Contributed Papers

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Influence of water activity on acoustic emission of breakfast cereals

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The aim of this contribution is to investigate corn flakes and wheat bran flakes. Flakes were equilibrated in hygrostats and at given water activities were subjected to compression test in texture analyzer TA.XT2i/25 (Stable Micro Systems). Acoustic energy emitted while breaking the layer of flakes was recorded in the range of frequencies from 0.01 kHz to 15 kHz. The spectrum of acoustic energy was analyzed with the aid of software WIDMOŚREDNI. The total acoustic energy emitted while crushing the layer of flakes was calculated as well as the partition power spectrum slope. Both the total acoustic energy and the slope were related to water activity of the flakes. The total acoustic energy decreased with increasing water activity for both analyzed types of flakes. Critical water activity was 0.555 for corn flakes and 0.438 for wheat bran flakes. The relationship between the slope of partition power spectrum and the water activity was dependent on the type of analyzed product. For corn flakes the slope sharply decreased at water activity equal to 0.688 while for wheat bran flakes a sharp increase was observed at water activity of 0.437. Samples of flakes equilibrated to prescribed water activities were analyzed in scanning electron microscope XL 30ESEM TMP (Philips). Microstructure of flakes was very different and was affected by adsorption of water. Hence, it may be suggested that acoustic emission is related to the microstructure of flakes.

1. Introduction

Breakfast cereals belong to the group of products, in which the quality is assessed mainly by texture. Consumer surveys have shown that products with vague flavor, such as lettuce, nuts and some cereal snacks are accepted by their texture and not by their taste (Surmacka-Szcześniak, 1995). Texture is a complex quality attribute and consist of preferred features (brittleness, crispness, crunchiness, juiciness, tenderness) and disliked features (cloudiness, wateriness, sliminess, hardness) by consumers. One of the preferred texture features is crispness (crunchiness), which is always associated with fresh and healthy foods. The lack of expected crunchiness is understood by consumers as quality failure (van Hecke *et al.*, 1995).

The most thorough assessment of texture is done during eating. However it is a subjective evaluation not very convenient for routine analysis. Moreover, the results obtained by different persons and under different condition cannot be compared. Hence, a lot of research has been done to develop an objective instrumental methods to measure texture and express it numerically (Peleg, 1983; van Hecke *et al.*, 1994). This is a difficult task because texture is perceived by all human senses and physical variables cannot be easily correlated with sensory feelings (Kapsalis and Moskowitz, 1977). Although combination of mechanical and acoustic measurements suggests that the results may be highly correlated with consumer's texture perception (Tesh *et al.*, 1993; Duzier, 2001), the number of publications considering this problem is rather small. Most of research is done with the use of mechanical tests such as compression, bending, penetration, and deformation with prescribed force, speed or degree. The relationship between force and displacement or stress and strain obtained in those tests is analyzed in respect of different texture features (Pątek and Dąbrowski, 1980; van Hecke *et al.*, 1994). However, the role the acoustic emission plays in the assessment of texture is not fully appreciated.

The significance of the sound in food quality evaluation was recognized in the early 60's. Drake (1963, 1965) analyzed sounds accompanying disintegration of different brittle products and found that the results differ in amplitude and frequency. Vickers and Bourne (1976) recorded sound generated during biting and chewing of crunchy dry and moist products and found that they differ in amplitude and the number of peaks. Lee *et al.*, (1988) analyzed acoustic characteristics of fresh and stale tortilla and potato chips. Fresh chips generated louder sound and at higher frequencies than that of stale product. Moreover, it was found that the amplitude was highly correlated with sensory assessment of crunchiness. The number of sound peaks was also suggested as a good measure of crispness of potato chips (Duizer, 2001).

Research performed on the basis of sound generation by food products shows that water content is an important variable. Kapur (1971) showed that the sound emitted during biting and chewing of dry wafers was 2.2 times more intense than that recorded for soggy product. Increase of acoustic emission with decreasing water content in corn extruded products was noted by Poliszko (1995). Crunchy cheese balls equilibrated to different water activities became silent at $a_w > 0.65$ (Tesh *et al.*, 1996). Lewicki *et* *al.*, (2002) analyzed acoustic emission power spectrum in two frequency regions. The proposed coefficient called the *partition power spectrum slope* was well correlated with crunchiness of flat extruded bread as a consequence of water adsorption. Roudaut *et al.*, (1998) investigated a possible mechanism of texture loss caused by water adsorption by crispy breads, using acoustic methods. Liu and Tan (1999) analyzed five types of snack food at two levels of moisture content. Acoustic signal was related to sensory analysis. It was shown that acoustic signal is useful in assessment and prediction of crunchiness of food.

2. Methods

Acoustic emission (AE) was generated during breaking of corn flakes and wheat bran flakes. Flakes were equilibrated to water activities in the range 0.03-0.66. Measurements were done using 10 replicates. Flakes were placed one over another in plastic cylinder forming a pile. Breaking of flakes was done applying the texture analyzer TA XT2i/25 (Stable Micro Systems) using spherical probe P/0.25 s. An accelerometric sensor, Brüel & Kjaer 4381V was mounted near the lower end of the upper head of the loading machine to achieve an acoustic contact with the flakes. Each AE signal registering session lasted 30 seconds, but analysis was done on the central 10 seconds of the record. The AE sensor was capable to register the acoustic signal at a frequency range from 1 to 15 000 Hz at the sensivity of 3 picocoulombs per m/s^2. The AE signal was transmitted from the sensor to a 20 dB low noise amplifier. Amplification of the signal was fixed experimentally at a level of 8±4 units over the RMS background noise level using the linear 255 units scale for each 10 second recording session. Finally, the AE signal was registered using a 44.1 kHz sampling sound card placed in PC computer. The card recorded the sound in the voltage range 1-200 mV. A special uniformity tests, including breaking of 0.5 mm HB pencil, was applied to keep sensivity control of the AE signal.

