

Effect of the aerated structure on selected properties of freeze-dried hydrocolloid gels**

Agnieszka Ciurzyńska and Andrzej Lenart*

Department of Food Engineering and Process Management, Warsaw University of Life Sciences, SGGW,
Nowoursynowska 159c, 02-776 Warszawa, Poland

Received March 15, 2015; accepted December 7, 2015

A b s t r a c t. The ability to create diverse structures and studies on the effect of the aerated structure on selected properties with the use of freeze-dried gels may provide knowledge about the properties of dried foods. Such gels can be a basis for obtaining innovative food products. For the gel preparation, 3 types of hydrocolloids were used: low-methoxyl pectin, a mixture of xanthan gum and locust-bean gum, and a mixture of xanthan gum and guar gum. Gels were aerated for 3 and 7 min, frozen at a temperature of -45°C 2 h^{-1} , and freeze-dried at a temperature of 30°C . For the samples obtained, structure, porosity, shrinkage, rehydration, and colour were investigated. It was shown that the type of the hydrocolloid and aeration time influence the structure of freeze-dried gels, which determines such properties of samples as porosity, shrinkage, density, rehydration, and colour. The bigger pores of low-methoxyl pectin gels undergo rehydration in the highest degree. The delicate and aerated structure of gels with the mixture of xanthan gum and locust-bean gum was damaged during freeze-drying and shrinkage exhibited the highest value. Small pores of samples with the mixture of xanthan gum and guar gum were responsible for the lower rehydration properties, but the highest porosity value contributed to the highest lightness value.

K e y w o r d s: aeration, hydrocolloids, freeze-drying, structure, rehydration food

INTRODUCTION

Structure plays a very important role in determining the physical properties of freeze-dried material (Ciurzyńska and Lenart, 2010b). Gibson and Ashby (1997) showed that dry gels are model systems for studies where the relation between the cell wall composition and the texture of the cellular solid are investigated. Dried gel is a product

walls are made of the gel solid. The gas content and the size distribution of gas cells influence the properties of aerated food and are difficult to control (Labbafi *et al.*, 2007). It is advisable to control the bubble size and shape, they should be small in food. Modification of the texture can change physical properties by increasing the interfacial area and reducing the caloric density (Buckman and Viney, 2002).

Designed aerated gels with tailored texture characterized by reduced caloric density and beneficial flavour may be used in developing new dietetic food (Campbell and Mougeot, 1999; Zúñiga and Aguilera, 2008). Aeration has become one of the fastest growing manufacturing features in the food industry and it could be treated as a simple method to introduce innovation in conventional food (Campbell and Mougeot, 1999; Labbafi *et al.*, 2007). Aerated gels may be used in foods with reduced caloric density, which induce satiety. They can also be carriers of flavours and nutrients in modern food products (Zúñiga and Aguilera, 2008). Aeration may also improve the sensory and marketing advantages of typical products, as they became more softer, and distribution of flavours is more uniform (Labbafi *et al.*, 2007). Solid food with a different microstructure can influence the sense satiety by slower gastric emptying, but the mechanism which increases satiety may be different for different gels and needs to be studied. Enhancing satiation may restrict the daily food intake (Hoad *et al.*, 2004).

*Corresponding author e-mail: agnieszka_ciurzynska@sggw.pl

**The project was funded by the National Science Centre granted on the basis of the decision number DEC-2013/09/D/NZ9/04150.

Pectins are anionic polysaccharides (Galus and Lenart, 2013; Siew and Williams, 2008), those with a degree of methoxylation $DM < 50\%$, are named low-methoxylated (LMP) (Voragen *et al.*, 1995) and gel forming intermolecular ionic junction zones between smooth regions of neighbored chains (Braccini and Perez, 2001). This type of pectin can make gels even with no or small amounts of sugar and in different pH and Ca^{2+} addition (Capel *et al.*, 2006; Ngouimazong *et al.*, 2011). Amidation also influences the properties of LMP. In comparison non-amidated LM pectins amide pectins need less calcium to create gels, which are full well thermoreversible (Reitsma *et al.*, 1986).

The xanthan gum-locust bean gum combinations form a thermally reversible gel when solutions of these polymers are heated to above $54^{\circ}C$ and subsequently cooled. Xanthan gum-locust bean gum gel properties are influenced by the gum concentration and gum ratio (Copetti *et al.*, 1997; Renou *et al.*, 2013). At room temperature, xanthan gives weaker elastic gels, while heating of the polysaccharide mixture and the interaction with heat-disordered segments of xanthan gives a stronger gel that is highly dependent on the side chains of galactomannan (Mannion *et al.*, 1992). Guar gum and locust-bean gum are structurally similar, but the difference in the structure is sufficient to prevent the same type of gelation with locust-bean gum that occurs with guar gum (Clark, 1987). The synergistic gelling reaction between xanthan gum and locust-bean gum can reduce costs and increase the texture quality of food products (Williams and Philips, 2000).

Gels products can be preserved by the freeze-drying process, which ensures interesting properties of such a product (Cieurzyńska *et al.*, 2013) and does not damage their porous structure while convective drying (Sundaram and Durance, 2007). Freeze-dried gels are a suitable model system in the study of cellular solids. By selecting the gel composition and preparation conditions, gels with controlled microstructure and properties may be obtained (Nussinovitch *et al.*, 1993). In aerated food, the gas phase can be spread into a continuous matrix by *eg* whipping, foaming or mixing. Sample composition and operating conditions of gas dispersion are strongly related (Labbafi *et al.*, 2007).

