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INFLUENCE OF MOISTURE ON THE PHYSICAL PROPERTIES AND PARAMETERS OF THE COMPRESSION PROCESS OF CEREAL GRAINS

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A b s t r a c t. The paper presents results of studies on the influence of moisture on the physical properties and parameters of the pressure compression process of cereal grains. The studies covered ground grains of wheat, barley, oat and rye with varied moisture levels. Quantitative coefficients of the material's ability for compression were also determined. They can be used for the classification of raw materials and fodder mixes with respect to their granulability.

K e y w o r d s: biological materials, physical properties, compression, granulability

INTRODUCTION

The agglomeration process is widely used in many branches of economy, eg. in agri-food, chemical and metallurgical industry, in pharmacy or pottery [4]. Hence, this process is studied at various aspects by different sciences [1-3,5-9,15-19]. Individual research on the agglomeration process is carried out on raw materials and fodder mixes. One of the aims of the study is explanation of the phenomena occurring during process of changes in the material at the compression stage [11,12,14]. Information on the influence of variable physical properties on the course of this process has also remarkable practical meaning.

The results of studies presented here are the continuation of analysis [12], in which the influence of moisture on the physical properties and pressure parameters for legumes' seeds was analysed. The present research has been carried out by means of the same methods as presented in many analyses [10-12,14].

MATERIALS AND METHODS

The studies included ground kernels of barley (variety Edgar), oat (variety Dragon), wheat (variety Almary) and rye (variety Dankowska Nowa).

Raw materials were ground in a mill type Bak H 111/3 with sieves with 3 mm mesh. An average particle size (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) of the raw materials at the moisture level of 14% was: 0.955 mm for barley, 1.136 mm for oat, 1.192 mm for wheat, and 1.025 mm for rye.

The analyses of physical properties and compression process were made for raw materials at varied moisture levels ranging from 10 to 18% (every 2%).

Studies on the physical properties of raw materials included:

- density in the bulk state (ρ_n) - relation of the mass of loosely poured material to the volume it takes up (according to PN-73/R-74007),
- density in the shaken up state (ρ_u) - relation of the material mass after shaking up (on the device type Backer-Rosenmuller) to the volume it takes up (according to PN-70/R-74010),

- angle of repose (γ_u) - angle of inclination of the cone's generating line to the cone's base in the cone created by the material loosely poured from the height of 0.07 m on to a flat metal disc with 0.12 m diameter (according to PN-65/Z-04005),
- angle of slide (γ_z) - the minimal angle of inclination of a tilting plate (an ebonite plate was used) at which the material placed on the plate's surfaces starts sliding down,
- coefficient of internal friction (μ_b) - calculated on the apparatus for direct cutting (the principle of calculation was presented elsewhere [12]).

Studies on the compression process of material samples were carried out on a hydraulic press type ZD 40 [13] according to the methods by the present authors [10,12]. The testing apparatus and measuring conditions were the same as in the studies on legumes' seeds [12].

A measuring set with a computer recording of the compressing force value and material deformation, adjusted to cooperate with the ZD-40 press was presented in the paper [13]. A densifying set was used for the present study. It contained a closed matrix (an inner diameter of the cylinder d = 25 mm) [12].

Material samples of 20 g were compressed. The maximum densifying force was F_{max} = 100 kN, and the piston speed v = 0.3 mm s^{-1}. A compression curve presented in the paper [12] was observed during the experiment.

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

- compression pressure P_b (MPa),
- the specific compression work (L_b') (J g^{-1}),
- the total specific compression work (L_c') (J g^{-1}).

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

- coefficient denoting changes in the material density under pressure the so called coefficient of the material ability to densify k_1 (MPa^{-1}),
- coefficient k_2 ((J g^{-1})(g cm^{-3})$^{-1}$) determining the value of the specific compression work related to the increase in the material density,
- coefficient k_3 ((J g^{-1})(g cm^{-3})$^{-1}$) determining the value of total specific compression work related to the increase of density [10,12].

The tablets obtained were subjected to resistance tests in the axial compression trials carried out on an universal Instron type 4302. The agglomerate in the shape of a cylinder was axially compressed between two parallel plates. The maximum force destroying the briquette was determined and the resistance σ_n (MPa) was calculated. For the evaluation of the obtained compressed product (briquette), the coefficient of the shape preservation ability k_4 was calculated as a quotient of the agglomerate endurance σ_n to the densifying pressure P_b [12].