Software used to analyze the AE signal consisted of three programs. Program Wave Studio for Windows 95 (Creative Labs) was used to register the AE signals. Program *Widmośredni* 225 analyzed the spectral characteristics of the signal in the frequency range 1-15 kHz in sections of 0.25 s. 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 enables to suppress the random noise-accompanying recording of the AE signal. Finally the spectral characteristics of the AE signal were averaged. The results were graphically displayed with the use of program *Akustogram 3*. The spectral resolution of the software was 11 Hz.

2.1. Microstructure of flakes

Microstructure of corn and wheat bran flakes was analyzed with the use of electron scanning microscope XL 30 ESEM TMP (Philips). The structure of cross-sectioned flakes was taken at the magnification of 50 and 100 times. The walls of pores and starch granules were viewed at the magnification from 200 to 800 times. Microphotographs of structure of the flakes were taken at two water activities 0.320 and 0.750. Dry flakes were directly placed in the microscope. Wet flakes were dehydrated with ethyl alcohol 96% v/v and acetone and dried in triple point. Microstructure analysis was done in Electron Microscopy Laboratory of Warsaw Agricultural University (SGGW).

2.2. Mathematical analysis

Energy of the AE signal was calculated from the equation:

$$E = \sum_{m=1}^{n} v(mT_1),$$

where: v is the amplitude [mV], m is the consecutive number of a signal sample, T_1 is the time delay between consecutive execution of taking a sample, and T is the total session time.

The AE signal power spectrum was calculated from the formula:

$$P_{7\text{-}9} = \sum_{n\to 7\,\mathrm{kHz}}^{n\to 15\,\mathrm{kHz}} c_n, \qquad P_{14\text{-}15} = \sum_{n\to 14\,\mathrm{kHz}}^{n\to 15\,\mathrm{kHz}} c_n,$$

where

$$c_n \approx \frac{1}{N} \sum_{m=0}^{N-1} v\,(mT_1)\ \mathrm{mod}\left(e \frac{jn2\pi m}{N} \right).$$

Here N is the number of samples registered at time T, and j denotes $\sqrt{-1}$.

The partition power spectrum slope-β was calculated as:

$$\beta = \frac{P_{7\text{-}9}}{P_{14\text{-}15}},$$

where $P_{7\text{-}9}$ is the AE signal power spectrum registered in the frequency range 7-9 kHz, and $P_{14\text{-}15}$ is the AE signal power spectrum registered in the frequency range 14-15 kHz.

The relation between both the AE signal and the slope β and water activity was calculated by using the equations

$$Y(a_w) = \frac{Y_0 - Y_\tau}{1 + \exp \frac{a_w - a_{wc}}{b}} + Y_\tau,$$

$$Y(a_w) = \frac{Y_0 - Y_\tau + k\, a_w}{1 + \exp \frac{a_w - a_{wc}}{b}} + Y_\tau,$$

where a_w is the water activity, k and b are constants, Y_0 is the magnitude in the dry state, and Y_r is the residual level of $Y(a_w)$.

3. Results

Spectral characteristic of acoustic emission of corn flakes at water activity 0.345 is presented in Fig. 1. The analysis was done for the frequency range 0-15 kHz and showed that in the investigated flakes two characteristic frequency regions are dominant. The regions high AE activity occurred at 7-9 and 14-15 kHz. Independent of the water activity the AE signal energy was the highest in those regions. The disturbing sounds (loading machine noise, speech, and ventilation fan noise) also generated high-energy signal, which occurred at that frequency range and was not taken into account when the slope β was calculated.

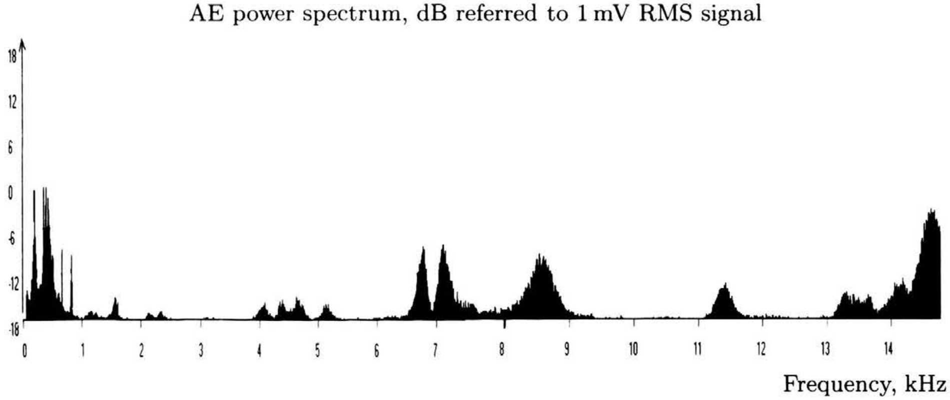

FIGURE 1. AE signal spectral characteristics of corn flakes at $a_w = 0.345$.

