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# Influence of water activity on acoustic emission of flat extruded bread

Agata Marzec [a], Piotr P. Lewicki [a,*], Zbigniew Ranachowski [b]

[a] Department of Food Engineering and Process Management, Warsaw Agricultural University (SGGW), Nowoursynowska 159c, 02-776 Warszawa, Poland

[b] Institute of Fundamental Technological Research, Polish Academy of Sciences Świętokrzyska 21, 00-049 Warszawa, Poland

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**Abstract**

Flat extruded wheat bread and rye bread were subjected to three-point breaking test with simultaneous registration of generated vibrations. Piezoelectric sensor was used to detect vibrations and amplitude–time records were analyzed. It was found that breaking of flat extruded bread generated vibrations in whole audible spectrum. Acoustic emission signal energy expressed in arbitrary units was more dependent on water activity in low frequencies region than those in high frequencies. Transformation of amplitude–time records from time domain to frequency domain showed that regions with high level of power spectrum occurred. Dominating power spectra were in 1–3 and 7–15 kHz. It was proposed to use a ratio between those power spectra as a measure of acoustic activity of the investigated material. This descriptor was called partition power spectrum slope–$\beta$. The slope was doubled in the water activity range 0–0.5 and at higher water activities it increased sharply with increasing wetness of the material.

Special software was developed to analyze amplitude–time records and detect single acoustic emission events. Majority of acoustic emission events lasted 68.1 μs, and their energy statistically was not dependent on water activity. However, number of acoustic emission events depended strongly on water activity and decreased almost 20 fold in the $a_w$ range from 0.03 to 0.75.

Analysis of acoustic activity of extruded breads in both time and frequency domains suggested that it originated from simultaneous disintegration and structure microdislocations. Breaking of air cell walls caused large displacements and generated vibrations with low frequencies. Deformation of substructures, splitting of fibers, vibrations and dislocations of macromolecules in the network of the solid matrix could be responsible for generation of high frequency vibrations. It was also noted that both breads were alike when acoustic emission was analyzed in frequency domain, but they were different in the time domain. Combining both frequency and time domains showed that the breads, from the acoustic point of view, are different.



*Keywords:* Spectral characteristics; Acoustic event; Acoustic signal energy; Acoustogram; Wheat bread; Rye bread

## 1. Introduction

Heterogeneous distribution of internal energy is characteristic for each product, especially for extruded materials. The spatial distribution of the internal energy can be influenced by the external stresses such as force, chemical reaction, temperature change, or by internal strains. Under this situation, a part of accumulated internal energy is released as an elastic waves, which propagate to the surface of the material (Malecki & Opilski, 1994), at which they can be detected. Elastic waves cause vibration of the surrounding air and a sound pressure is produced. Hence, acoustic emission (AE) is understood as a process of generation and propagation of elastic waves produced by sudden release of internal energy accumulated at a point of investigated material (Witos, 1994).

The human ear is extremely sensitive as far as amplitude, frequency and duration of the sound are considered. It is

* Corresponding author. Tel.: +48 22 5937560; fax: +48 22 5937576.
*E-mail address:* lewicki@sggw.waw.pl (P.P. Lewicki).

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accepted that the lowest detectable frequency is 16 Hz, and the upper limit depends on the age of a man. For children it is 20 kHz, and for adults is not more than 16 kHz (Ozimek, 2002). Sound percept by the human ear is precisely analyzed, and the result of this analysis decides about the consumer judgment of feelings associated with eating and biting of food. Thus, materials emitting sounds expected by a consumer are considered as attractive and those sounds are regarded as signs of freshness and propriety of processing. Crunchiness and crispness are the sensory attributes arising from the reaction of senses to mechanical disintegration accompanied by acoustic emission. Acoustic wave generated during disintegration of food in the course of eating is conducted by air, bones and soft tissue. The sound wave conducted by air reaches the ear and through auditory canal gets to eardrum and is transported to the inner ear. Mandibular bones transmit the sound directly to the inner ear (Ozimek, 2002). Soft tissues of cheeks and tongue have dampening effect on sound produced during mastication of food. Hence, the respective contribution of both air and bone conduction to the percept sound is important, especially when chewing is done with a closed mouth.

It is often stated that eating stimulates all five senses, that is taste, smell, vision, touch and hearing. Role of the first four in perception of quality of food is well documented, but the sound generated during mastication has not been a subject of thorough studies. Although there are no comparative studies considering sensation of taste, touch and appearance of crunchy products they role in appreciation of the product quality can be estimated. Supplementation of this analysis with acoustic sensations accompanying eating can bring about better understanding of consumer perception of crunchiness and crispness of snack foods. Moreover, analysis of acoustic emission associated with mechanical testing can result in rational correlation between composition, structure and texture of the food.

The role of sound in food quality assessment was first recognized by Drake (1963), who showed that sounds generated during breaking of food differ by amplitude, frequency and pitch. Drake (1963) suggested that sound and vibrations accompanying mastication can be used to supplement sensory analysis of food. In further studies (Drake, 1965) it was shown that amplitude of eating sounds was well correlated with sensory perception of loudness of crunchy products. Vickers and Bourne (1976a, 1976b) found that food yields characteristic acoustic profile during eating and suggested that amplitude of generated sounds is the most salient dimension of crispness. Crunchy and crispy foods emitted sounds, the acoustic energy of which was in the frequency range 0–10 kHz. Each product has had its own frequency pattern but the most interesting were those frequency ranges, which were present in all sounds emitted by crunchy products. Terminology of texture includes many descriptions such as crispness, crunchiness, brittleness, hardness, etc., which are related to sound percept during biting and mastication (Surmacka-Szczesniak, 2002). Dry foods were divided into crunchy, crispy and crackly according to the spectral characteristics of sounds emitted during biting. Crispy foods generate high pitched sounds with frequencies higher than 5 kHz, crunchy foods yield low pitched sounds with a characteristic peak on frequency range 1.25–2 kHz, and cruckly foods emit low pitched sounds with a high level of bone conduction (Dacremont, 1995).

Tesch, Normand, and Peleg (1996) studied the effect of water activity on mechanical and acoustic properties of two crunchy foods. At water activities higher than 0.65 acoustic emission decreased so much that the product became ''silent'', this effect was accompanied by smoothing of the stress–strain relationship. Moreover it was shown that plasticizing effect of water on the analyzed products could be demonstrated by mechanical (fracture force, Young's modulus) or acoustic (maximum amplitude) variables studied (Tesch et al., 1996).

Numerous authors investigated the effect of water content or water activity on acoustic properties of cereal products (Dacremont, 1995; Duizer, Campanella, & Barnes, 1998; Roudaut, Dacremont, & Le Meste, 1998; Tesch et al., 1996; Wollny & Peleg, 1994) and showed that the intensity of emitted sound was strongly related to moistness of the material. Recordings of the sound emitted during biting or mastication of food were done either by the use of microphone in a soundproof room (Alchakra, Allaf, & Ville, 1997; Dacremont, 1995; Juodeikiene & Basinskiene, 2003; Liu & Tan, 1999; Seymour & Hamann, 1988; Vickers & Bourne, 1976b) or by placing contact microphone on the cheek close to the ear (Duizer et al., 1998) or on the mastoid bone behind the ear pavilion (Dacremont, 1995).

Amplitude–time plots recorded during the experiment were used to characterize acoustic properties of the material. Different acoustic parameters were used as a measure of crispness, crunchiness or crackliness of food. Drake (1965) and Kapur (1971) used amplitude of acoustic waves while Edmister and Vickers (1985) used mean height of peaks or number of sound bursts. Alchakra, Allaf, and Jemai (1996) Mohamed, Jowitt, and Brennan (1982) used acoustic energy to characterize sounds emitted by food. Seymour and Hamann (1988) used mean sound pressure or acoustic intensity, while Dacremont (1995), Lee, Deibel, Glembin, and Munday (1988) used Fast Fourier Analysis to determine frequencies most evident during biting and chewing. Fractal analysis has been used by Tesch et al. (1996) and Duizer et al. (1998).

