Int. Agrophysics, 2001, 15, 173-179

INTERNATIONAL
Agrophysics
www.ipan.lublin.pl/int-agrophysics

Influence of material's temperature on compression parameters of ground barley grains

J. Laskowski and S. Skonecki*

Department of Machine Operation in the Food Industry, University of Agriculture, Doświadczalna 44, 20-236 Lublin, Poland

Received December 4, 2000; accepted January 29, 2001

A b s t r a c t. The paper presents the results of studies on the influence of temperature on the parameters of the pressure compression process and on indicators of material's compression ability for grains of four barley cultivars (Ars, Edgar, Klimek and Kos). The quality of the obtained agglomerates was also evaluated. During tests, the rise in compression temperature resulted in compression pressure and compression work drop and improved the compression ability of barley grains. The obtained agglomerates had higher density. Tests on the resistance of the agglomerate's compression and the coefficient of the ability to maintain shape, proved that the higher the temperature of compression, the better the quality of agglomerates obtained.

K e y w o r d s: agglomeration, barley, temperature, parameters of material's compression

INTRODUCTION

The agglomeration process is widely used in many branches of the economy, e.g., in agri-food, chemical, metallurgical industries as well as in pharmacy or pottery, hence it is studied in various scientific fields (Bailey *et al.*, 1995; Bilański *et al.*, 1985; Ewsuk, 1997; Ferrero and Molenda, 1999; Le Deschault de Monredon, 1990; Georget *et al.*, 1994; Kumar, 1973; Laskowski *et al.*, 1997; Melcion, 1995; O'Dogherty, 1989; Paronen and Juslin, 1983).

Individual research on the agglomeration process is carried out on raw materials and feed mixtures (Laskowski *et al.*, 1994; Laskowski and Skonecki, 1997, 1999, 2000). Paper Laskowski *et al.* (1994) presents the procedure of laboratory experiments on the agglomeration of raw materials and feed mixtures and describes the phases of the granulation process. The results obtained show that the process of pressure compression of raw materials and feed mixtures is the basis for the description of phenomena accompanying granulation process. Thus a good knowledge of the compression process carried out at variable technological parameters and for varied raw materials is of great scientific importance. Research on these issues was described, among others, in the works Laskowski and Skonecki (1997, 1999, 2000). The main results of these tests are presented below. The symbols used were explained in the methodology for this research.

Articles by Laskowski and Skonecki (1997, 1999) present research results concerning the influence of moisture on the compression process parameters and on the material's compressibility in legumes' seeds (horse bean, bean, lupine and vetch) and cereal grains (barley, oat, wheat and rye).

It was found that the compression parameters (P_b, L_b' and L_c') drop in direct proportion to the rise in the moisture of the raw materials (in the range of moisture from 10 to 18%, the compression temperature 20°C). The highest parameters' values were obtained for bean (Laskowski and Skonecki, 1997), wheat and rye (Laskowski and Skonecki, 1999); the lowest ones for lupine (Laskowski and Skonecki, 1997) and oats (Laskowski and Skonecki, 1999).

It was also found that a rise in moisture has a positive effect on the raw material's agglomeration ability (described by coefficients k_z and k_c). The best agglomeration ability was shown by lupine seeds (Laskowski and Skonecki, 1997) and oats grains (Laskowski and Skonecki, 1999).

The quality of the obtained agglomerates (endurability assessment) was described by coefficient k_k. It was found that the agglomerate's endurability grows with the rise in the material's moisture (Laskowski and Skonecki, 1997, 1999).

Article by Laskowski and Skonecki (2000) deals with the influence of temperature (t=20-80°C) on compression process parameters in legumes' seeds (the same materials were tested as in paper by Laskowski and Skonecki (1997) at the materials' moisture 14%).

*Corresponding author

It was found, that with the rise of temperature in the range of 20 to 80°C, the density (ρ_b and ρ_c) of the horse bean, bean, lupine and vetch seeds in the chamber, drops for the characteristic points on the compression curve, whereas the agglomerate's density (ρ_k and ρ_{k1}) grows (Laskowski and Skonecki, 2000).