The above mentioned features of the compression process were determined for the analysed material and for a given moisture level in three repetitions.

The study results were subjected to statistical analysis. For each of the raw materials relations between the physical parameters, pressing parameters and coefficients (k_1, k_2, k_3, k_4) and the material moisture (W) were determined. Using the statistic file 'Statistica' regression relations and the values of the determination coefficient (R^2) were found. The statistical analysis allowed for the assumption of the linear relations or polynomials of the second degree. The study results were presented in tables in the form of regression relations. Some chosen relations were presented on graphs.

RESULTS AND ANALYSIS

Results and studies on the physical properties of the raw materials

Relations of the density in the bulk state (ρ_n) and density in the shaken up state (ρ_u) to the raw material moisture level were given in Table 1 in the form of regression equations and the values of the determination coefficients R^2.

As the analysis of the regression equations shows, changes in the density levels with the increase in the moisture level are similar for the

Table 1. Regression equations of the relation between the density in the bulk state (ρ_n) and density in the shaken up state (ρ_u) to material moisture (w) and the values of determination coefficients (R^2)

Density	Material	R^2	Regression equation
In the bulk state	barley	0.641	$\rho_n = -0.0001\ w^2 + 0.548$
	oat	0.562	$\rho_n = -0.001\ w^2 + 0.0269\ w + 0.1719$
	wheat	0.751	$\rho_n = -0.023\ w^2 + 0.0611\ w + 0.2607$
	rye	0.821	$\rho_n = 0.0001\ w^2 - 0.0081\ w + 0.7504$
In the shaken up state	barley	0.887	$\rho_u = -0.0053\ w + 0.673$
	oat	0.615	$\rho_u = -0.0015\ w^2 + 0.0419\ w + 0.1243$
	wheat	0.926	$\rho_u = -0.0019\ w^2 + 0.0473\ w + 0.4228$
	rye	0.771	$\rho_u = -0.0007\ w^2 - 0.0171\ w + 0.8326$

studied materials. Differences appear in individual values. Figure 1 presents some examples of the relations for the density in the bulk state. They are included in the interval from 0.340 to 0.678 g cm^{-3}. The values of the density in the shaken up state range from 0.390 to 0.752 g cm^{-3}. The highest density values were obtained for wheat and rye (similar values) and the lowest for oat. The analysis of the results shows that both density in the bulk state and density in the shaken up state change little with the change in moisture level. For barley and rye a slight decrease of density has been observed with the increase in the material moisturge level.

Relation between the angle of repose (γ_u) and angle of slide (γ_z) was given in Table 2 in the form of regression equations. Figure 2 shows examples of the relations for the angle of repose, which are included in the interval from 37.9 to 48.2^o. The highest and the lowest values were obtained for oat. In this material the angle of repose remarkably increases with the increase in moisture level. It may be related to a greater loosening (bulging) of the fibre structure of oat accompanying moisture increase, which can result in the greater internal friction on cohesion forces. Wheat and rye with the moisture level of 10 to 18% show the increase in the angle of repose ranging from 39.1 to 43^o. In barley the angle of repose increases slightly from 44 to 45.5^o with the increase in moisture level.

The values of the angle of slide range from 16 to 36.5^o. The highest values were obtained for oat and wheat and the lowest for barley and rye (similar values). For barley, wheat and rye

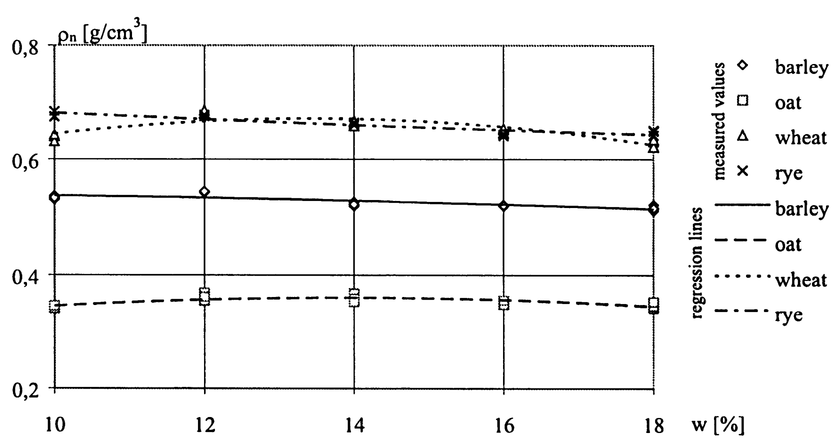

Fig. 1. Relation of density in the bulk state (ρ_n) to material moisture (w).