Above presented information shows that there is no straightforward method to analyze and describe sounds generated during biting and chewing of crunchy foods, and there are methodological differences in the detection, recording and analysis of emitted sound.

The aim of this work was to investigate vibrations generated during mechanical breaking of flat extruded bread in the audible frequency range and to analyze it in relation to water activity of the material. It was assumed that detection of vibrations by a direct contact of a sensor with the sample simulates process of biting and bone conduction of the sound.

## 2. Materials and methods

Extruded flat bread samples taken directly from the production line were removed from the retail packages and stored in desiccators over solutions with specified relative humidity in the range from 0% to 75% (sulfuric acid and saturated salt solutions) for three months at 25 °C. Specimens were taken from desiccators at specified time and their water content and water activity were measured.

Moisture content of the extruded bread specimens was measured before and after the storage period according to Polish Standard PN-84/A-86361. Water activity ($a_w$) was measured using the Higroscope DT 2 (Rotronic AG) of accuracy ±0.001 of $a_w$ unit at 25 °C.

Slices of extruded flat bread with dimensions 120 × 55 × 7 mm were subjected to a three-point-breaking test done in a silent Zwick 1445 loading machine. The loading was performed at the constant head speed of 20 mm/min. An accelerometric sensor, Brüel & Kjaer 4381 V was mounted near the lower end of the upper head of loading machine to achieve an acoustic contact with the bread sample. The AE sensor was capable to register the acoustic signal at a frequency range from 0.1 Hz to 15 kHz. The sensor was not registering vibrations conducted by air. 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. Program Wave Studio (Creative Labs.) was used to register the AE signal. A special uniformity test, including 0.5-mm pencil HB break was applied to keep the sensitivity control of the AE signal.

### 2.1. Acoustic emission signal energy

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 execution of taking a sample. Hence, $v(mT_1)$ was here understood as an 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

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

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 water activity.

### 2.2. Single acoustic emission event

The amplitude–time records of vibrations generated during breaking of flat extruded bread were analyzed with specially developed software and parameters of a single AE event were estimated. Sampling frequency was 22.7 μs. The AE event duration was measured as a time period in which the signal level was greater than the average noise level. A procedure used to detect the beginning of the AE event summed up the signal readings (in volts) in each 68.1 μs of the record. A threshold level, equal to 5% of the average energy of the AE event, was applied, which recognized the occurrence of the AE event. The end of the AE event was also registered when sum of signal readings per 68.1 μs or more declined under the threshold level. To avoid repeated recognition of the same AE signal a record of 68.1 μs duration, after the AE event was ended, was not analyzed. The following parameters were calculated after detection of the occurrence of the AE event:

- number of events,
- energy of the AE event.

### 2.3. Spectral processing of recorded AE signal

The continuous AE signal was, in frequency domain, characterised by a specific attribute of emitted sound—a shape of its power spectrum. $A(\omega)$ was the power spectrum function in which $\omega$ is a linear analogue of frequency $f$, $\omega = 2\pi f$. A computer procedure was used to derive a discrete image of $A(\omega)$. If $v(t)$ was absolutely integrable, it could be associated with its spectral density function $A(\omega)$ using a Fourier transform

$$v(t) = \frac{1}{\pi} \int_0^\infty A(\omega) \sin[\omega t + \phi(\omega)] \mathrm{d}\omega, \tag{2}$$

where $\varphi$ is an argument representing a phase of transformed signal.

The procedure analysed recorded AE signal samples in time windows 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 their power spectrum function keeping the same phase of each burst at the transformation process. This algorithm called, "event filtering" enabled to suppress the random noise accompanying the recorded signal. As the result for each time section the procedure produced a series of coefficients $c_n$ and each of them represented AE signal power in frequency range of 11 Hz. The whole series of $c_n$ covered the desired spectral range of 1–15 kHz. The recorded time-dependent AE signal $v(t)$ of each recording was converted into a vector of digital samples where $T_1$ is an inverse of a sampling frequency. The algorithm performing the transformation from time domain to frequency domain $v(mT_1) \Rightarrow c_n(\omega)$ was based on the following approximated formula:

$$c_n \approx \frac{1}{N} \sum_{m=0}^{N-1} v(m \cdot T_1) \cdot \mathrm{mod}\left(\mathrm{e}^{\frac{jn2\pi m}{N}}\right), \tag{3}$$

where $j = \sqrt{-1}$, and $n$ was independent variable representing spectral coefficients in frequency domain.

It was found experimentally that there were two regions in frequency domain where the high level of power spectrum function was observed. These regions were 1–3 kHz and 7–15 kHz. Hence, the AE signal practical descriptor independent on the sample volume was proposed. This descriptor was called *partition power spectrum slope* ($\beta$) and was calculated as a ratio of AE signal power spectrum registered in the frequency range 7–15 kHz, labelled as $P_{7-15}$ and AE signal power registered in the frequency range 1–3 kHz, labelled as $P_{1-3}$.

$$P_{7-15} = \sum_{n \mapsto 7\ \text{kHz}}^{n \mapsto 15\ \text{kHz}} c_n, \quad P_{1-3} = \sum_{n \mapsto 1\ \text{kHz}}^{n \mapsto 3\ \text{kHz}} c_n, \quad (\beta) = \frac{P_{7-15}}{P_{1-3}}. \qquad (4)$$

### 2.4. Acustograms

Combining the AE signal in both time and frequency domains a relation between frequency, time and the AE signal energy was obtained. Colors represent the following acoustic signal energies: dark blue: 0 dB; blue: from −16 to −14 dB; light blue: from −14 to −10 dB; green: from −6 to −2 dB; yellow: from −2 to +2 dB; red: > +6 dB (in black