Figures 2, 3, 4 and 5 depict the influence of the water activity on the AE signal energy and the slope β. The data were correlated using the Fermi equation modified by Peleg (1993a, 1994, 1997, 1998). Harris and Peleg (1996), and Wollny and Peleg (1994) used those equations to describe relationship

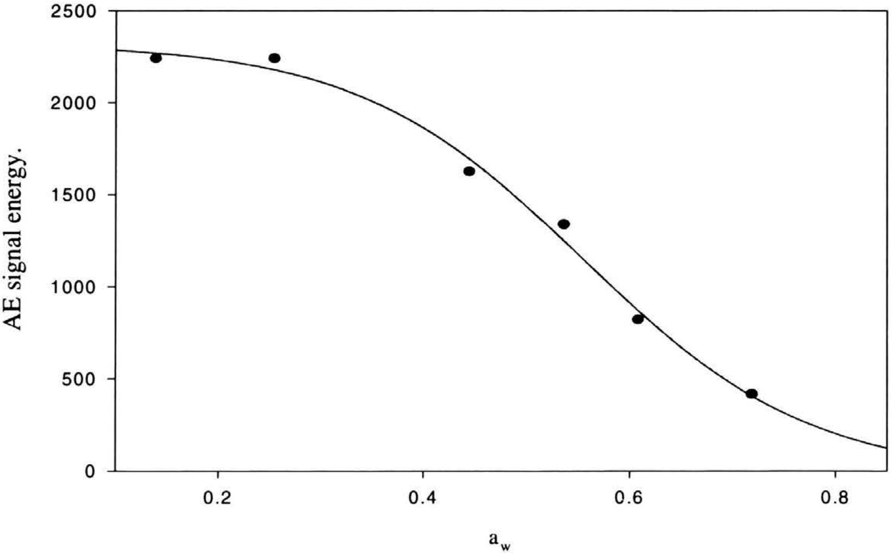

FIGURE 2. Influence of the water activity a_w on the total AE signal energy of corn flakes.

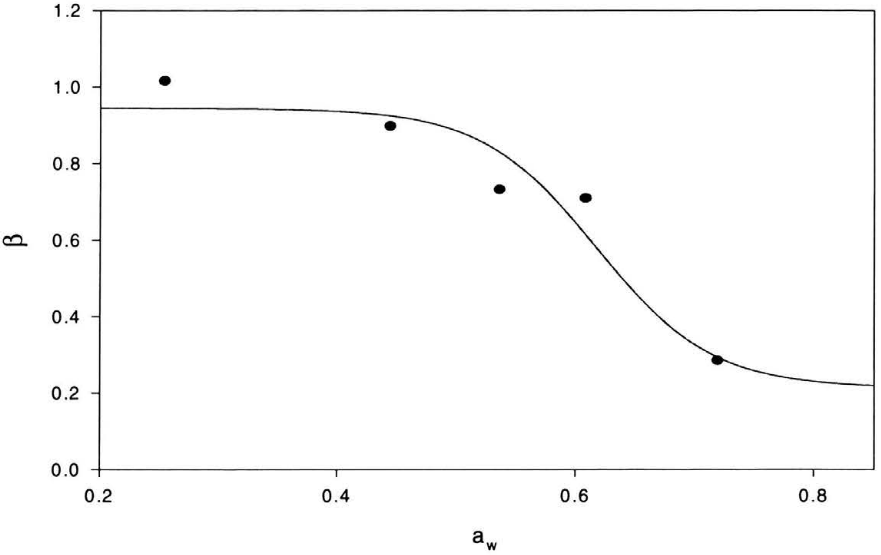

FIGURE 3. Influence of the water activity a_w on the slope β measured in corn flakes.

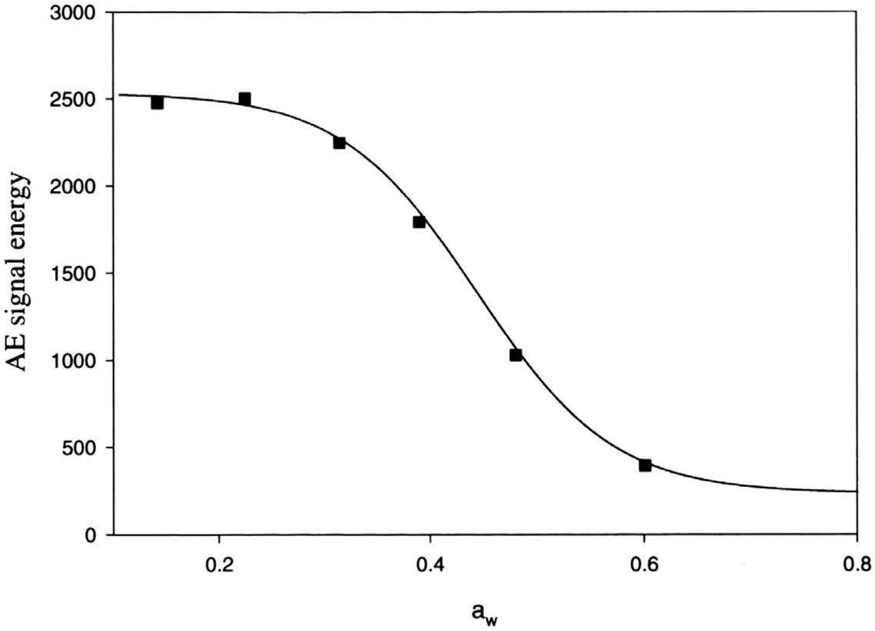

FIGURE 4. Influence of the water activity a_w on the total AE signal energy of wheat bran flakes.