The aim of this project is explanation of the influence of the aerated structure created by hydrocolloids and different aeration time in freeze-dried gels on the physical properties of the final product. Freeze-dried hydrocolloid gels with tailored structure can be used to elaborate innovative food products, whose properties can be predictable as an effect of those investigations. The scope of the research involved analysis of the effect of the aeration time and hydrocolloid type on the structure and physical properties of the final product. Choosing the optimal composition and the conditions for obtaining freeze-dried gels allow designing products that will be attractive for the consumer and have additional health benefits.

MATERIALS AND METHODS

The composition of the examined gels included: low-methoxyl pectin (LMP), a mixture of xanthan gum (KG) and locust-bean gum (LBG) and also a mixture of xanthan gum (KG) and guar gum (GG). Pectin Amid AF 020-E amidation degree 18-23% (Herbstreith and Fox KG Pektin Fabriken, Germany), xanthan gum E 415, guar gum 5000-5500 CPE E 412, locust-bean gum E 410 (Company Trade and Industry 'Standard' Lublin, Poland) were bought in Sovit Jarosław Buczkowski general partnership. Calcium lactate (manufactured by Hortimex, Poland) was added to gels with low-methoxyl pectin.

Preparation of gel involved combining the dried ingredients in the right proportions at water temperature $70^{\circ}C$, and subjecting the mixture to aeration for 3 and 7 min with a hand mixer Bosch MSM87160 at a temperature $\sim 60^{\circ}C$ with maximum speed (turbo). The temperature of $60^{\circ}C$ prevented quick gelation during aeration. It was also important for samples with the mixture of xanthan gum and guar gum, which form stronger gel at high temperature. It was decided to maintain the same gel preparation parameters for all types of hydrocolloids. For gel preparation, the concentration used allowed obtaining a solid gel that can be cut into cubes after gelation. The freeze-dried hydrocolloid gels obtained are presented in Table 1.

Aerated samples of the gel were poured out on a plate, creating a 1 cm higher layer, and cut into cubes with 1 cm sides after solidification. Before the freeze-drying process, the hydrocolloid gels obtained were frozen in a freezer mod 51.20, IRINOX SPA (Italy), using a low freezing temperature ($-45^{\circ}C$) for 2 h. Previously frozen hydrocolloid gels were placed on the shelves of the freeze-dryer Alpha 1-4 LSC Plus Christ Company (Germany). The process was conducted with constant parameters: pressure 63 Pa, safety pressure 137 Pa, temperature of freeze-drier heating shelves $30^{\circ}C$, time: 24 h. After the freeze-drying process, the gel cubes were moved to dried glass vessels, which were tightly closed and stored in a dark place at room temperature until the time of analyses.

Water activity was measured in triplicate by HygroLab Rotronic Company (Germany) apparatus according to the instruction of the manufacturer.

Dry matter content was measured by the drying method. Material (1-2 g) weighted in a weighing bottle was dried in a convective dryer at a temperature of $60^{\circ}C$ for 24 h in triplicate. The analysed freeze-dried material was weighted on analytical scales before and after drying with an accuracy of 0.0001 g (Cieurzyńska *et al.*, 2013).

The colour of the freeze-dried gel surface was determined with the use of Konica Minolta Company Spectrophotometer CM-5 in the CIE L^* , a^* , b^* system. The examination was conducted with diffused lighting at an angle of 0° , the diameter of the measurement hole was 3 mm, and standard light of the C type. The measurements were made

Table 1. Composition of freeze-dried gels in 100 g gel

Sample No.	Low-methoxyl pectin (LMP)	Xanthan gum (KG)	Locust bean gum (LBG)	Guar gum (GG)	Calcium lactate	Aeration time	Freezing	
							(%)	(temp/time)
1A	3	-	-	-	0.2	3		
1B	3	-	-	-	0.2	7		
2A	-	1.0	0.5	-	-	3	-45°C 2 h ⁻¹	30°C 24 h ⁻¹
2B	-	1.0	0.5	-	-	7		
3A	-	0.5	-	1.5	-	3		
3B	-	0.5	-	1.5	-	7		

in 5 repetitions for all the dried samples. The average value was calculated for the results obtained (Cieurzyńska and Lenart, 2009).

Shrinkage was measured with a volumetric method (Mazza, 1983) for gel cubes before freeze-drying (using hexane displacement) and for freeze-dried material using sea sand in three repetitions. For gels before and after freeze-drying, eight gel cubes weighed on analytical scales were placed in a graduated cylinder. Then, for gels before freeze-drying, hexane was poured onto the samples from a burette of the same volume as the cylinder until the lower meniscus of liquid reached a value equal to the burette volume. The volume of gel cubes was calculated as the difference between the nominal cylinder volume and the volume of the hexane residue in the burette. For gels after freeze-drying, two the same volume cylinders were used. Sea sand was transferred onto the samples from the first cylinder of the same volume until the higher meniscus of the solid reached a value equal to the second cylinder volume.

The shrinkage was calculated on the basis of dependency:

$$S = \left(1 - \frac{V_0}{V_1}\right) 100\%, \quad (1)$$

where: S – shrinkage (%), V_0 – volume of cubes before freeze-drying (m³), V_1 – volume of cubes after freeze-drying (m³).

Real density:

$$\rho_d = \frac{m}{V_1}, \quad (2)$$

where: ρ_d – real density of particles (kg m⁻³), m – particle mass (kg).