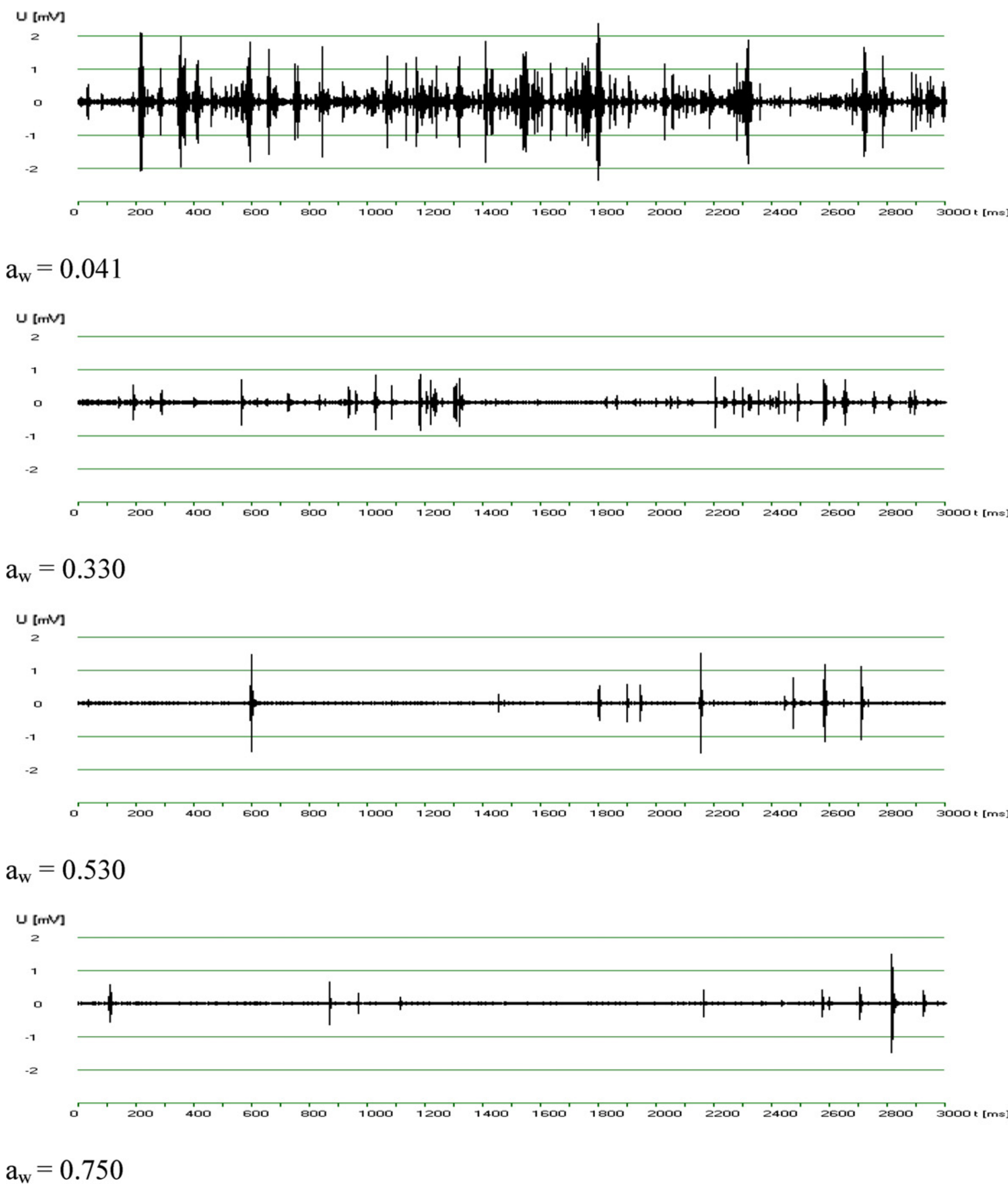


Fig. 1. Influence of water activity on relationship between amplitude of acoustic emission and time of breaking of flat extruded wheat bread.

and white: light gray is a background, the darker is the color the stronger is the acoustic signal).

## 3. Results

Acoustic emission of flat extruded bread subjected to three-point breaking test, was strongly affected by water activity of the sample. The amplitude–time curves presented in Figs. 1 and 2 showed that the amplitude was little dependent on water activity, while the number of acoustic events was strongly affected by the wetness of the material. At low water activities the average amplitude was large and was ±1.92 V and ±1.36 V for extruded wheat and rye bread, respectively. At water activity 0.530 the amplitude decreased to about ±1.00 V for both wheat and rye extruded bread. At water activity as high as 0.750 amplitudes lower than ±1 V were recorded. Analysis of the amplitude–time curves showed also that the background noise was small in comparison to the recorded vibration signals.

First three seconds of the AE signal presented in Figs. 1 and 2 showed that number of acoustic events is strongly dependent on water activity of the analyzed breads. Calculated number of sound bursts generated during one second of deformation in relation to water activity is presented in

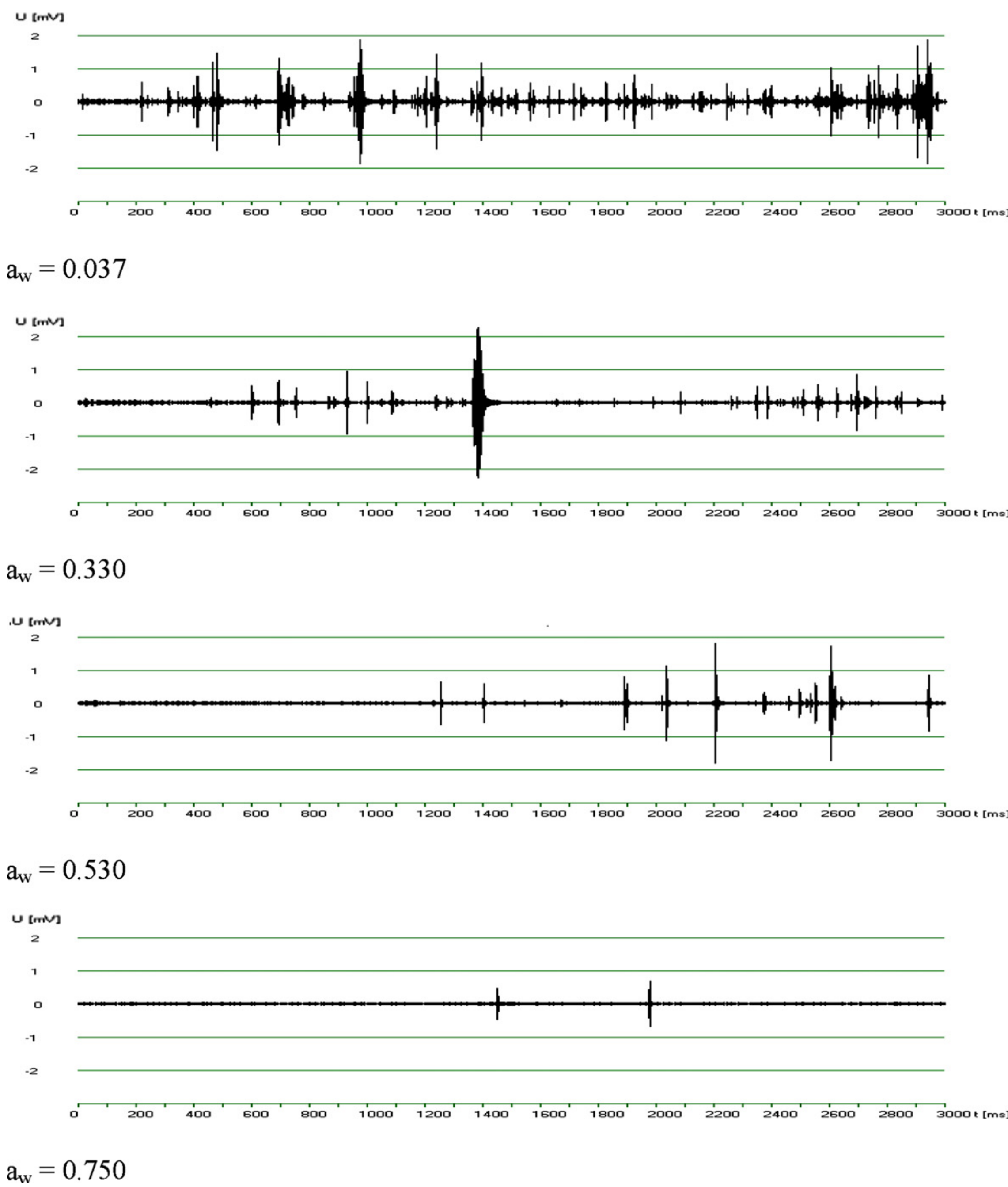


Fig. 2. Influence of water activity on relationship between amplitude of acoustic emission and time of breaking of flat extruded rye bread.

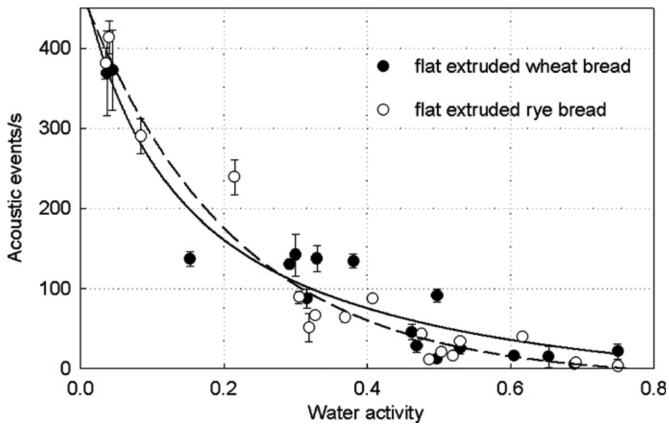


Fig. 3. Relationship between water activity and number of acoustic events generated during 1 s of breaking of flat extruded bread.