Table 2. Regression equations of the relation between the angle of repose (γ_u) and the angle of slide (γ_z) to material moisture (w) and the values of determination coefficients (R^2)

Angle	Material	R^2	Regression equation
Of repose	barley	0.606	$\gamma_u = 0.0065\ w^2 + 43.39$
	oat	0.958	$\gamma_u = -\ 0.0381\ w^2 + 2.32\ w + 18.49$
	wheat	0.966	$\gamma_u = 0.00058\ w^2 + 38.17$
	rye	0.785	$\gamma_u = 0.4\ w^2 + 35.527$
Of slide	barley	0.849	$\gamma_z = 0.825\ w + 8.983$
	oat	0.826	$\gamma_z = 0.4137\ w^2 + 11.325\ w - 44.22$
	wheat	0.942	$\gamma_z = 0.0286\ w^2 + 26.39$
	rye	0.800	$\gamma_z = 0.0145\ w^2 + 18.71$

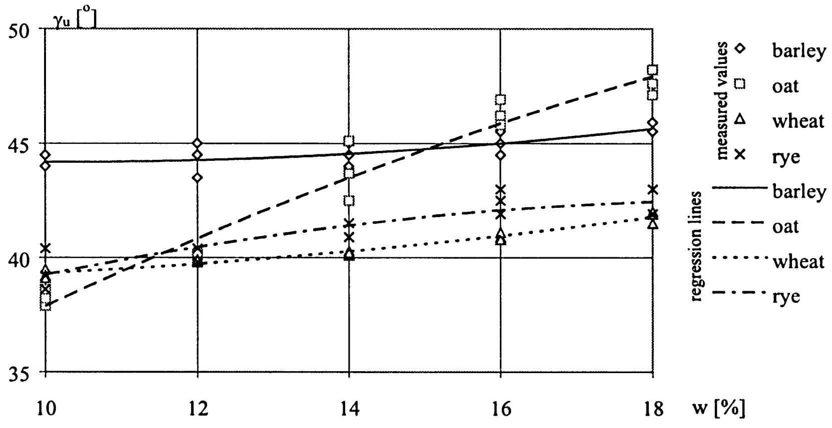

Fig. 2. Relation of the angle of repose (γ_u) to material moisture (w).

values of the angle of slide increase with the increase in moisture level. And for oat the angle of slide increases for the moisture range from 10 to 14% and decreases for the range from 14 to 18%.

Table 3 shows the relation between the coefficient of internal friction (μ_b) and material moisture in the form of regression equations. The relations are shown on graphs in Fig. 3. The values of coefficients of internal friction range from 0.51 to 0.88. The highest values were obtained for wheat and the lowest for barley. The coefficient of internal friction in barley, rye and wheat has higher values with the increase in moisture level and for oat it changes slightly (it increases in the moisture range from 10 to 14%, and decreases in the moisture range from 14 to 18%).

Table 3. Regression equations of the relation of the internal friction coefficient (μ_b) to material moisture (w) and the values of determination coefficients (R^2)

Parameter	Material	R^2	Regression equation
Internal friction coefficient	barley	0.807	$\mu_b = 0.00068\ w^2 + 0.426$
	oat	0.860	$\mu_b = -0.0018\ w^2 + 0.0502\ w + 0.2754$
	wheat	0.843	$\mu_b = -0.0025\ w^2 + 0.0927\ w - 0.008$
	rye	0.841	$\mu_b = 0.00072\ w^2 + 0.549$

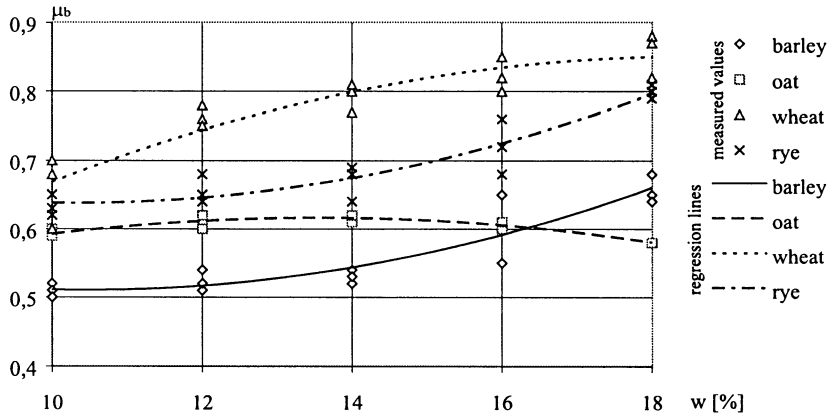

Fig. 3. Relation of the coefficient of internal friction (μ_b) to material moisture (w).