The results showed that the compression pressure P_b and the specific works L_b' and L_c' drop with the rise of temperature. The highest values P_b were obtained for bean - from 122.5 (for t=20°C) to 63.5MPa (for t=80°C) and the lowest ones for lupine - from 69.9 (for t=20°C) to 41.2MPa (for t=80°C). The values L_b' were contained within 8600 to 1850 J kg^{-1} and L_c' from 12950 to 6450 J kg^{-1}. The highest work inputs were shown for horse bean and vetch, the lowest ones for lupine (Laskowski and Skonecki, 2000).

It was also found that the material's compression ability grows with the rise of temperature. The coefficient k_z ranged from 0.016 to 0.065MPa^{-1} and the coefficient k_c from 15.91 to 7.13 J m^{3}kg^{-2} (within the temperature range from 20 to 80°C). Lupine shows the highest compression ability. A similar one is shown by horse bean, bean and vetch (Laskowski and Skonecki, 2000).

A rise in temperature also results in a higher quality of the agglomerate. It was found that coefficient k_k grows with a rise in temperature. The values of this coefficient ranged from 0.01 to 0.208 (the highest values were shown for lupine, the lowest ones for horse bean) (Laskowski and Skonecki, 2000).

This work is a continuation of research on the influence of temperature on the compression parameters of feed materials.

The present study aims at the determination of the influence of material's temperature on the compression process parameters, the product's quality and the compression ability of barley grains.

MATERIALS AND METHODS

The tests involved the following cultivars of barley grains: Ars, Edgar, Klimek and Kos. Raw materials were ground in a general-purpose hammer mill, type Bąk H 111/3 with sieves with a 3 mm mesh. An average particle size of the ground materials (determined according to the standard PN-89/R-64798 - the mesh used was square and sized: 2.0, 1.6, 1.2, 1.0, 0.8, 0.5, 0.4, 0.315, 0.256 mm) was for the cultivar Ars 0.94 mm, Edgar 0.96mm, Klimek 0.99mm and Kos 0.86 mm.

Tests on the compression process of materials' samples were carried out according to the individual methodology of the authors (Laskowski and Skonecki, 1994, 1997, 1999) on a hydraulic press type ZD 40 (Laskowski *et al.*, 1995). The same testing apparatus was used as in the research described in the papers (Laskowski and Skonecki, 1997, 1999, 2000) and the conditions of measurements were the same as in the paper (Laskowski and Skonecki, 2000). A measuring set with a computer recording of the compressing force value and material's deformation was presented in paper (Laskowski and Skonecki, 1995). A densifying set with a closed matrix was used in the tests (an inner diameter of the cylinder d = 25 mm (Laskowski and Skonecki, 1997)). The compression chamber consisted of a cylinder with a piston. The outer part of the cylinder was heated to the required temperature by means of a resistance heater connected to a temperature controller. Temperature was measured by means of a thermoelement (iron-constant) placed in the compression chamber.

The conditions of the compression tests were as follows:

– raw material's humidity 14% (+/- 0.15 %),
– compressed material's mass 0.02 kg,
– compressed material's temperature 20, 40, 60, 80°C,
– piston's speed 0.3 mm s^{-1},
– maximum compression force 100 kN (the maximum unit force 200 MPa).

The tests were carried out as follows. The raw material was adequately moistened. The weight of the 0.02 kg of the raw material was poured into the compression unit chamber, pre-heated to the required temperature. The chamber was immediately closed with a piston so that the sample did not have a chance to change its moisture level. The raw material prepared in that way was then axially compressed (at each time in three repetitions).

During the tests the compression curve was recorded (the change of compression force from the piston's move - material's strain) described in papers (Laskowski and Skonecki, 1994, 1997). Characteristic points B and C were marked on the curve. Compression was carried out for the material from the bulk density ρ_n (when there is no piston pressure) to the maximum density of the material in the chamber ρ_c (at the maximum piston pressure - point C on the curve). Point B divides the compression process into phases. Up to point B, the force grows curvilinearly with the piston's move, the main compression phase occurs. Above point B, up to point C, the pressure is proportional to piston movement.

The following parameters were adopted for the evaluation of the process:

– compression pressure P_b identified for the point B (MPa),
– specific compression work L_b' (the compression work L_b identified up till the point B on the compression curve divided by the mass of the compressed material m, $L_b'=L_b$ m^{-1}) (J kg^{-1}),
– total specific compression work L_c' (the total compression work L_c identified up till the point C on the compression curve divided by the mass of the compressed material m, $L_c'=L_c$ m^{-1}) (J kg^{-1}).