Determination of porosity of the raw material was measured with a Quantachrome helium pycnometer according to the producer instruction. The material with a known mass and unknown volume was introduced to a large measurement cell with a known volume. Next, the cell was placed

in the apparatus. Helium flowing through the samples filled all the interspaces and pores between the cubes, which enabled the measurement of the volume of the studied samples. Each sample was rinsed three times with the gas. The helium pycnometer determined the value of pressure. After introduction of the values obtained to the Pycnometer software version 2.7, the apparent density of the investigated samples was determined (Cieurzyńska *et al.*, 2014; Szulc and Lenart, 2013).

Volume of samples:

$$V_p = \frac{V_c + V_a}{1 - \frac{P_1}{P_2}}, \quad (3)$$

where: V_p – volume of sample (m³), V_c – volume of cell (m³), V_a – reference volume (m³), P_1, P_2 – helium pressure, which was read from the measurement equipment (Pa).

Apparent density:

$$\rho_s = \frac{m}{V_p}, \quad (4)$$

where: ρ_s – apparent density of particles (kg m⁻³), m – particle mass (kg).

Porosity:

$$\varepsilon = \left(1 - \frac{\rho_b}{\rho_s}\right) 100\%, \quad (5)$$

where: ε – porosity (%), ρ_b – real density of particles (kg m⁻³)

Changes in the structure were determined with the use of a scanning electron microscope TM-3000 HITACHI. Freeze-dried gels were cut along their axis by a razor blade and a piece with about 1 mm thickness was cut out from the lower part of the cubes. Structural changes were determined at 50x magnification. Using the computer program

Multi Scan, average cross-section area (μm^2), perimeter (μm), and diameter (μm) for individual spaces formed from cells in freeze-dried gels were calculated (Ciurzyńska and Lenart, 2010b).

Statgrafics Plus, version 4.1. (Microsoft), Excel 2010 (Microsoft) was used in the statistical analysis. Tukey test was used for verification of the hypothesis of equality of means for the analysed coefficients in measured samples. The analyses were done with the significance level of 0.05.

RESULTS

Freeze-dried samples with low-methoxyl pectin (LMP) had an aerated structure with visibly noticeable pores, whose size increased with aeration time (Fig. 1a, Table 2). The structure obtained was delicate but evenly aerated, and the pores had thin cell walls. Prolongation of the aeration time induced a statistically significant decrease in porosity

(Fig. 2), which can be connected with shrinkage (Fig. 4). The freeze-dried gels (LMP) were characterized by low shrinkage in the range of 3-5%, which insignificantly increased with prolongation of the aeration time from 3 to 7 min. The decrease in porosity caused an increase of real density with the increase in the aeration time (Fig. 3) and a statistically significant decrease in the lightness coefficient (L^*) in comparison to the sample aerated for 3 min. The formed structure influenced the rehydration properties of the freeze-dried gels. The samples were characterized by very good rehydration properties. It was shown that samples with low-methoxyl pectin underwent rehydration in the highest degree after 5, 30, 60, and 120 min of the rehydration time in comparison to the other samples (Fig. 6). The increase in the aeration time from 3 to 7 min caused an increase in water absorbance capacity, probably due to the bigger pores (Fig. 1a). Those samples absorbed more water.