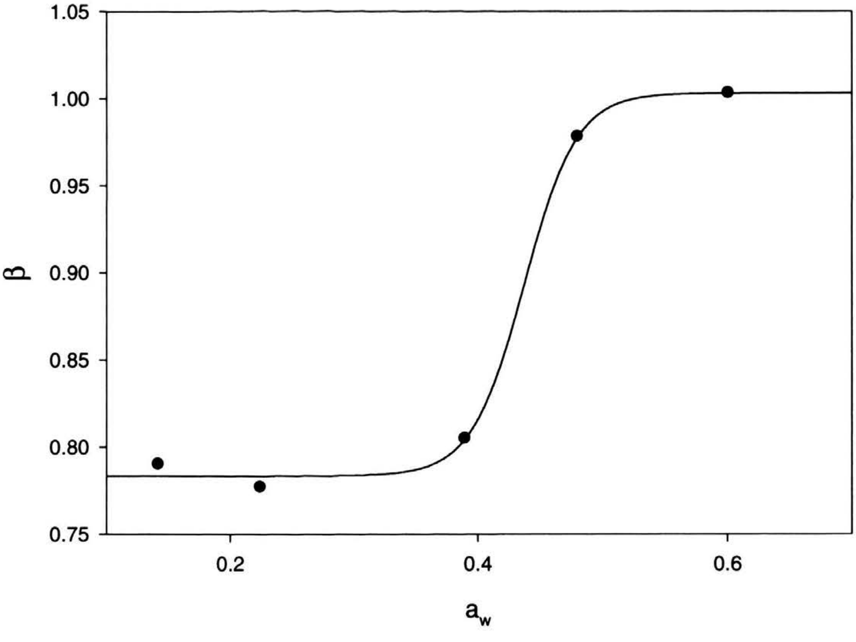

FIGURE 5. Influence of the water activity a_w on the slope β measured in wheat bran flakes.

between some texture features of selected food products and the water activity. Calculated constants are collected in Table 1. The determined coefficients are high and show statistical significance of the analyzed relationships. At high and low water activity both the AE signal energy and the slope β are not affected by the thermodynamic state of water. However, a large change of both descriptors of sound is observed at mid values of water activity a_w. The change is assigned to the glass transition caused by water adsorption, observed in mechanical and AE tests (Poliszko *et al.*, 1995; Tesh *et al.*, 1996; Fountanet *et al.*, 1997).

TABLE 1. Constants of Fermi's equations.

Product	**Parameter**	Y_s	Y_r	a_{wc}	b	r^2
Corn flakes	Total AE signal energy	2322.6	26.962	0.555	0.1102	0.9928
Wheat bran flakes	Total AE signal energy	2534.8	29.296	0.438	0.0632	0.9689
Corn flakes	β	0.9446	0.2137	0.6177	0.0485	0.9686
Corn flakes	β	0.7835	1.003	0.4369	0.0210	0.9983

In both corn flakes and wheat bran flakes the AE signal energy is decreasing with the increase of water activity. Beyond some terminal water activity the product becomes silent and the parameter Y_r represents the energy of background. Kapur (1971), who noted that the sound intensity for dry wafers was 2.2 times larger than that for wet material observed such influence of water on AE. Rodaut *et al.* (1998) noted that crispy bread is losing its signal in the range of water contents from 9 to 11%. Increasing water activity of flat extruded bread decreases the AE signal and at water activity above 0.75 the bread becomes silent (Lewicki *et al.*, 2002).

The influence of water on the AE signal energy is explained by the difference in the spatial distribution of stress in dry and wet material. In dry material the structure is stiff and the stress is not evenly distributed in space. Adsorption of water causes glass-rubber transition and dissipation of elastic energy. Consequently, the internal stress is relaxed and the probability of brittle breaks is low (Poliszko *et al.*, 1995).

The slope of the relationship between the AE signal energy and water activity (b) shows that the plasticization by water for wheat bran flakes proceeds faster at low water activities than that observed for corn flakes. The same effect of the kind of flakes is observed when the relationship between the partition power spectrum slope and water activity is analyzed. The critical