Density values were determined for raw materials in the compression chamber ρ_b and ρ_c (kg m^{-3}) for the characteristic points B and C on the compression curve (Laskowski and Skonecki, 1994).

Coefficients were also determined for the evaluation of the material's susceptibility to granulation:

– coefficient denoting changes in the material's density under pressure: the so called coefficient of the material's ability to densify k_z (MPa^{-1}), $\{k_z=(\rho_b \rho_n^{-1}) P_b^{-1}$, where ρ_n - bulk density (the initial material's density in the compression chamber (kg m^{-3}))$\}$;
– coefficient k_c (J m^{3}kg^{-2}), determining the value of total specific pressing work in relation to the increase in density $\{k_c=(L_c') (\rho_c - \rho_n)^{-1}\}$ (Laskowski and Skonecki, 1997).

The following values were determined for the obtained agglomerates:

– density value just after the agglomerate has left the compression chamber, ρ_k (kg m^{-3});
– density value of the agglomerate after 24 h ρ_{k1} (kg m^{-3}).

After the compression process, the agglomerates were stored in hermetic containers at a temperature of 20°C. After 24 h they underwent resistance tests in the axial compression trials carried out on universal Instron type 4302 (addresses of the firm: Instron Limited, European Headquarters, Coronation Road, High Wycombe, Bucks, HP 12 3SY). The measurements were taken in a room where the temperature was 20°C and the relative air humidity was 65%. An agglomerate in the shape of a cylinder was axially compressed between two parallel plates. The determined values were maximum force destroying a briquette and its resistance ρ_n (MPa). The coefficient of the shape preservation ability k_k (calculated as a quotient of agglomerate's resistance σ_n to compression pressure P_b) was determined, in order to evaluate the quality of the agglomerate.

Results of the tests were statistically analysed. For each raw material, relationships were determined between the tested qualities (material's densities ρ_b, ρ_c, ρ_k, ρ_{k1}; compression parameters P_b, L_b', L_c' and coefficients k_z, k_c, k_k) and the raw material's temperature (t). The measurements were carried out by means of the computer program Statistica (of the firm StatSoft Inc. 2300 East 14 th Street, Tulsa OK 74104). This analysis showed that the interdependencies can be described by linear equations. The obtained regression relations were shown in the tables or presented graphically.

RESULTS AND DISCUSSION

Density of raw material in the compression chamber and of the agglomerate

On the basis of tests' results (Table 1) it can be observed that densities for particular raw materials change similarly depending on temperature. Density of the material in the compression chamber ρ_b and ρ_c drops and density of the agglomerate ρ_k and ρ_{k1} rises with the rise of temperature (Fig. 1). The same changes were observed in tests on leguminous seeds (Laskowski and Skonecki, 2000).

The first change can be related to the volumetric expansion of the material. As for agglomerates obtained in higher temperatures, they show better consistency, which results in their smaller expansion. Exemplary changes in density for particular raw materials are shown in Fig. 2 (density ρ_b, for ρ_c the changes are similar - the values are greater) and in Fig. 3 (density ρ_k, for ρ_{k1} the changes are similar - the values are smaller). The highest density in the agglomeration chamber (ρ_b and ρ_c) and the highest density of the agglomerates (ρ_k and ρ_{k1}) were obtained for the barley cultivar Kos. The other cultivars have comparable density values.

Table 1. Regression equations describing relations of densities ρ_b, ρ_c, ρ_k and ρ_{k1} to temperature t and the values of correlation coefficients R