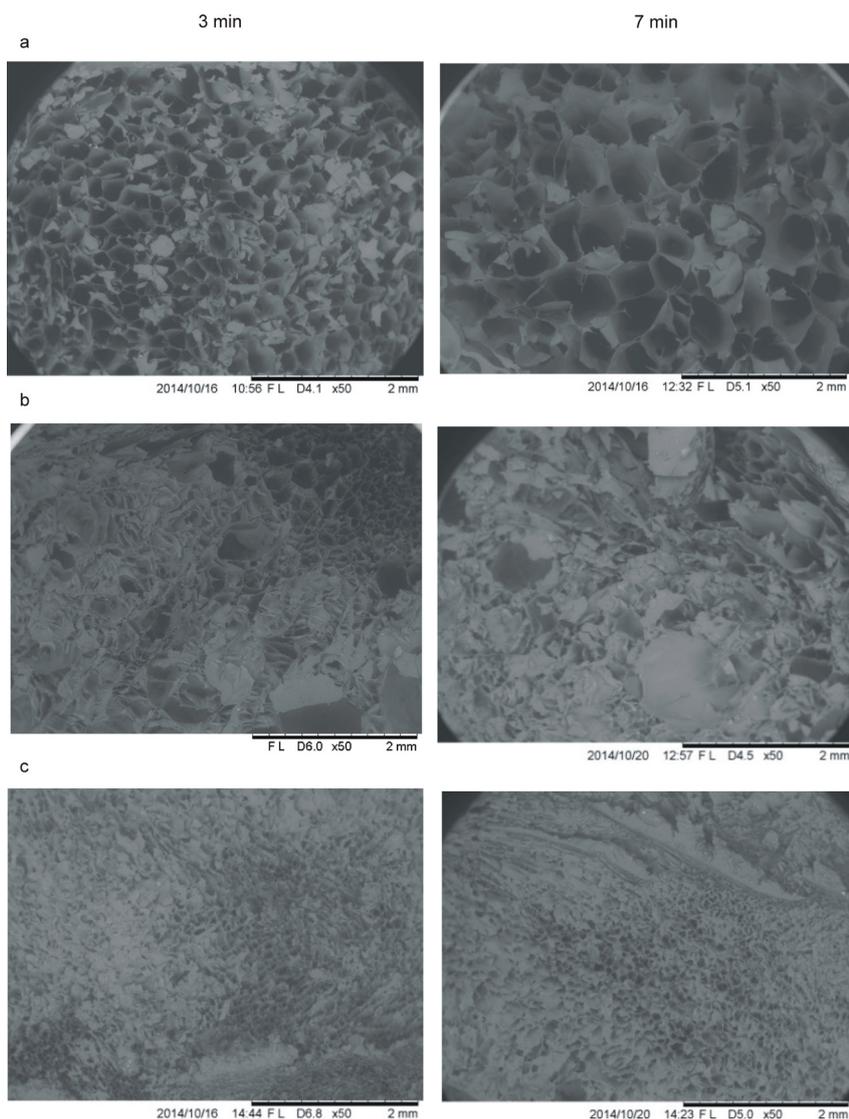


Fig. 1. Structure of freeze-dried gels with: a – low-methoxyl pectine (LMP), b – mixture of xanthan gum and locust bean gum (KG+LBG), c – mixture of xanthan gum and guar gum (KG+GG). Aeration time: 3 and 7 min. Magnification 50x.

Table 2. Average cross-section area (μm^2), perimeter (μm), and diameter (μm) values for an individual cell of freeze-dried gels obtained with different hydrocolloids and aeration time

Cross-section area (μm^2)			
LMP		KG+GG	
Aeration time (min)			
3	7	3	7
46200.97 \pm 17485.94a	202224.4 \pm 68208.36b	9876.35 \pm 4983.90a	24282.53 \pm 7001.49c
Perimeter (μm)			
911.80 \pm 172.92a	1818.02 \pm 328.06b	415.74 \pm 111.51c	678.71 \pm 99.32c
Diameter (μm)			
273.98 \pm 77.19a	494.72 \pm 79.62b	108.63 \pm 17.42c	186.90 \pm 30.51c

The values are mean ($n=20$) \pm SE. Means followed by the same letter are not significantly different according to ANOVA and Tukey multiple comparison tests. Designation of samples – Table 1.

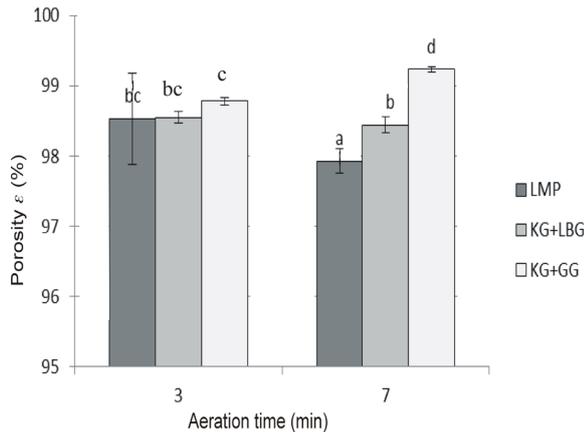


Fig. 2. Porosity of aerated freeze-dried gels from different hydrocolloids and aeration time. The values are mean ($n=6$) \pm SE. Means followed by the same letter (a) in the bar diagram are not significantly different according to ANOVA and Tukey multiple comparison tests. Designation of samples – Table 1.

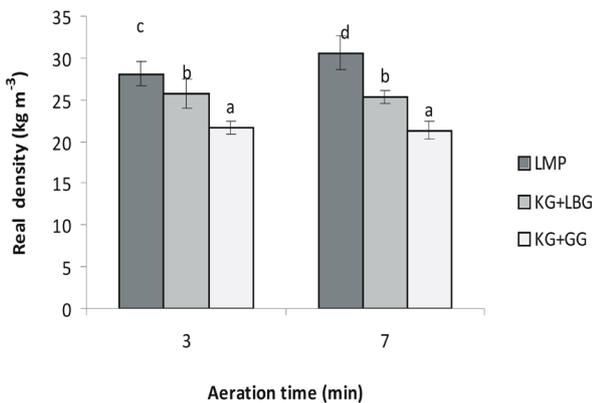


Fig. 3. Real density of aerated freeze-dried gels with different hydrocolloids and aeration time. Explanations as in Fig. 2.

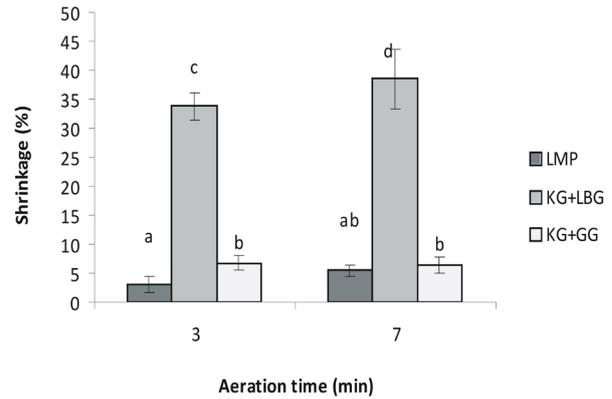


Fig. 4. Shrinkage of aerated freeze-dried gels from different hydrocolloids. Explanations as in Fig. 2.