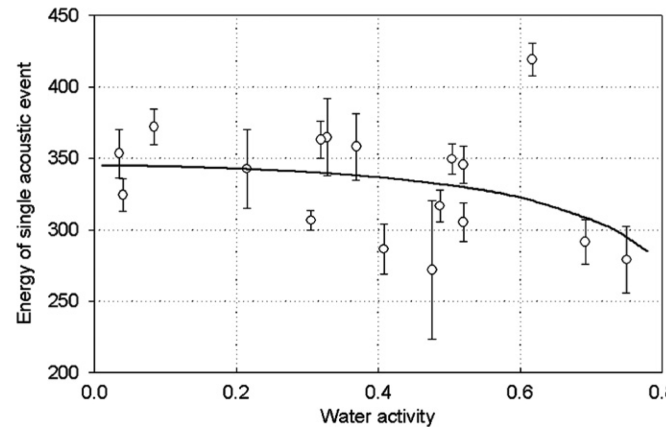


Fig. 5. Relationship between water activity and energy of single acoustic event generated during breaking of flat extruded rye bread.

Fig. 3. At low water activity flat extruded wheat bread generated 370 ± 53 sound events in each second of breaking test. Increasing water activity substantially decreased acoustic activity of the bread. At water activity close to 0.5 number of bursts was 40 ± 8 and at $a_w = 0.75$ it was 22 ± 9. The largest decrease of acoustic activity was observed at water activities lower than 0.3; the number of sound events per second dropped from 400 to 100. At higher water activities the decrease was much smaller, that was from 100 to about 25 sound bursts per second.

Flat extruded rye bread generated similar number of sound events per second as wheat bread. At low water activity it generated 380 ± 19 bursts/s during breaking. Increasing water activity decreased acoustic activity of the bread. At $a_w = 0.3$ it generated about 90 ± 8, at $a_w = 0.5$ about 25 ± 4 and at $a_w = 0.75$ some 3 ± 1 events/s.

Calculation of energy of one sound event showed that the energy was practically independent on water activity (Figs. 4 and 5). Energy of a single acoustic event showed a tendency to decrease with increasing water activity, especially at water activities higher than 0.4, but tendency was not statistically significant. Average signal energy of one sound event generated during breaking flat extruded wheat bread was 341.2 ± 27.3 and for the rye bread the equivalent value was (332.3 ± 17.8) V μs.

Taking energy of one sound event and number of events generated during the breaking test a total acoustic energy was calculated. Fig. 6 present total energy of acoustic events generated during 1 s of the breaking test. It decreased with water activity and the decrease was dependent on the kind of analyzed material. At water activity 0.75 the total energy of acoustic events accounted for 5.5% and 0.7% of the energy generated at low water activities in wheat and rye extruded bread, respectively. The decrease was not linear and strongest influence of water activity on the total energy of acoustic events was observed at water activities lower than 0.4.

Another descriptor of acoustic activity of investigated materials used in this work was acoustic emission signal energy expressed in arbitrary units. This descriptor also strongly depended on water activity (Fig. 7) and was the lower the higher was the water activity. Relationship was curvilinear and showed that extruded flat wheat bread acoustic activity was a little less dependent on water activity than that of rye bread. The slope at water activity 0.2 was −6000 and −4350 arbitrary units per unit of water activity for rye and wheat extruded bread, respectively.

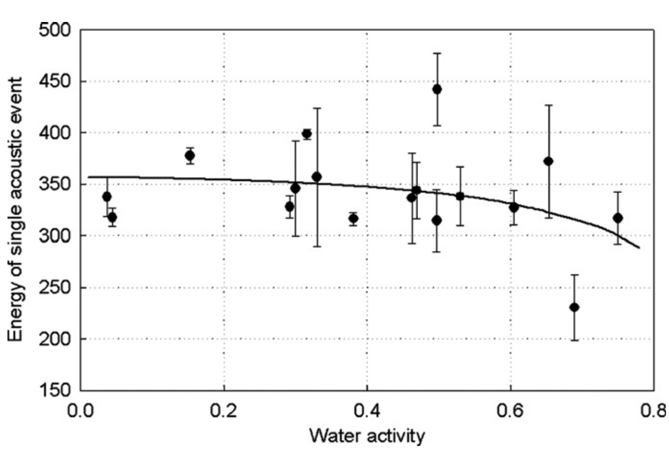


Fig. 4. Relationship between water activity and energy of single acoustic event generated during breaking of flat extruded wheat bread.

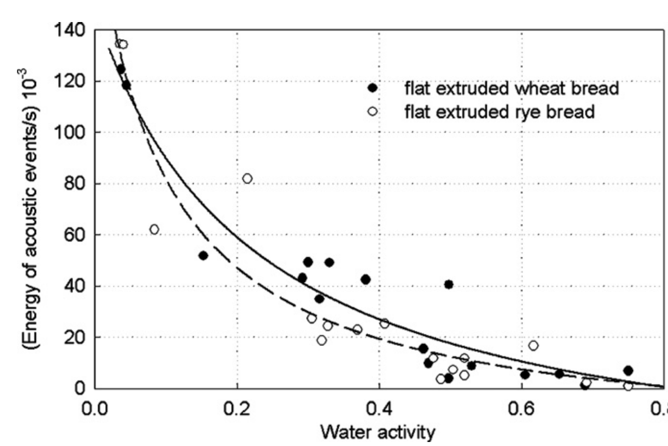


Fig. 6. Influence of water activity on total energy of acoustic events generated during 1 s of breaking of extruded flat bread.

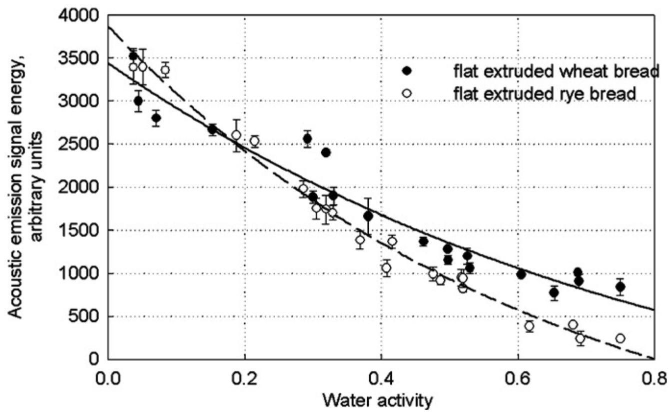


Fig. 7. Influence of water activity on acoustic emission signal energy generated during breaking of flat extruded bread.

Respective values at water activity 0.6 were −3300 and −2700.

Spectral characteristics of acoustic signal were analyzed on the basis of averaged relationship between amplitude and time for the breaking test. These characteristics are presented in Figs. 8 and 9 and evidence substantial influence of water activity on acoustic activity of extruded flat bread. Increasing water activity decreased the energy of emitted signals and ended up with a product, which could be considered as silent. It was interesting to note that the intensity of acoustic emission decreased with increasing water activity but the spectral characteristics was independent on that variable. Spectral density was high in two frequency domains that are between 1 and 7 kHz and 10 and 15 kHz.