Density	Barley cultivars	R	Regression equation
For point B	Ars	0.911	ρ_b = 1510.8 - 0.596 t
	Edgar	0.889	ρ_b = 1507.8 - 0.533 t
	Klimek	0.919	ρ_b = 1517.8 - 0.758 t
	Kos	0.901	ρ_b = 1512.7 - 0.517 t
For point C	Ars	0.802	ρ_c = 1546.7 - 0.192 t
	Edgar	0.728	ρ_c = 1541.8 - 0.118 t
	Klimek	0.756	ρ_c = 1554.2 - 0.340 t
	Kos	0.712	ρ_c = 1547.7 - 0.083 t
Agglomerate	Ars	0.721	ρ_k = 1202.0 + 0.182 t
	Edgar	0.697	ρ_k = 1204.3 + 0.098 t
	Klimek	0.732	ρ_k = 1205.2 + 0.095 t
	Kos	0.829	ρ_k = 1202.4 + 0.246 t
Agglomerate after 24 h	Ars	0.815	ρ_{k1} = 1135.9 + 0.799 t
	Edgar	0.750	ρ_{k1} = 1164.8 + 0.497 t
	Klimek	0.715	ρ_{k1} = 1151.6 + 0.582 t
	Kos	0.694	ρ_{k1} = 1164.2 + 0.576 t

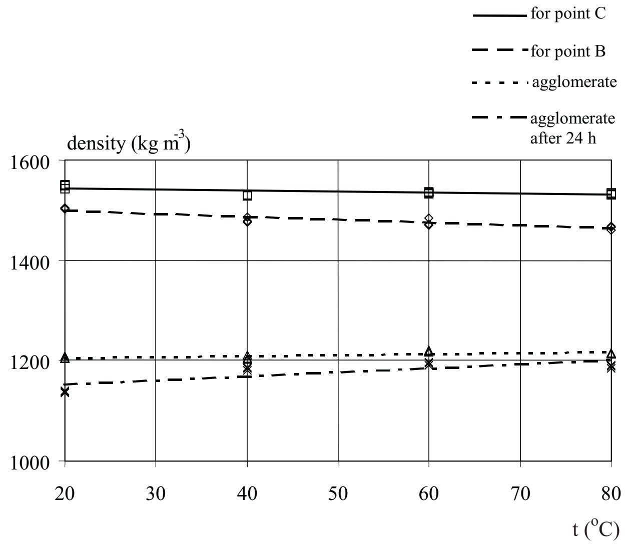

Fig. 1. Relation of barley Ars density for point B (ρ_b) and point C (ρ_c) on the compression curve and of the agglomerate's density on leaving the compression chamber (ρ_k) and after 24 h (ρ_{k1}) to temperature (t).

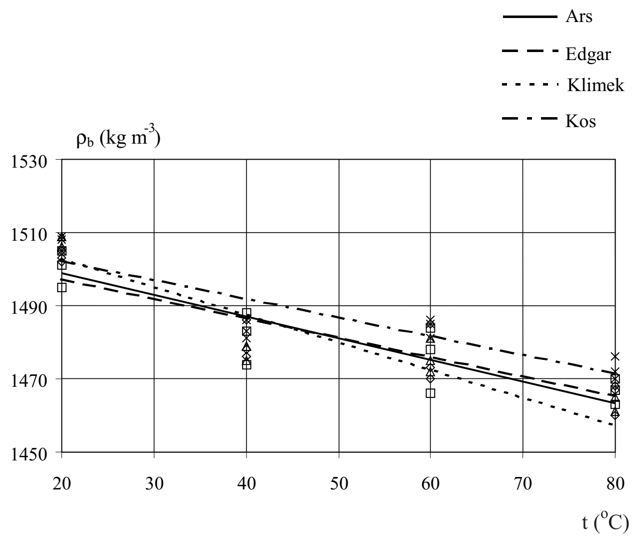

Fig. 2. Relation of density (ρ_b) to temperature (t) for particular barley cultivars.

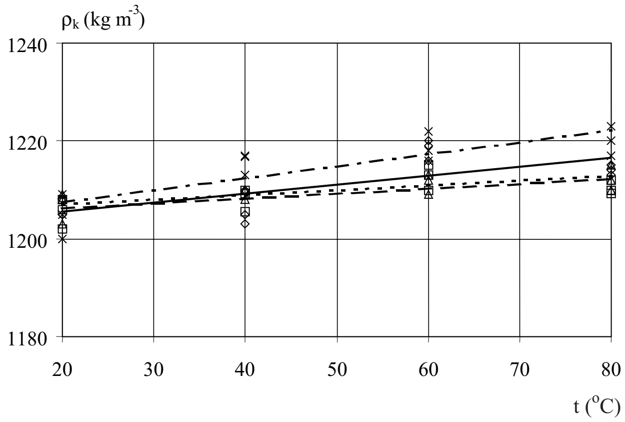

Fig. 3. Relation of the agglomerate's density (ρ_k) to temperature (t) for particular barley cultivars. Legend as in Fig. 2.