During the freezing and freeze-drying process of gels obtained from the mixture of xanthan gum and locust-bean gum (KG+LBG) aerated in a high degree, the very delicate structure was damaged and the very thin cell walls were disrupted (Fig. 1b). The structure of gels (KG+LBG) that were aerated for 3 and 7 min was similar. It was impossible to designate parameters of the pores obtained. Also in porosity determination, it was shown that aeration time did not produce statistically significant differences in the investigated factor, and porosity was 98.5% (Fig. 2); therefore, an increase in the aeration time does not change significantly the real density of gels (Fig. 3). The lower porosity, in comparison to the other samples, is connected with the highest value of shrinkage in a range of 34–38% (Fig. 4), which reflects changes in the structure of the samples (KG+LBG) (Fig. 1b). Statistically significantly higher shrinkage was noted for gel aerated for 7 min. For gels (KG+LBG), higher porosity reflects a higher value of the lightness coefficient (Fig. 5). Prolongation of the aeration time caused a significant increase in that factor. The unfavorable structure

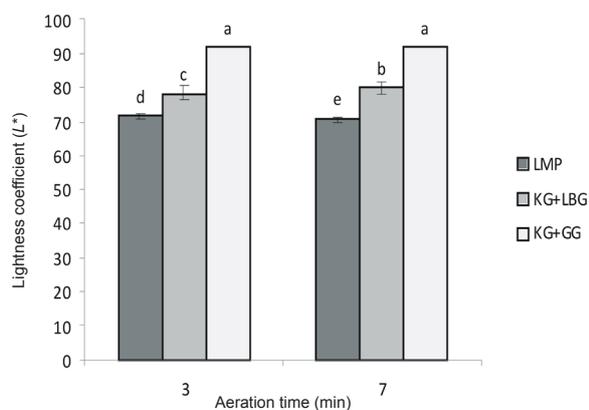


Fig. 5. Lightness coefficient of aerated freeze-dried gels from different hydrocolloids. Explanations as in Fig. 2.

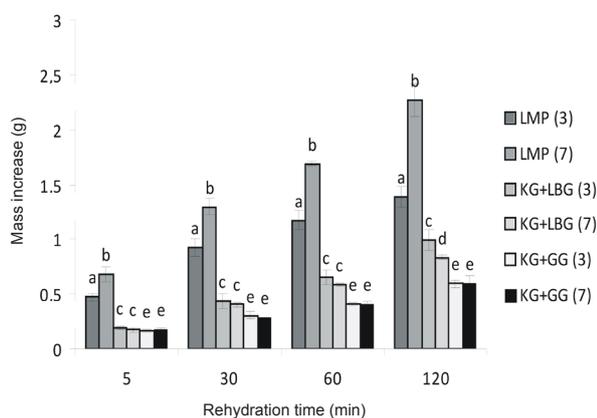


Fig. 6. Rehydration properties of aerated freeze-dried gels with low-methoxyl pectin (LMP). Explanations as in Fig. 2.

changes caused lower rehydration ability. Prolongation of the aeration time from 3 to 7 min caused a decrease in water absorption, which can be connected with higher shrinkage of those samples (Fig. 4).

The structure of freeze-dried gels obtained from the mixture of xanthan gum and guar gum (KG+GG) was also well aerated (porosity value ~99%) (Fig. 2). Despite the fact that the air bubbles in the dried samples were invisible, microscopic images revealed a high value of aeration. The air bubbles were small (Table 2), but numerous. In samples aerated for 7 min, the air bubbles were less regular and insignificantly bigger. The investigation of porosity also confirmed that samples aerated for 7 min had a statistically significant higher value of porosity in comparison to samples aerated for 3 min (Fig. 2). Similar real density is connected with similar porosity (Fig. 3). Gels (KG+GG) exhibited shrinkage in the range of 6.5-6.8% and the aeration time did not cause statistically significant changes in this factor. The highest porosity value yielded the highest value of the lightness coefficient for the mixture of xan-

than gum and guar gum (KG+GG) (Fig. 5), which did not change significantly with the aeration time. The lowest value of the rehydration ability was obtained for samples with (KG+GG), and prolongation of the aeration time did not influence water absorption, which can be connected with a similar shrinkage value (Fig. 4). The smallest pore diameter for samples obtained with the mixture of xanthan gum and guar gum (KG+GG) (Fig. 1c) (Table 2) could influence the limited water absorption capacity (Fig. 6).

The investigations of the influence of the hydrocolloid type showed that samples with the low-methoxyl pectin (LMP) were characterized by a porous structure with a high value of porosity ~98% (Fig. 2), and air bubbles created irregular and large spaces (Fig. 1a). The mixture of xanthan gum and locust-bean gum (KG+LBG) and the mixture of xanthan gum and guar gum (KG+GG) created a more porous structure ~99% (Fig. 2) and lower real density (Fig. 4), but the free spaces (pores) were smaller and much more irregular (Fig. 1b, c). The high value of shrinkage for (KG+LBG) is connected with the highest damage degree in comparison to the other samples (Figs 1a-c, and 4). The type of the hydrocolloid induced statistically significant differences in the lightness coefficient (L^*) (Fig. 5). Samples with low-methoxyl pectin (LMP) had the lowest value of the investigated factor as a result of the lowest porosity value.

For freeze-dried gels with low-methoxyl pectin (LMP), water activity (a_w) had a low value in a range of 0.051-0.067 (Table 3). The increase in the aeration time from 3 to 7 min increased statistically significant the water activity of the samples obtained. For gels with the mixture of xanthan gum (KG) and locust-bean gum (LBG) hydrocolloids, freeze-dried gels had a lower average value of water activity (a_w), *ie* 0.019 (Table 3). It was shown that the increase in the aeration time from 3 to 7 minutes caused a insignificant decrease in the investigated factor. For gels obtained from the mixture of xanthan gum (KG) and guar gum (GG) hydrocolloids, freeze-dried gels had low water activity (a_w) in the range of 0.023-0.026 (Table 3). It was shown that the increase in the aeration time from 3 to 7 min caused a statistically insignificant decrease in water activity.