To detect frequency domains with the highest acoustic activity the spectral characteristics was divided into four

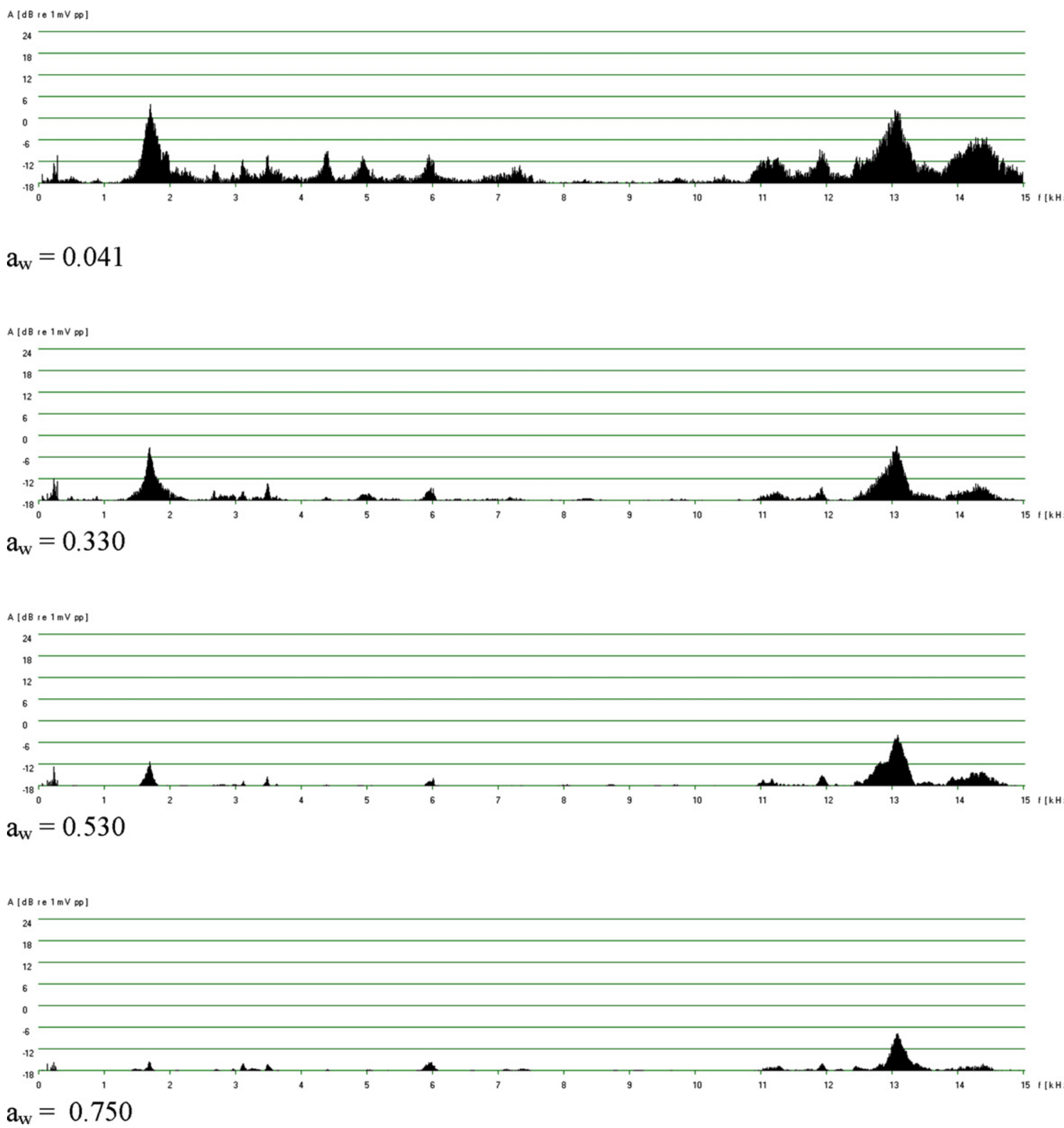


Fig. 8. Influence of water activity on spectral characteristics of flat extruded wheat bread. Vertical axis—sound intensity in dB, horizontal axis—frequency in kHz.

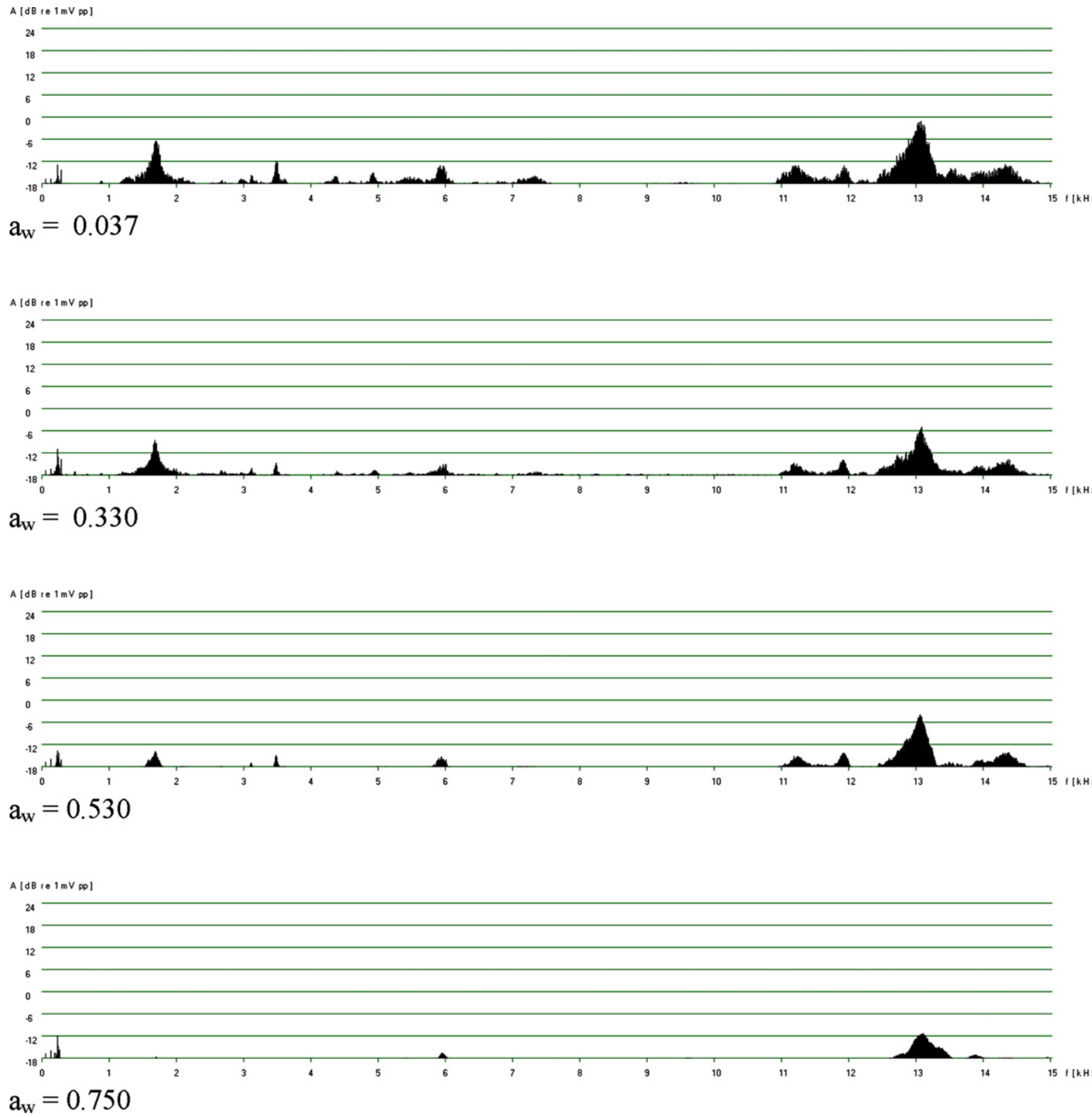


Fig. 9. Influence of water activity on spectral characteristics of flat extruded rye bread. Vertical axis—sound intensity in dB, horizontal axis—frequency in kHz.