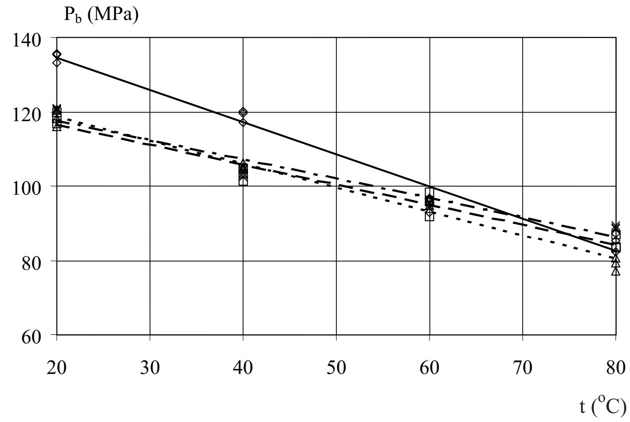

Fig. 4. Relation of compression pressure (P_b) to temperature (t) for particular barley cultivars. Legend as in Fig. 2.

The results of tests obtained on density can be explained by the different chemical composition of particular barley cultivars. Cultivare Kos differed from the others as it had the lowest fibre content 3.42% (other cultivars 4.09-4.71%), protein content 8.82% (other cultivars 10.39-10.94%) and ash content 2.19% (other cultivars 2.24-2.84%). Fat content in this cultivar was 2.05% (in cultivar Ars 2.11, Edgar 1.75, and Klimek 1.71%). It is possible to assume that cultivar Kos shows the highest density in a given temperature because of its low fiber and protein content. The growth of compression temperature in the range of 20-80°C causes changes in protein structure, and starch loses its granular structure. This is confirmed by Korol (1998) who says that protein forms a structure (skeleton) in which starch is placed in the form of gel. And as to fiber, the lower its content, the smaller the elastic strain of the material. This results in a smaller expansion of the agglomerate after its removal from the die (with the growth in temperature the obtained densities σ_b and σ_c drop and the agglomerate's densities σ_k and σ_{k1} grow). It should be stressed that tests on the agglomerate's density (Fig. 1) show a significant material's expansion immediately after its removal from the die (comparing densities σ_c and σ_k). During storage the agglomerate's expansion continues, but to a much smaller extent, and its density drops. After 24 h from the compression process the density of the agglomerate obtained σ_{k1} may be treated as the final agglomerate's density.

Agglomeration parameters

The relation of compression pressure for point B (P_b) to the raw material's temperature is shown in Fig. 4. The highest values of agglomeration pressure were obtained for the barley cultivar Ars - from 135.7 MPa (at t=20°C) to 82.3 MPa (at t=80°C); for the remaining cultivars the pressure values vary from 126 MPa (at t=20°C) to 77 MPa (at t=80°C). As Table 2 and Fig. 4 show, compression pressure values drop linearly along with the temperature rise for all the tested raw materials.

The highest density parameters obtained in a given temperature by cultivar Ars result from the highest fiber and ash content. These factors may cause the stronger material's friction against compression chamber walls as well as friction within the material, whereas a rise in compression temperature results both in a change in chemical properties

T a b l e 2. Regression equations describing relation of compression parameters P_b, L_b' and L_c' to temperature t and the values of correlation coefficients R

Parameter	Barley cultivars	R	Regression equation
Compression pressure	Ars	0.987	P_b = 151.7-0.864 t
	Edgar	0.981	P_b = 127.5-0.543 t
	Klimek	0.989	P_b = 131.5-0.637 t
	Kos	0.969	P_b = 128.0-0.521 t
Specific compression work	Ars	0.986	L_b'= 12375.0-79.8 t
	Edgar	0.978	L_b'= 8975.0-58.3 t
	Klimek	0.973	L_b'= 9108.3-56.8 t
	Kos	0.973	L_b'= 9200.0-48.4 t
Total specific compression work	Ars	0.957	L_c'= 14783.3-59.3 t
	Edgar	0.973	L_c'= 11283.3-33.0 t
	Klimek	0.961	L_c'= 11598.3-39.0 t
	Kos	0.955	L_c'= 11800.0-30.4 t

