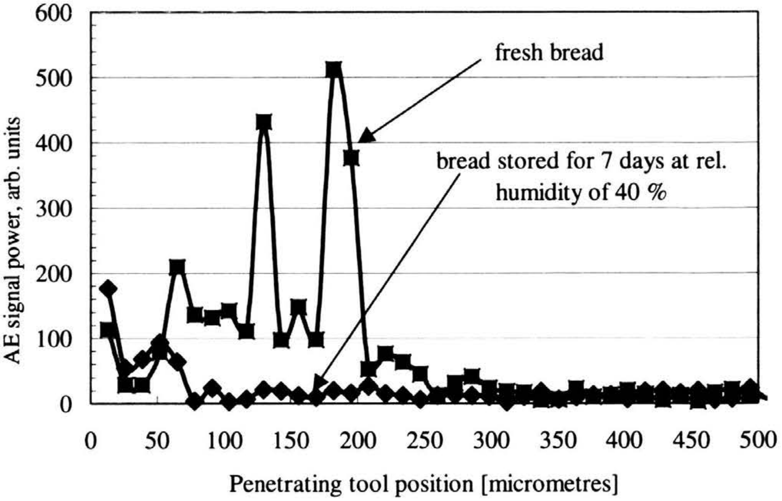
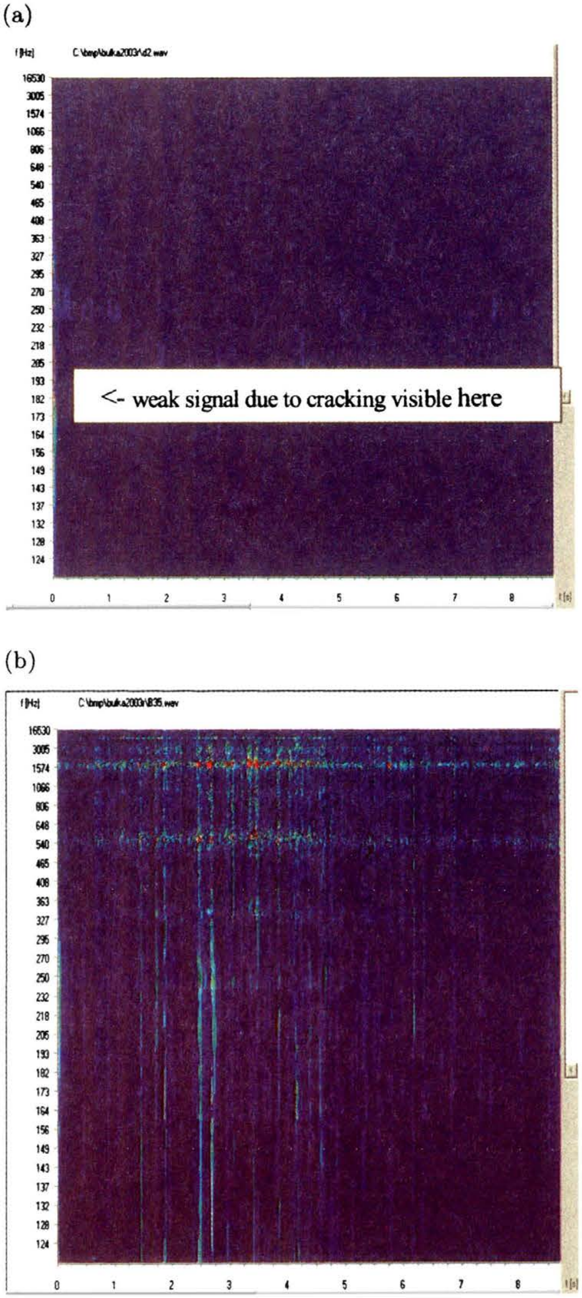


FIGURE 18. AE signal power at center frequency of 250 Hz in relation to the position of the penetrating tool in loaf of wheat bread.



<- weak signal due to cracking visible here

FIGURE 19. Wavelet decomposition of AE signal recorded during penetration of a wheat bread stored for 7 days in desiccator at the relative humidity of 40% (a) and stored for 7 days at the relative humidity of 20% (b). Acoustic emission activity of breadcrumb visible in (b) and weak acoustic activity of surface layer visible in (a).

8. Final remarks

In extruded flat bread samples the AE signal activity presented characteristic frequency regions of increased power (1-3 kHz) and (>7 kHz). With water activity increase there was faster energy loss in the lower frequency region than in the higher frequency region.

The experimental results have also shown that the >7 kHz frequency region became dominant in registered AE signal for the specimens with the water activity level higher than 0.50. In authors' opinion the presented data confirm that changes of moisture content of extruded flat bread specimen cause a significant change in the distribution of power spectrum function of emitted acoustic emission signal. Therefore, the coefficient β describing those changes can be applied as a quality measure of investigated flat product. The processes of moisture sorption can be also monitored using the acoustic methods of testing.

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