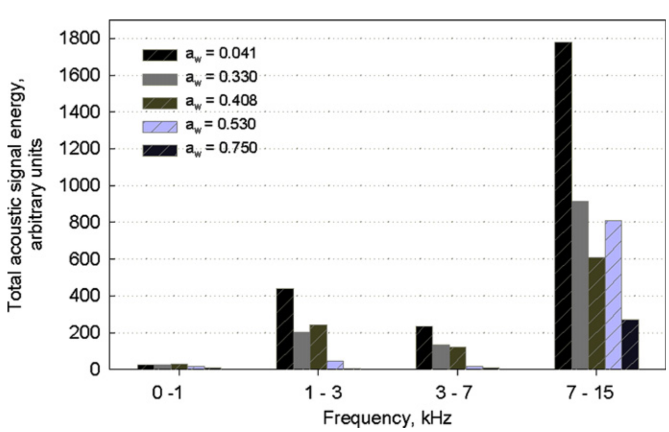


Fig. 10. Influence of water activity on total acoustic signal energy generated during breaking of flat extruded wheat bread at specified frequency ranges.

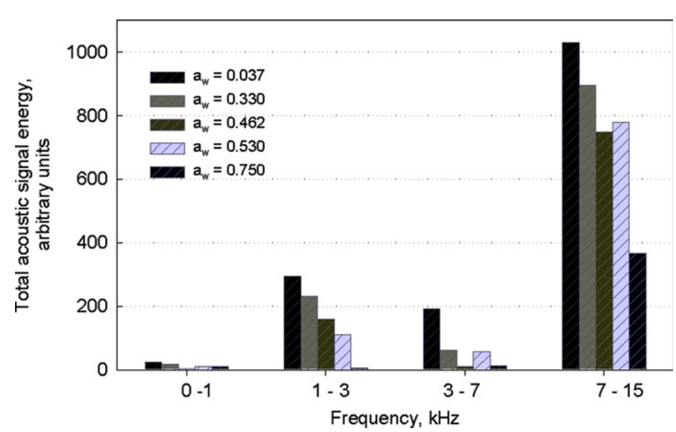


Fig. 11. Influence of water activity on total acoustic signal energy generated during breaking of flat extruded rye bread at specified frequency ranges.

sections with frequencies 0–1; 1–3; 3–7 and 7–15 kHz. For each section acoustic emission signal energy was calculated according to Eq. (3). Results are presented in Figs. 10 and 11. It was evident that two frequency domains were dominating in the spectral characteristics of acoustic signals emitted by flat extruded bread. Both wheat and rye bread showed highest acoustic emission signal energy in frequency regions 1–3 kHz and 7–15 kHz. Moreover, the analysis showed that both breads, independently on water activity, propagate preferentially acoustic signals with high frequencies. At water activity 0.03–0.04 acoustic emission signal energy accounted to 50% and 31% of total signal energy generated during breaking of the wheat and rye bread, respectively. At water activity 0.75 respective values were 35 and almost 100%.

It was suggested to use ratio of acoustic emission signal energy at the above-detected frequencies as an index of acoustic properties of the analyzed materials. The index was called partition power spectrum slope and its relation to water activity is presented in Fig. 12. In the range of water activities below 0.5 the partition power spectrum slope was almost doubled. Then in a narrow range of water activities it increased steeply, and at $a_w = 0.75$ it was 12 and 15 times larger than that observed at low water activities for wheat and rye bread, respectively. The partition power spectrum slope statistically was not dependent on the kind of investigated bread.

Analysis of spectral characteristics of emitted acoustic signal during breaking test showed that the acoustic intensity was dependent not only on water activity but also on time, or extent of deformation (Fig. 13). At low water activities the material subjected to the breaking test was acoustically active all the time. The signal in all frequency domains was emitted until the specimen was broken. With increasing water activity that property was fulfilled only in high frequency domain. In low frequency domains there were moments in which the material became silent. It mostly accounted for the first 1–1.5 s of deformation of flat extruded rye bread (Fig. 14). In wheat bread some acoustic activity in low frequency region occurred during the initial stages of deformation.

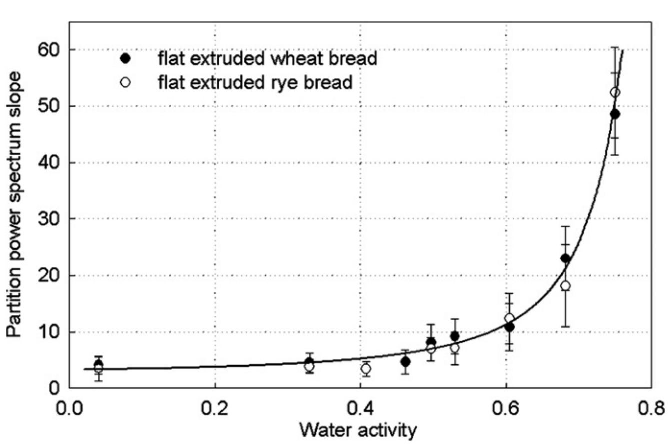


Fig. 12. Relationship between partition power spectrum slope and water activity.

## 4. Discussion

Flat extruded bread is a porous structure with numerous, irregular air cells. Due to extrusion process surface layer has a different structure than that of the interior. Surface layer of the slice, due to extrusion process, contains numerous small air cells with rather thick cell walls, while the interior is highly porous with large air cells and thins cell walls (Fig. 15). Bending of the slice caused stretching of the surface leaning on supports and compression of the surface pressed by plunger. Breaking of the air cell walls in both the upper and lower surface layers generated strong numerous vibrations. Hence, large amplitude and multiple sound bursts were detected. The resistance to deformation of the surface layers is different than that of the interior (Marzec & Lewicki, 2006).

Analysis of frequency characteristics showed that there were structures, which generated high frequency sounds during breaking. The sounds were generated during the whole breaking test and did not depend on water activity of the material as much as low frequency sounds. Hence, the mechanism of disintegration should be the same for dry and wet material. On the other hand there were structures, which generated sounds with low frequencies, and the occurrence of these acoustic events was strongly dependent on water activity. With increasing water activity the number and intensity of these events decreased, especially during the beginning of the deformation process.

According to the literature frequencies the most important to crisp foods are in the range of 5–12.8 kHz (Dacremont, 1995). However, mastication of potato chips yielded 3–6 kHz, while instrumental compression showed that crispy sounds were emitted at 1.9–3.3 kHz (Seymour & Hamann, 1988). Dacremont (1995) using Fast Fourier Transform showed that crunchy and crackly products were characterized by sounds with frequencies 1.25–2 kHz. Chewing tortilla and potato chips showed that first chew was the most important in assessment of acoustic properties, and frequencies between 3 and 4 kHz were paramount for these products. Duizer et al. (1998) found that biting corn based extrudates generated sounds with two peaks at 1–2 kHz and 6–7 kHz. Low level sounds at 8 kHz were recorded. At the same time it was suggested that in dry cellular products subjected to continuous force the cell walls bend and break and cause vibrations, which generated sound waves (Vickers & Bourne, 1976b). From the above information, it could be inferred that breaking of air cell walls generated sounds with low frequencies probably not exceeding 6–7 kHz.