Relations between the specific compression work (L_b') and temperature are presented in Fig. 5. The specific compression work values vary from 3900 to 10750 J kg^{-1}. The highest work expenditure was obtained for the cultivar Ars. As Fig. 5 shows, specific compression work drops linearly along with the temperature rise. Total specific compression work (L_c') changes similarly (Table 2). The values of this work for the tested materials vary from 8450 to 13700 J kg^{-1}. Generally, it is possible to conclude that specific works L_b' and L_c' drop along with the temperature rise of ground barley grains.

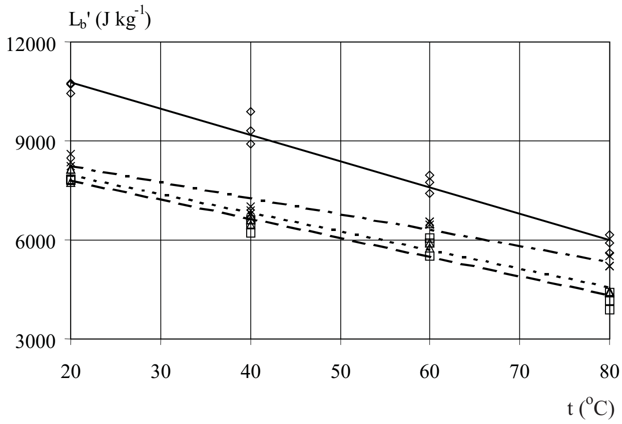

Fig. 5. Relation of specific compression work (L_b') to temperature (t) for particular barley cultivars. Legend as in Fig. 2.

and in physical properties (mainly mechanical) in the material's grain. The conditions of the material's friction can change and the raw material can become softer and more plastic which results in a greater plastic strain of the material and thus in smaller pressure P_b and compression works L_b' and L_c'.

Changes of barley's compression parameters resulting from a rise in temperature are similar to those of the leguminous seeds compression. For the cultivars Edgar, Klimek and Kos the values are comparable to the parameters obtained for horse bean, bean and vetch (Laskowski and Skonecki, 2000).

Evaluation of the material's compressibility

The material's compression ability was determined using coefficients k_z and k_c. Table 3 shows regression equations describing relations of these coefficients to temperature.

Figure 6 presents changes of material's compressibility coefficient (k_z) depending on temperature. For the tested materials this coefficient varies from 0.0218 to 0.0357 MPa^{-1}. The value of this coefficient is fairly similar for particular barley cultivars. Coefficient k_z rises along with the temperature rise in all the tested materials.

Figure 7 presents relation of coefficient k_c to the material's temperature. Values of this coefficient vary from 13.12 to 8.33 J m^{3}kg^{-2} (in the material's temperature's range from 20 to 80°C). Coefficient k_c is in direct proportion to total specific compression work. The higher the value of this

T a b l e 3. Regression equations describing relation of coefficients k_z, k_c and k_k to temperature t and the values of correlation coefficients R

Parameter	Barley cultivars	R	Regression equation
k_z	Ars	0.974	k_z = 0.0174+0.00020 t
	Edgar	0.983	k_z = 0.0214+0.00014 t
	Klimek	0.954	k_z = 0.0202+0.00021 t
	Kos	0.953	k_z = 0.0205+0.00013 t
k_c	Ars	0.967	k_c = 13.958-0.0529 t
	Edgar	0.971	k_c = 11.107-0.0319 t
	Klimek	0.963	k_c = 11.681-0.0339 t
	Kos	0.984	k_c = 11.830-0.0305 t
k_k	Ars	0.977	k_k = 0.0175+0.000701 t
	Edgar	0.948	k_k = 0.0128+0.000460 t
	Klimek	0.968	k_k = 0.0158+0.000495 t
	Kos	0.949	k_k = 0.0125+0.000412 t