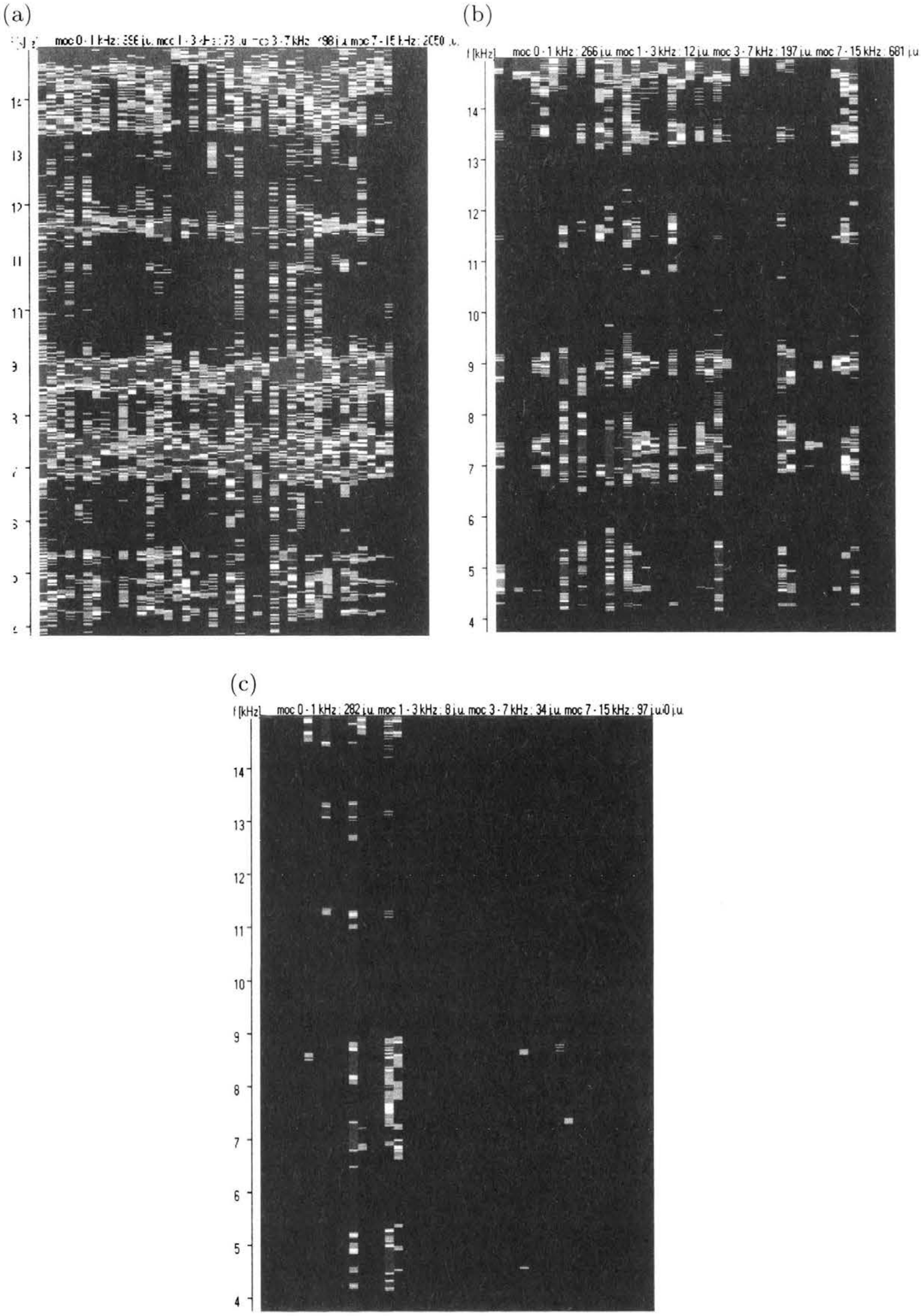

FIGURE 6. Acustograms of corn flakes at different water activity levels: (a) 0.199, (b) 0.537, (c) 0.720.

water activity (a_{wc}) at which the Y_{aw} value is reduced by 50% is much lower for wheat bran flakes than that for corn flakes. It shows that the wheat bran flakes are more sensitive to water than corn flakes. If critical water content is related to mechanical response of flakes to adsorption of water the following is observed. The change in mechanical properties occurs at higher water activities than that of AE. Hence AE of flakes seems to be much better indicator of structural changes in flakes caused by water adsorption than measurement of mechanical properties. Intensity and quality of emitted sound pronounce the undesirable effect of water adsorption firstly.

The results presented in Figs. 3 and 5 are important from the point of view of flake structure. In the case of corn flakes the partition power spectrum slope decreases with increasing water activity. It means that increasing water activity promotes generation of sound with high frequency. In wheat bran flakes an opposite relationship is observed. Increasing water activity favour generation of sound with low frequencies. The difference can be either due to different raw material or to different processing technology (extrusion and traditional). Both, no doubt, affect internal structure of flakes.

Acustograms for analyzed flakes at different water activity are presented in Fig. 6. A characteristic spectral frequency and signal intensity are seen as the change in pattern and colour. The influence of water activity on the spectral characteristics and signal intensity is also evident.

4. Analysis of microstructure

Microstructure of investigated flakes shows large differences in their internal structure. Porous structure in which cell walls of air cells are compact, homogeneous and continuous (Fig. 7) characterizes corn flakes. The flakes are the result of high degree of processing which leads to starch gelatinization (Fig. 8) and formation of more or less uniform structure, especially when the walls of air cells are conceived. Adsorption of water by gelatinized starch-protein matrix causes swelling. The walls of air cells increase in thickness, air cells become smaller (Fig. 9) and the structure creates good conditions for propagation of the sound especially at low frequencies.