The type of the hydrocolloid used for the preparation of freeze-dried gels influenced the water activity of the samples obtained (Table 3). Gels (LMP) had statistically significant higher water activity in comparison to gels with the mixture of (KG) and (LBG) also for the mixture of (KG) and (GG) in the investigated aeration time. For gels obtained from the mixtures of xanthan gum (KG) and locust-bean gum (LBG), the results were the lowest in every aeration time in comparison to freeze-dried gels with the use of the mixture of xanthan gum (KG) and guar gum (GG), and the differences were statistically significant.

For freeze-dried gels obtained from low-methoxyl pectin (LMP), it was shown that the samples reached a high value of dry matter content (Table 3). The aeration time

Table 3. Water activity (a_w) and dry matter content (d.m.) (%) of aerated freeze-dried gels from different hydrocolloids and aeration time

Water activity (a_w)					
LMP		KG+LBG		KG+GG	
Aeration time (min)					
3	7	3	7	3	7
0.05±0.01c	0.07±0.00d	0.02±0.01a	0.02±0.00a	0.03±0.01b	0.02±0.01b
Dry matter content (d.m.) (%)					
97.00±0.44bc	98.63±0.40bc	98.57±0.065bc	98.44±0.11c	96.66±1.57b	95.03±1.71a

The values are mean (n=6) ± SE. Means followed by the same letter (abc) are not significantly different according to ANOVA and Tukey multiple comparison tests. Designation of samples – Table 1.

did not change the investigated coefficient significantly. Similar relationships were obtained for xanthan gum (KG) and locust-bean gum (LBG) (Table 3). For freeze-dried gels with the mixture from xanthan gum (KG) and guar gum (GG), the dry matter content was in the range of 95-97% (Fig. 4). For those samples, the increase in the aeration time caused a significant decrease in the dry matter content, which can be connected with structure damage. Investigations of the influence of the hydrocolloid type showed that the samples obtained had a similar value of dry matter content after the tested aeration time. Differences were in most cases statistically insignificant.

DISCUSSION

It was expected that prolongation of the aeration time would increase porosity and create a more delicate structure, but it was also expected that the hydrocolloid type will diversify the structure and properties of gels. At the stage of gel preparation, it was confirmed that hydrocolloids create different gels, which is connected with the hydrocolloid types. Gel properties can be significantly changed by mixing gelling agents (Aguilera and Rademacher, 2004). The use of a hydrocolloid mixture improves the properties of a single gel component and sometimes synergistic effects may be found (Zúñiga and Aguilera, 2008). Samples obtained with the mixture of xanthan gum and locust-bean gum (KG+LBG) were characterised by a high value of aeration. The gel obtained was very elastic and formed cubes easily. The gel was delicate, because the aeration value was very high, bubbles were visible in all sample cross-sections, but this structure was damaged during the freeze-drying process. The gel with the mixture of xanthan gum and guar gum (KG+GG) was the most delicate. The formation of cubes was more difficult, because the gel was less stable. The air bubbles were very small and difficult to observe, because the whole mass was very foamy. Samples with the low-methoxyl pectin (LMP) created elastic gel, forming cubes easily. The aeration was

visible but the air bubbles were smaller than for the gel with the mixture of (KG+LBG). During the freeze-drying process, the effect of hydrocolloid type was more pronounced.

Buckman and Viney (2002) argue that air cells smaller than 80 µm would be largely unnoticeable to the eye. Control of the bubble size and size distribution in aerated products is a big challenge. The conventional foaming methods (eg whipping or rotorstator foaming) allow little control over the formation of separate bubbles, which are not uniformly distributed within the product (Weaire and Hutzler, 1999). The use of a hand blender to aerate the solution during gel production caused such widely distributed bubbles, which created a diverse structure. Also Nussinovitch *et al.* (2001) claimed that controlling the cell size, through the freezing rate and/or by aeration, can produce solid sponges with different cellular structures.

The structure created by low-methoxyl pectin is similar to that obtained by Kang *et al.* (1999) for the freeze-dried hydrogel. They demonstrated a network structure of heterogeneous pores. The pores had partially angular edges and some shapes of the pores were close to polygons. Changes that were shown in the microscopic image are confirmed in investigations of physical properties and some of them are associated with the real density, which informs about the structure openness (Ashby, 1983). The higher value of real density (LMP) can cause a decrease in porosity of samples aerated for 7 min. Jakubczyk *et al.* (2011) obtained a density value of about 40 kg m⁻³ for freeze-dried agar gels, but it can be connected with the type of the hydrocolloid and the gel concentration used. The almost 1.5-fold higher real density value for low-methoxyl pectin (LMP) can be explained by the calcium addition effect. Nussinovitch *et al.* (2001) also obtained a density value 2-3 times higher for gels with alginate and calcium salt than that of comparable dried gels based on other gums without calcium salt. Probably, the added calcium salt has a significant influence on the solid walls. For dried gels obtained with different hydrocolloids: agar, kappa carrageenan, and gellan gels, Nussinovitch *et al.* (2000)

showed that the apparent densities of the three dry gels made from pure gums were almost the same. Probably, the results obtained can be connected with the different concentration of freeze-dried gels in this work, while Nussinovitch *et al.* (2000) obtained 2% gels for all hydrocolloids used.