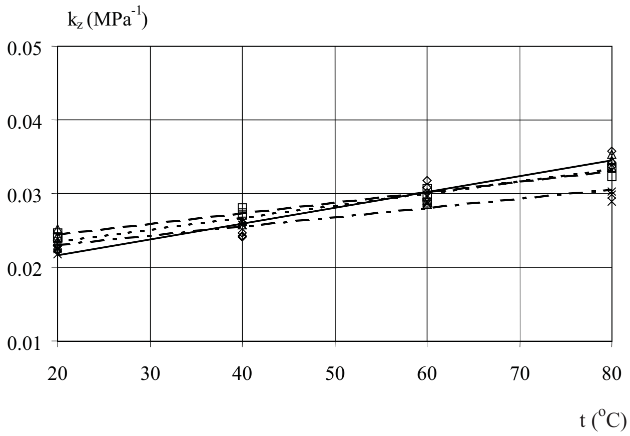

Fig. 6. Relation of the materials compressibility coefficient (k_z) to temperature (t) for particular barley cultivars. Legend as in Fig. 2.

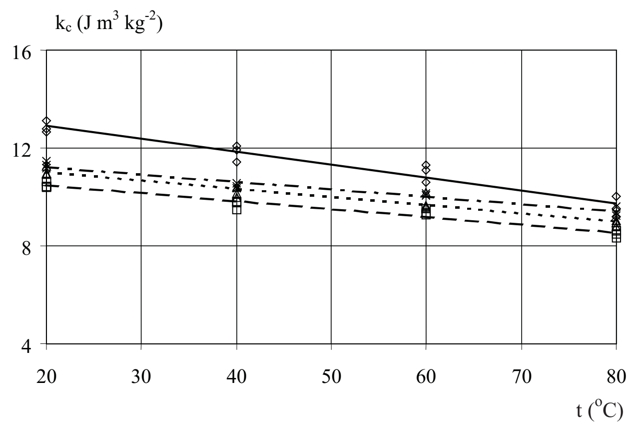

Fig. 7. Relation of the materials compressibility coefficient (k_c) to temperature (t) for particular barley cultivars. Legend as in Fig. 2.

work, the higher the coefficient is. It is also affected by density in the bulk state and final density of the material in the compression process. The results lead to the conclusion that coefficient k_c drops along with the temperature rise in the tested materials (and the material's compressibility increases). The highest values of the coefficient were obtained for the cultivar Ars. It may be explained similarly as changes of compression parameters.

Generally one can notice that the barley cultivars studied have a similar compression ability with ground seeds of the horse-bean, bean and vetch (Laskowski and Skonecki, 2000). The growth of compression ability with an increase of temperature may be explained, as for compression parameters, by changes of chemical and physical properties.

Hence changes of coefficients k_z and k_c are related to changes of compression parameters. They contain both changes of density and compression pressure (coefficient k_z) or changes of compression work (coefficient k_c). Therefore of this, they characterize material's compression ability in a more efficient way.

Evaluation of the quality of the obtained agglomerates

Table 3 presents regression equations describing relations between the coefficient of shape preservation k_k and temperature; Fig. 8 shows their graphic interpretation. The value of the coefficient of shape preservation is evidently affected by compression pressure and the agglomerate's resistance to compression. Results of the tests prove that this coefficient rises along with the rise of temperature (Fig. 8). Its values vary from 0.017 to 0.074. The highest values were obtained for the barley cultivar Ars and the lowest ones for the cultivar Kos. The influence of compression temperature on agglomerate quality can be explained by changes of chemical properties (similar to changes of density).

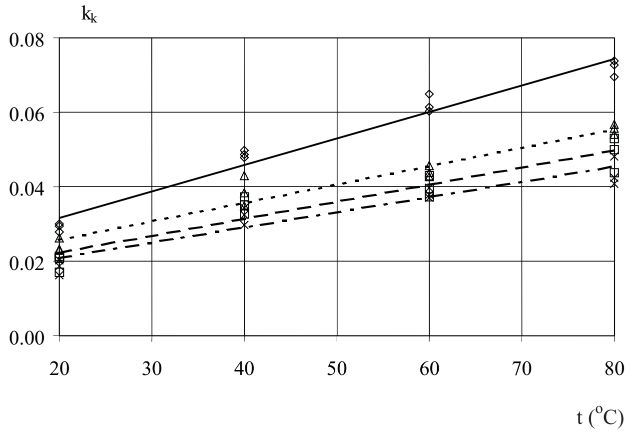

Fig. 8. Relation of the materials compressibility coefficient (k_k) to temperature (t) for particular barley cultivars. Legend as in Fig. 2.