Wheat bran flakes have a very variable internal structure. Walls of the air cells are visible, however they are not continuous. Numerous breaks, cracks and large discontinuities are present. The structure suggests that the degree of processing is low. In Figs. 10 and 11 some morphology elements of wheat grain are shown, such as brush, aleurone cells and fragments of the seed coat. Non gelatinized starch grains are visible (Fig. 12), although places with gelatinized starch are also present (Fig. 13). Such variable structure should respond to water adsorption in different way than the more uniform one. Non

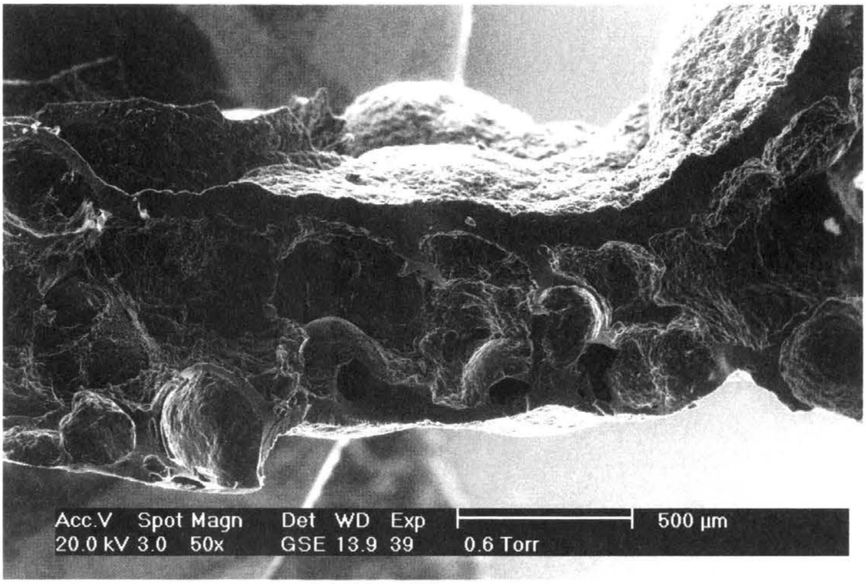

FIGURE 7. Cross-section of corn flake at $a_w = 0.320$ taken directly from the package.

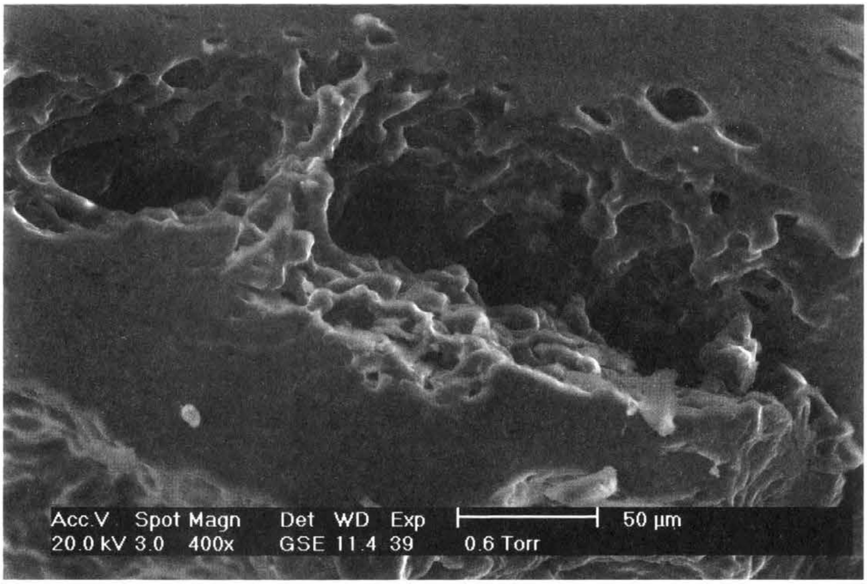

FIGURE 8. Wall of air cell in corn flake $a_w = 0.320$. Gelatinized starch is seen in the center of the microphotograph.

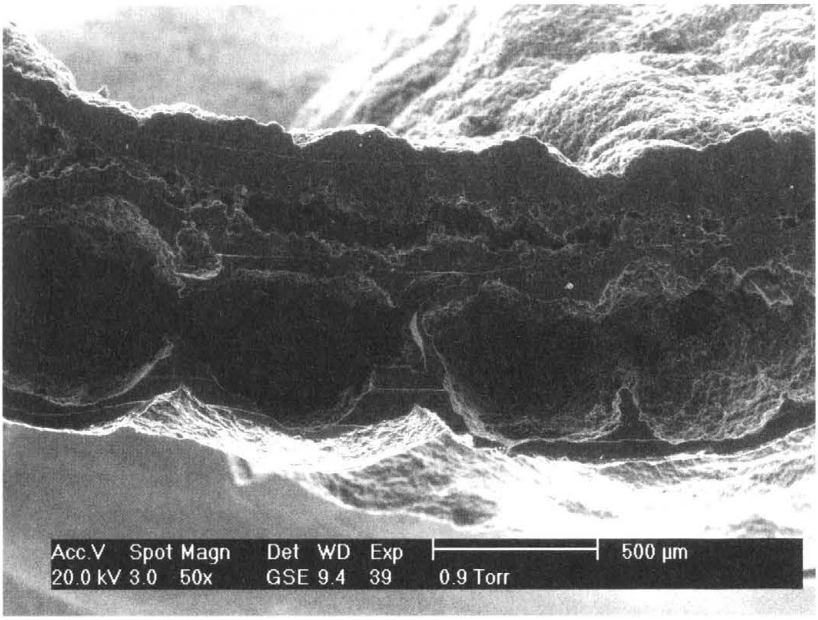

FIGURE 9. Cross section of corn flake equilibrated at $a_w = 0.755$.