The above presented statement well correlates with data obtained in this work. At low water activities acoustic activity of the extruded bread was high, numerous acoustic events were present and energy of emitted acoustic signal was high. It suggested that numerous breaks of air cell

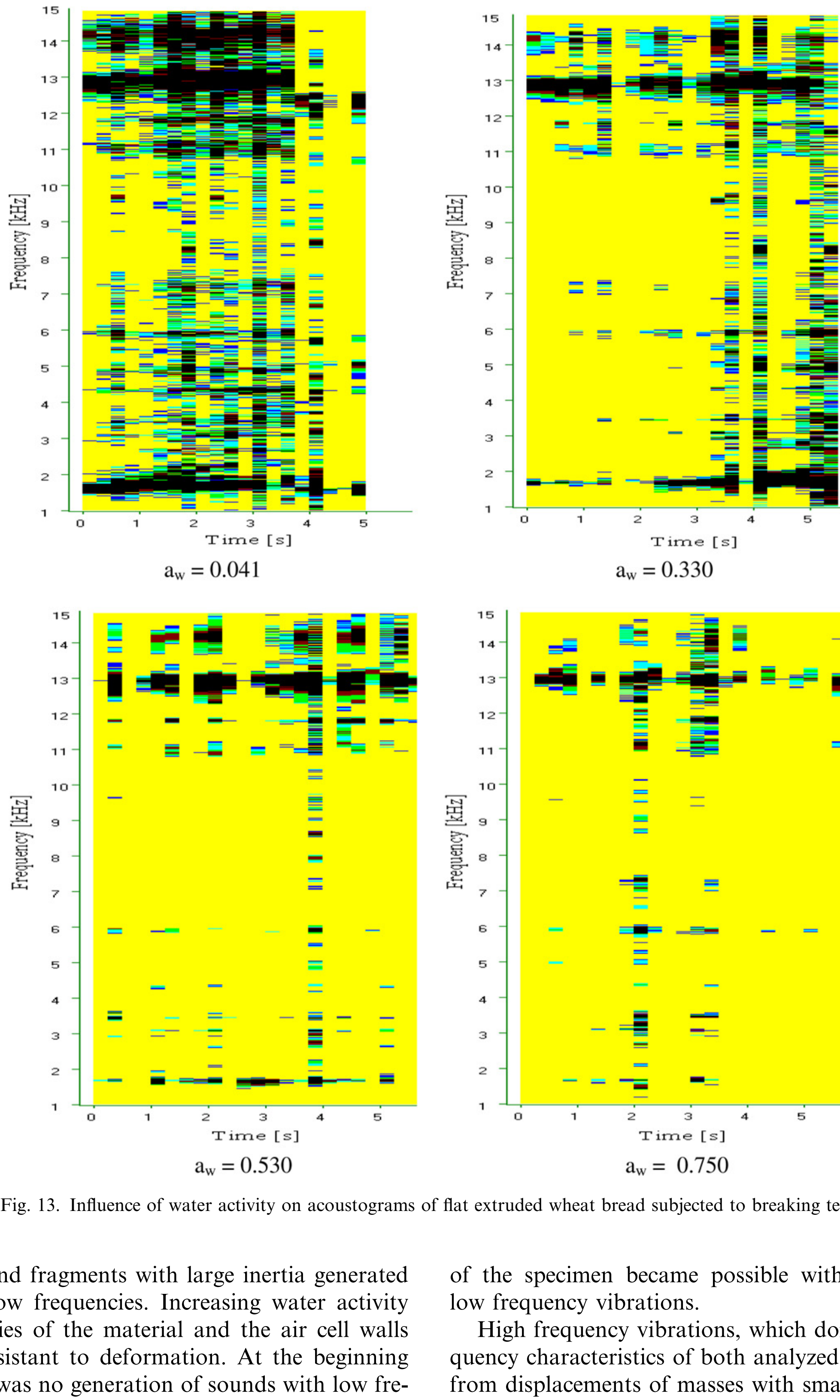


Fig. 13. Influence of water activity on acoustograms of flat extruded wheat bread subjected to breaking test.

walls occurred and fragments with large inertia generated vibration with low frequencies. Increasing water activity changed properties of the material and the air cell walls became more resistant to deformation. At the beginning of the test there was no generation of sounds with low frequencies, or sporadic acoustic events were observed. Probably air cell walls became antiplasticized by water and did not break during the first 1–2 s of deformation test. Multiphase character and heterogeneity of constituents' spatial distribution in the bread lead to antiplasticization of one domain and plasticization of others. Hence, deformation of the specimen became possible without generation of low frequency vibrations.

High frequency vibrations, which dominated in the frequency characteristics of both analyzed breads, originated from displacements of masses with small inertia. Since air cells in extruded bread were rather large, on a microscopic scale, breaking of the walls resulted in large displacements and low frequency vibrations. Hence, high frequency vibrations must be generated by other mechanical incidents than air cell walls disruption. Probably these small displacements reflected deformation (bending) of substructures of

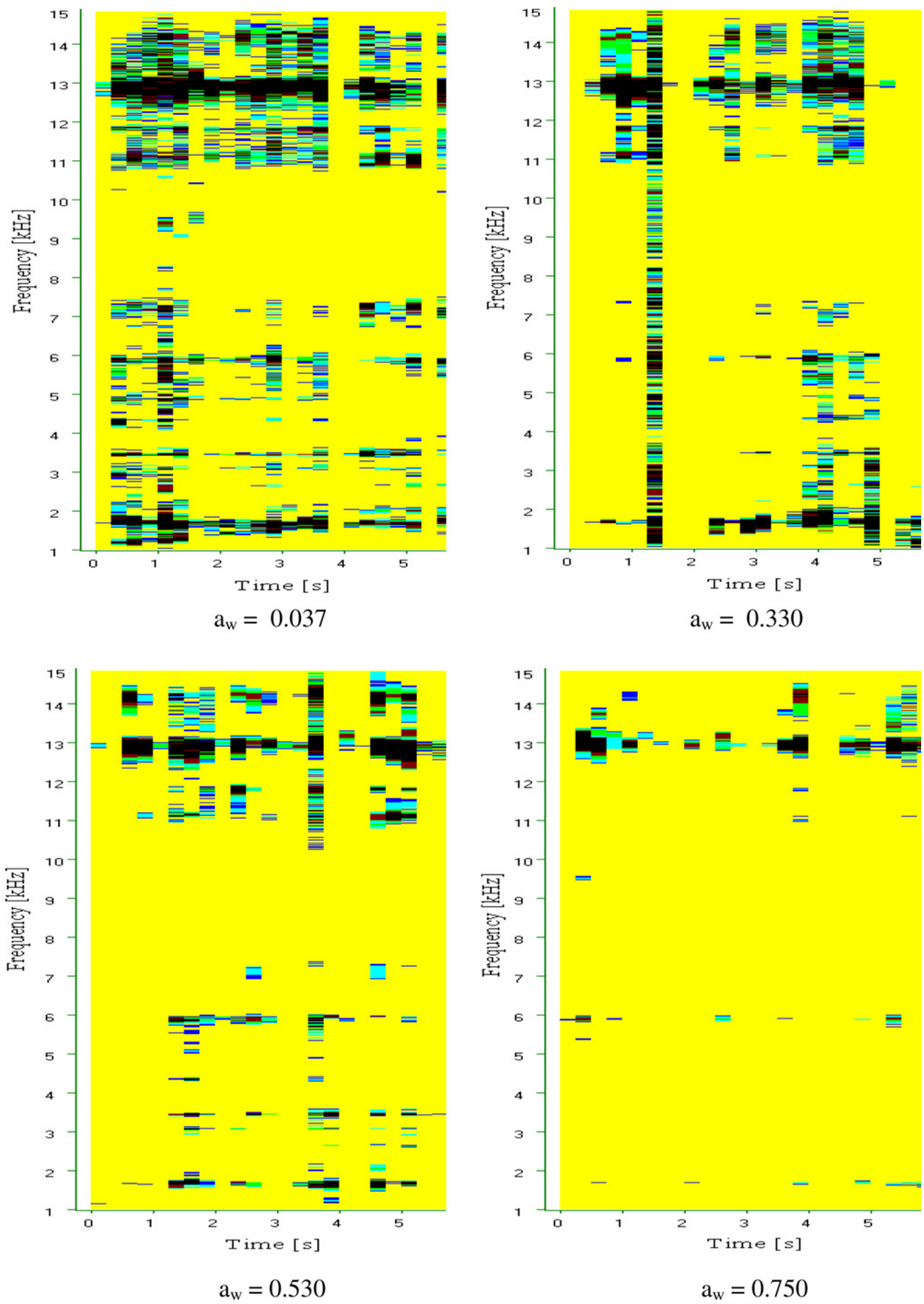


Fig. 14. Influence of water activity on acoustograms of flat extruded rye bread subjected to breaking test.

the solid matrix of the extruded bread. These could include fracture at the interface between gluten matrix and starch granule, fiber debonding, fiber breaking, biopolymers chain rotation and movement (Luyten, Plijter, & van Vliet, 2004) or the dislocation of one structure against the other. Thus the friction could be responsible, in part, for the high frequency vibrations.