CONCLUSIONS

1. Compression temperature affects both the density of the raw material in the process of compression in the chamber and the density of the agglomerate.

2. Along with the rise of temperature, the value of barley's density in the chamber drops for the curve's characteristic points, and the density of the obtained agglomerate rises.

3. A rise in the temperature of the material results in the change of the compression process parameters. Values of compression pressure and specific compression work drop along with the rise in temperature. The highest values of compression barley cultivar Ars whereas the remaining cultivars stay fairly similar.

4. Tests on the coefficients of material's compressibility show the higher temperature gets, the better is the material's ability for compression. The tested barley cultivars show fairly similar compressibility.

5. A rise in the temperature of the material results in better endurance quality of the obtained agglomerates. Cultivar Ars shows the best quality of the agglomerates.

REFERENCES

Bailey A.C., Raper R.L, Johnson C.E., and Burt E.C., 1995. An integrated approach to soil compaction prediction. J. Agric. Engng Res., 61, 73-80.

Bilański W.K., Graham V.A., and Hanusiak J.A., 1985. Mechanics of bulk forage deformation with application to wafering. Trans. ASAE, 28 (3): May-June, 697-702.

Ewsuk K.G., 1997. Compaction science and technology. Materials Research Society Bulletin, 22(12), 14-18.

Faborode M.O. and O'Callaghan J.R., 1986. Theoretical analysis of the compression of fibrous agricultural materials. J. Agric. Engng Res., 35, 175-191.

Ferrero A. and Molenda M., 1999. Device for continuous measurement of straw briquette expansion. Int. Agrophysics, 13, 87-92.

Georget D.M.R., Parker R., and Smith A.C., 1994. A study of the effects of water content on the compaction behaviour of breakfast cereal flakes. Powder Technology, 81, 189-195.

Korol W., 1998. Influence of thermal treatment on the nutritious components of feed - fundamental alimentary components (p.1) (in Polish). Pasze Przemysłowe, 4, 21-24.

Kumar M., 1973. Compaction behaviour of ground corn. J. Food Sci., 38, 877-878.

Laskowski J., de Monredon F., Skonecki S., and Melcion J.-P., 1994. Testing procedure of pelletability of ingredients and compound feeds. Int. Agrophysics, 8, 643-648.

Laskowski J., Le Deschault de Monredon F., and Soumah A.T., 1997. Multidimensional analysis of the pelletability of feeds and feed mixtures. Int. Agophysics, 11, 229-233.

Laskowski J. and Skonecki S., 1994. The method for the determination of the biological materials pressure agglomeration (in Polish). Proc. Conf. Theory and Technology Development in Agriculture Technical Modernisation, Univeristy of Technology and Agriculture, Olsztyn, 29-33.

Laskowski J. and Skonecki S., 1997. Influence of moisture on the physical properties and parameters of the compression process of legumes' seeds. Int. Agrophysics, 11, 245-256.

Laskowski J. and Skonecki S., 1999. Influence of moisture on the physical properties and parameters of the compression process of cereal grains. Int. Agrophysics, 13, 477-486.

Laskowski J. and Skonecki S., 2000. Effect of material temperature on densification parameters of leguminous seeds (in Polish). Inżynieria Rolnicza, 5(16), 133-146.

Laskowski J., Skonecki S., and Gowin J., 1995. Measuring system for testing machines of type ZD with computer registration and analysis of compression process parameters (in Polish). Zesz. Probl. Post. Nauk Roln., 424, 279-284.

Le Deschault de Monredon F., 1990. Axial compression as a model for studying the granulation of feed powders. Sci. Des Aliments, 10, 189-202.

Melcion J.P., 1995. Testing procedures for pelleting research. Feed Mix, 3(5), 33-37.

O'Dogherty M.J., 1989. A Review of the mechanical behaviour of straw when compressed to high densities. J. Agric. Engng Res., 44, 241-265.

Paronen P. and Juslin M., 1983. Compressional characteristics of four starches. J. Pharm. Pharmocol., 35, 627-635.