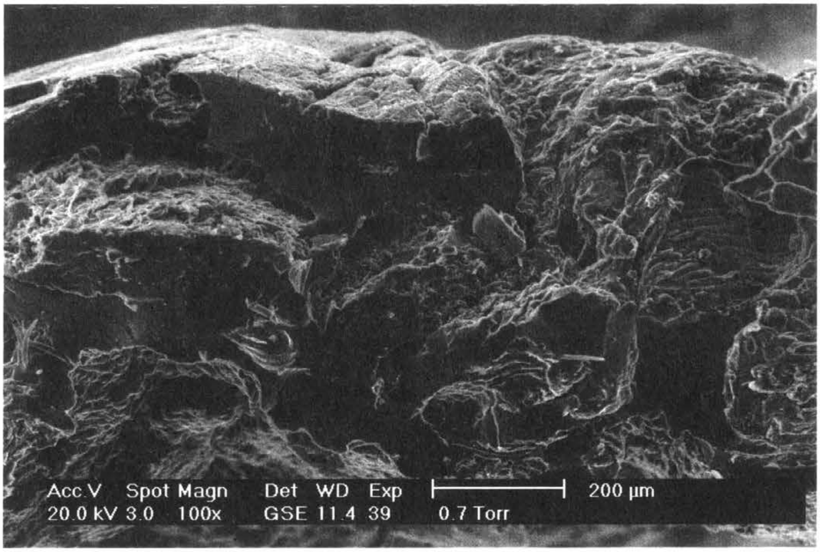

FIGURE 10. Cross section of wheat bran flake $a_w = 0.315$.

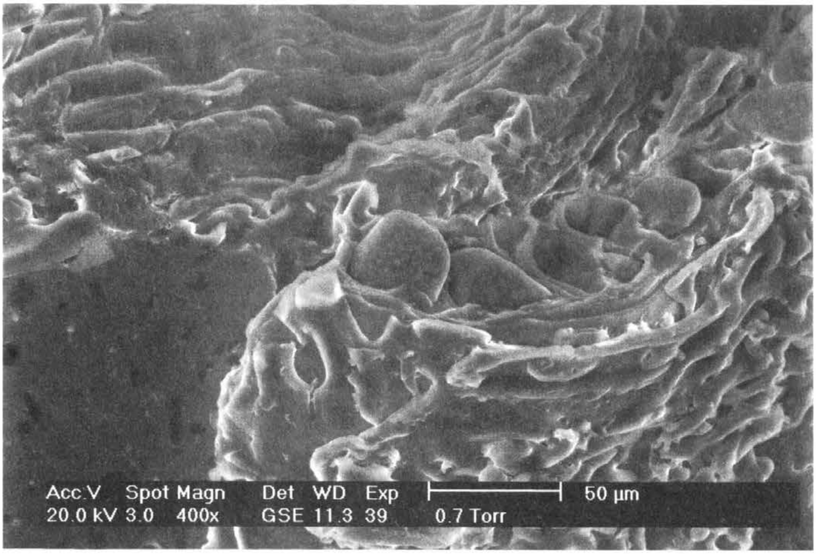

FIGURE 11. Cross section of wheat bran flake at $a_w = 0.315$. Fragments of seed coat and aleurone cells are seen in the microphotograph.

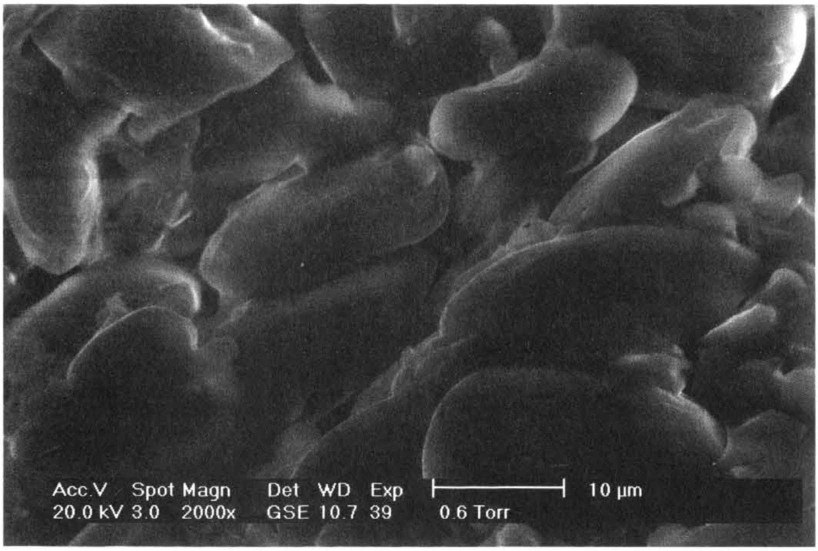

FIGURE 12. Cross section of wheat bran flake at $a_w = 0.315$. Granules of native starch.