It is believed that changes in the structure occurring during different aeration times resulted in different binding of water, which could produce diverse water activity for the samples obtained. When between polymer molecules or aggregates 'junction zones' are created food polymers can produce gels and expansion of the network is limited. The water can be firmly held in the network structure and then the gel will behave more like a sponge (Hermansson, 2007). Polymer molecules connect together creating a three-dimensional structure, which binds the liquid. The structure is created from the polymer solution to the gel state and the properties are connected with conditions such as gelling time and solution composition (pH, presence of specific ions). The network structure and its relation with the liquid phase give gels their characteristic textural properties (Zúñiga and Aguilera, 2008). Also Jakubczyk *et al.* (2011) obtained a similar value of water activity for freeze-dried agar gels frozen in -35°C . In gels (LMP), the presence of calcium lactate strengthened the structure, which limited water removal during freeze-drying in comparison to samples with the mixture of (KG+LBG) and with (KG+GG). The amide group is suggested to play a role in the interaction, possibly by formation of strong inter- and intra-molecular hydrogen bonds, which results in a substance with a more hydrophobic appearance (Tho *et al.*, 2005).

It was expected that the structure of freeze-dried gels created by different hydrocolloids and aeration time influenced the colour of the investigated samples. Appearance is an important factor that gives quality to gelled products. Several gums make gels transparent, whereas others contribute to some opacity, but during the freeze-drying process the appearance of those samples is changing. Introducing a gas phase into a food matrix not only affects its texture and firmness, making the product softer, but also changes the appearance and colour (Campbell and Mougeot, 1999); that is why samples with higher porosity are characterized by a higher lightness value.

The type of hydrocolloids and structure changes during aeration influenced the rehydration capacity of gels. Low-methoxyl pectin is a different hydrocolloid type than gums; hence, it absorbs water in a different degree. Also, bigger pores increase this ability. Erle and Schubert (2001) demonstrated that the high rehydration degree is influenced by the protective effect of osmotic dehydration on the structure of dried material, as well as by its beneficial effect preservation of the volume and shape at a tissue level. Damage of the structure in samples with xanthan gum and locust-bean gum (KG+LBG) and the smaller pore diameter in samples with xanthan gum and guar gum (KG+GG) con-

tributed to the lower rehydration capacity of those samples. Ciurzyńska and Lenart (2010a) confirmed that a damaged structure decreases rehydration properties.

CONCLUSIONS

1. The expected influence of the hydrocolloid type on the structure and physical properties of freeze-dried gels was confirmed, but the effect of the aeration time was different for the different samples.
2. Low-methoxyl pectin gels have a delicate, evenly aerated structure. Prolongation of the aeration time decreases porosity and increases shrinkage, which decreases the lightness coefficient. The rehydration ability was the highest because of the bigger pores.
3. During freeze-drying, the aerated structure of gels with xanthan gum and locust-bean gum was damaged and shrinkage was the highest. The higher shrinkage for gels aerated for 7 min explained the lower rehydration ability, but in most cases insignificantly. The lightness coefficient was high because of the high porosity value.
4. The structure of freeze-dried gels with xanthan gum and guar gum was also well aerated. Small pore size resulted in lower rehydration ability. Shrinkage has a low value and the aeration time does not induce significant changes in this factor as well as rehydration ability. Aeration for 7 min increased porosity, which increased the lightness value, and air bubbles were less regular but bigger.

REFERENCES

- Ashby M.F., 1983. The mechanical properties of cellular solids. *Metal Transactions*, 14a, 1755-1764.
- Aguilera J.M. and Rademacher B., 2004. Protein gels. In: *Protein in Food Processing*. (Ed. R.Y. Yada). Woodhead Publishing Limited, Cambridge, UK.
- Braccini I. and Perez S., 2001. Molecular basis of Ca^{2+} induced gelation in alginates and pectins: the egg-box model revised. *Biomacromolecules*, 2, 1089-1096.
- Buckman J. and Viney C., 2002. The effect of commercial extended egg albumen on the microstructure of icing. *Food Sci. Technology Int.*, 8, 109-115.
- Campbell G.M. and Mougeot E., 1999. Creation and characterization of aerated food products. *Trends Food Sci. Technol.*, 10, 283-296.
- Capel F., Nicolai T., Durand D., Boulenger P., and Langendorff V., 2006. Calcium and acid induced gelation of (amidated) low methoxyl pectin. *Food Hydrocolloids*, 20, 901-907.
- Ciurzyńska A. and Lenart A., 2009. Colour changes of freeze-dried strawberries osmotically dehydrated before drying In: *Food Technology Operations New Vistas* (Eds W. Kopeć, M. Korzeniowska). Publisher University of Environmental and Life Sciences, Wrocław, Poland.
- Ciurzyńska A. and Lenart A., 2010a. Rehydration and sorption properties of osmotically pretreated freeze-dried strawberries. *J. Food Eng.*, 97, 267-274.
- Ciurzyńska A. and Lenart A., 2010b. Structural impact of osmotically pretreated freeze-dried strawberries on their mechanical properties. *Int. J. Food Properties*, 13(05), 1134 -1149.