Water absorption by the material could affect all the above mentioned events in two ways. On one hand, adsorbed water could act as a smear and should decrease the friction and ease the movement. On the other hand, absorbed water caused swelling and the movement of one substructure against the other became more difficult. Hence, at low and high water activity high frequency vibrations were present, but their intensity decreased with increasing wetness of the material.

Total energy of acoustic events decreased with increasing water activity. However detailed analysis showed that energy of individual acoustic event was little dependent on wetness of the material. In the range of water activities from 0.03 to 0.5 the energy was constant and thereafter it decreases by some 15%. On the other hand, the number

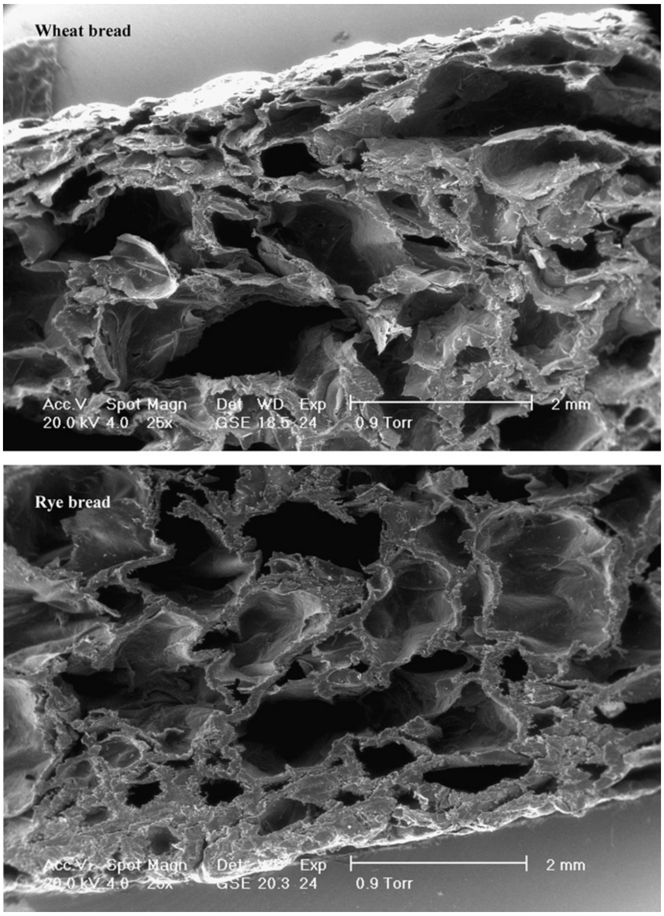


Fig. 15. Electron scanning microphotograph of flat extruded bread.

of acoustic events was strongly dependent on water activity and decreased with increasing moisture content. Combining these two observations it could be inferred that even at high water contents there still were domains able to break and generate vibrations with such energy as that emitted by dry material. The probability of occurrence of such domains decreased with increasing water activity and in flat extruded bread was close to zero at $a_w \approx 0.8$.

Analysis of acoustic indices calculated in this experiment showed clearly that acoustic activity of both wheat and rye flat extruded bread were strongly influenced by water activity. The effect of chemical composition on acoustic activity was not as evident as that of water activity. Neither energy nor the number of acoustic events was dependent on the chemical composition of the flat extruded bread. Moreover partition power spectrum slope also was not dependent on the kind of analyzed bread. Other indices were dependent on the kind of analyzed bread, and the dependence was the more visible the higher was the water activity. The share of high frequency acoustic signals in the frequency spectrum and the acoustic emission signal energy were dependent on the kind of investigated bread. Rye extruded flat bread propagated sound waves of high frequency better than the wheat bread. Acoustic emission signals energy of rye extruded bread was more dependent on water activity than that of wheat bread.

Observed differences in acoustic activity the most probably arose from different raw materials used in production of analyzed brads. One of the main differences in chemical composition was the content of pentosans, which in wheat flour constitute 2–3%, and in rye flour 2.8–5% of mass. They have a strong gel formation potential and very high water-holding capacity (Izydorczyk, Biliaderis, & Bushuk, 1990). Pentosans are able to bind water in the ratio 1:10 by weight. Unfreezable water in rye water-extractable arabinoxylans was estimated as 0.47 g/g d.m. (Girhammar & Nair, 1992). It was also observed that addition of isolated arabinoxylans to flour retarded retrogradation of starch due to reduced availability of water for that process (Gudmundsson, Eliasson, Bengtsson, & Åman, 1991). Moreover sorption isotherms of analyzed breads were statistically different at water activities lower than 0.7 (Marzec & Lewicki, 2006) and the rye bread isotherm was below that of wheat bread. It meant that at the same water content water activity of rye bread was lower than that of wheat bread. The energetic constant in the GAB equation was 42.01 and 70.95 for wheat and rye bread, respectively. Thus, water was bound by rye bread much stronger than by wheat bread.

From the above findings it can be inferred that water in rye bread was bound stronger than in wheat bread due to the presence of polysaccharides such as arabans and xylans. Hence, the ability to generate and propagate sound waves strongly affected by water activity–thermodynamic state of water, was modified to some extent by chemical composition of the investigated material.

## 5. Conclusions

Flat extruded bread subjected to continuous force underwent simultaneous disintegration and structure microdislocations. Breaking of air cell walls caused displacements of large fragments with high inertia and generated vibrations with low frequencies. On the other hand, dislocations on a molecular level accompanied by friction resulted in vibrations with high frequencies. Hence, breaking of flat extruded bread generated vibrations in the whole audible spectrum. Increasing water activity of the bread affected its susceptibility to breakage and mobility of microstructures as well. Antiplasticization of air cell walls by water increased their mechanical strength and fracturing was delayed in comparison to samples with low water activity. Then low frequency vibrations appeared when a certain degree of flat bread bending was reached. Moreover, some domains were sufficiently plasticized and did not break under applied force. The number of acoustic events decreased with increasing water activity. It showed that flat extruded bread was a very heterogeneous material from the adsorption of water point of view.

Increasing wetness of the material affected also high frequency vibrations. Water decreased friction but material could be compacted due to swelling. Hence, high frequency vibrations were affected by water activity not as strongly as those of low frequency. Adsorption of water was dependent on chemical composition of the material. The presence of arabans and xylans in rye flour created solid matrix more susceptible to water, and the response of acoustic activity of extruded rye bread to changing water activity was stronger than that observed for the wheat bread. Since manufacturing process was the same the microscopic structure was alike and breaking of the air cell walls was similar. It resulted in energy of acoustic event little dependent on water activity and slightly related to chemical composition of the material.

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