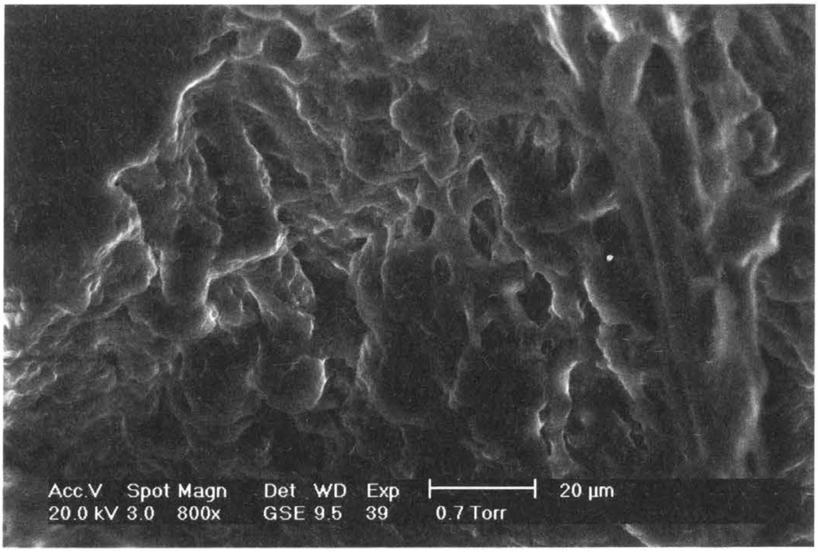

FIGURE 13. Cross section of wheat bran flake at $a_w = 0.315$. Gelatinized starch.

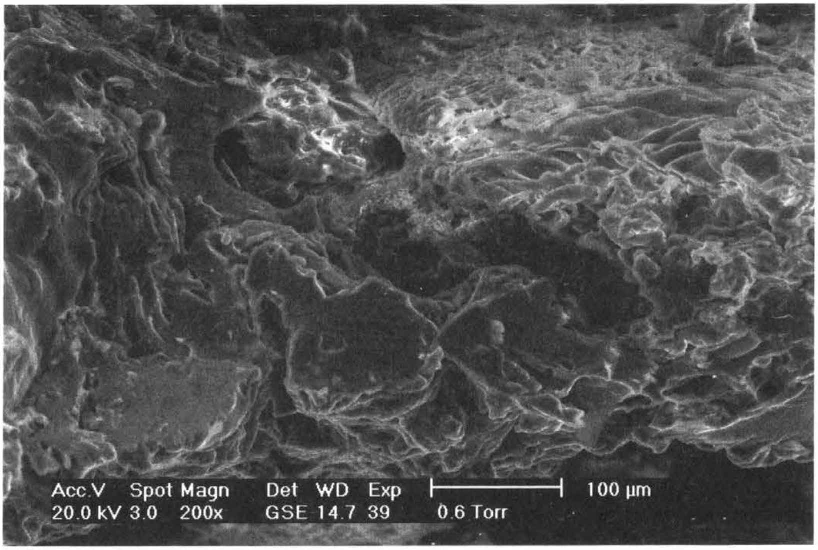

FIGURE 14. Cross section of wheat bran flake at $a_w = 0.755$.

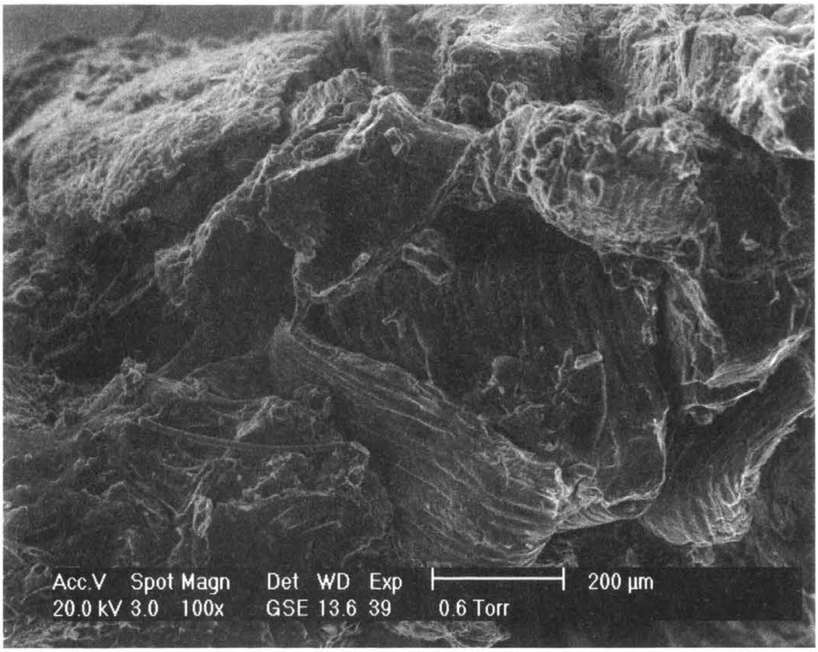

FIGURE 15. Cross section of wheat bran flake at $a_w = 0.755$.

gelatinized starch shell does not swell as well as the fragments of the seed coat. On the other hand gelatinized starch should swell considerably. Hence stresses can be created which will lead to dislocation of one element relatively to others. Enlargement of existing cracks and formation of new breaks can take place (Fig. 14 and 15). Hence, the conditions for the sound propagation are different from those observed in corn flakes.

The observed differences in microstructure of analyzed flakes can be responsible for the differences in the frequency characteristics of the flakes. However, to prove the effect of internal structure on acoustic characteristics of the crunchy food material more research is needed.

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