- Ciurzyńska A., Lenart A., and Gręda K.J., 2014.** Effect of pre-treatment conditions on content and activity of water and colour of freeze-dried pumpkin. *LWT – Food Sci. Technol.*, 59(2), 1075-1081.
- Ciurzyńska A., Lenart A., and Traczyk W., 2013.** Influence of chemical composition and structure of strawberry gels on the chosen physical properties of freeze-dried final product. *Italian J. Food Sci.*, 2(25), 149-159.
- Clark R.C., 1987.** Viscoelastic response of xanthan/guar gum blends. In: *Gums and Stabilisers for the Food Industry* (Eds G.O. Phillips, P.A. Williams, D.J. Wedlock). Oxford Press, UK.
- Copetti G., Grassi M., Lapasin R., and Priel S., 1997.** Synergistic gelation of xanthan gum with locust bean gum: a rheological investigation. *Glycoconjugate J.*, 14(8), 951-961.
- Erle U. and Schubert H., 2001.** Combined osmotic and microwave – vacuum dehydration of apples and strawberries. *J. Food Eng.*, 49, 193-199.
- Galus S. and Lenart A., 2013.** Development and characterization of composite edible films based on sodium alginate and pectin. *J. Food Eng.*, 115, 459-465.
- Gibson L. and Ashby M., 1997.** *Cellular Solids Structure and Properties*. Cambridge University Press, UK.
- Hermansson A.M., 2007.** Structuring water by gelation. In: *Food materials science*. (Eds J.M. Aguiler, P.J. Lilford). Springer, New York, USA.
- Hoad C.L., Rayment P., Spiller R.C., Marciani L., Alonso Bde C., Traynor C., Mela D.J., Peters H.P., and Gowland P.A., 2004.** *In vivo* imaging of intragastric gelation and its effect on satiety in humans. *J. Nutrition*, 134, 2293-2300.
- Jakubczyk E., Banaś K., and Gondek E., 2011.** Characteristic of mechanical properties of freeze-dried agar gel (in Polish). *Zesz. Probl. Post. Nauk Roln.*, 558, 83-92.
- Kang H.W., Tabata Y., and Ikada Y., 1999.** Fabrication of porous gelatin scaffolds for tissue engineering. *Biomaterials*, 20(14), 1339-1344.
- Labbafi M., Thakur R.K., Vial Ch., and Djelveh G., 2007.** Development of an on-line optical method for assessment of the bubble size and morphology in aerated food products. *Food Chemistry*, 102, 454-465.
- Mannion R.O., Melia C.D., Launay B., Cuvelier G., Hill D.E., Harding S.E., and Mitchell J.R., 1992.** Xanthan/locust bean gum interactions at room temperature. *Carbohydrate Polymers*, 19, 91-97.
- Mazza G., 1983.** Dehydration of carrots. Effect of pre-drying treatment on moisture transport and product quality. *J. Food Technol.*, 18, 113-123.
- Ngouimazong D., Tengweh F.F., Fraeye I., Duvetter T., Cardinaels R., van Loey A., Moldenaers P., and Hendrickx M.E., 2011.** Effect of de-methylesterification on network development relationship of pectin. *Food Hydrocolloids*, 26, 89-98.
- Nussinovitch A., Corradini M.G., Normand M.D., and Peleg M., 2000.** Effect of sucrose on the mechanical and K-carrageenan and gellan gels. *J. Texture Studies*, 31, 205-223.
- Nussinovitch A., Corradini M.G., Normand M.D., and Peleg M., 2001.** Effect of starch, sucrose and their combinations on the mechanical and acoustic properties of freeze-dried alginate gels. *Food Res. Int.*, 34, 871-878.
- Nussinovitch A., Velez-Silvestre R., and Peleg M., 1993.** Compressive characteristics of freeze dried agar and alginate gel sponges. *Bio-technology Progress*, 9, 101-104.
- Reitsma J.C.E., Thibault J.F., and Pilnik W., 1986.** Properties of amidated pectins. I. Preparation and characterisation of amidated pectins and amidated pectin acids. *Food Hydrocolloids*, 1, 121-127.
- Renou F., Petibon O., Malhiac C., and Grisel M., 2013.** Effect of xanthan structure on its interaction with locust bean gum: Toward prediction of rheological properties. *Food Hydrocolloids*, 32, 2, 331-340.
- Siew C.K. and Williams P.A., 2008.** Role of protein and ferulic acid in the emulsification properties of sugar beet pectin. *J. Agric. Food Chemistry*, 56, 4164-4171.
- Sundaram J. and Durance T.D., 2007.** Influence of processing methods on mechanical and structural characteristics of vacuum microwave dried biopolymer foams. *Food Bioproducts Proc.*, 85(3), 264-272.
- Szulc K. and Lenart A., 2013.** Surface modification of dairy powders: Effects of fluid-bed agglomeration and coating. *Int. Dairy J.*, 33(1), 55-61.
- Tho I., Sande S.A., and Kleinebudde P., 2005.** Cross-linking of amidated low-methoxylated pectin with calcium during extrusion/spheronisation: Effect of particle size and shape. *Chemical Eng. Sci.*, 60, 3899-3907.
- Voragen A.G.J., Pilnik W., Thibault J.F., Axelos M.A.V., and Renard C.M.G., 1995.** *Pectins*. In: *Food polysaccharides and their application* (Ed. A.M. Stephen). Marcel Dekker Inc., New York, USA.
- Weaire D. and Hutzler S., 1999.** *The physics of foams*. New York: Oxford University Press.
- Williams P.A. and Philips G.O., 2000.** *Introduction to food hydrocolloids*. In: *Handbook of hydrocolloids*. (Eds G.O. Phillips, P.A. Williams). Boca Raton, CRC Press, FL, USA.
- Zúñiga R.N. and Aguilera J.M., 2008.** Aerated food gels: fabrication and potential applications. *Trends Food Sci. Technol.*, 19, 176-187.