Results and studies on the process of pressure compression

Figure 4 shows the relation of compression pressure (P_b) to material moisture level. Regression equations describing these relations and the values of determination coefficient R^2 were given in Table 4.

The highest values of compression pressure were obtained in wheat - from 146.08 MPa (for W= 10%) to 79.73 MPa (for W= 18%) and rye - from 142.17 to 90.73 MPa, and the lowest for oat - from 104.34 to 61.47 MPa (Fig. 4). The values of pressure for barley ranged from 133.94 to 95.87 MPa (in the range of moisture levels from 10 to 18%). As shown in Table 4 and Fig. 4 compression pressure decreases linearly with the increase in moisture level for all the studied materials.

Figure 5 shows relations between specific energy expenditure for compression (L_b') and moisture. Regression equations describing these relations and the values of coefficient R^2 are presented in Table 4.

The values of the specific work for compression ranged from 3.85 to 11.85 J g^{-1} (Fig. 5). The highest expenditure of this work was obtained for rye, and the values vary with the increase in moisture level in the range from 11.85 to 5.5 J g^{-1}, and the lowest ones for oat from 7.75 to 3.85 J g^{-1}. As shown in Fig. 5 specific work for compression decreases linearly with the increase in material moisture level.

Total specific compression work (L_c') changed similarly to the specific work for compression (Table 4). The value of this work for the studied materials ranged from 15.6 to 9.1 J g^{-1}. The range is the same as for the values obtained for rye. In this material the greatest decrease of the total specific compression work value was observed with the increase in the moisture level. Generally it has been observed that specific works (L_b' and L_c') decreased in direct proportion to the increase in the moisture level of the ground cereal kernels.

Studies on the material compression ability

Material compression ability was determined by means of coefficients (k_1, k_2, k_3). Table 5 shows regression equations describing relations of these coefficients to moisture and the values of determination coefficients of (R^2).

Figure 6 presents the relation of material compression ability coefficient (k_1) to material moisture. For the studied materials this coefficient ranges from 0.016 to 0.069 MPa^{-1}. The value of this coefficient increases with the increase in moisture level for all the studied materials. The greatest changes and the highest values of the coefficient were obtained for oat (0.041 - 0.026 MPa^{-1}), and the lowest for wheat (0.016 - 0.029 MPa^{-1}) and rye (0.016-0.026 MPa^{-1}).

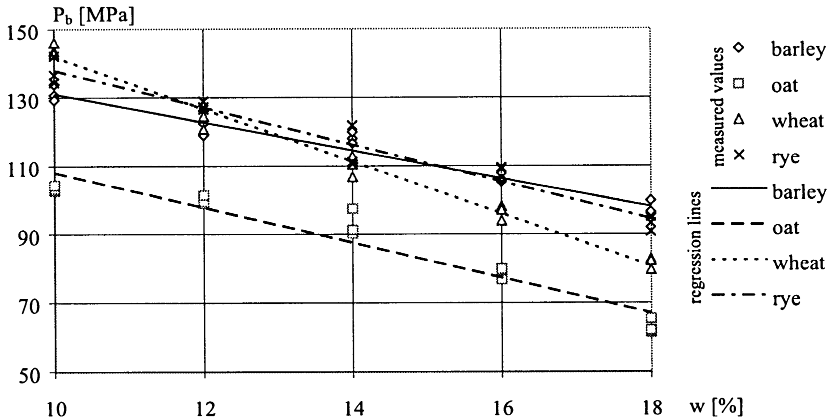

Fig. 4. Relation of compression pressure (P_b) to material moisture (w).

T a b l e 4. Regression equations of the relation between compression pressure (P_b), specific works (L_b') and (L_c') to material moisture (w) and the values of determination coefficients (R^2)

Parameter	Material	R^2	Regression equation
Compression pressure	barley	0.955	$P_b = -4.1208\,w + 172.31$
	oat	0.921	$P_b = -5.1249\,w + 159.31$
	wheat	0.986	$P_b = -7.6503\,w + 218.48$
	rye	0.953	$P_b = -5.4306\,w + 192.34$
Specific works	barley	0.913	$L_b' = -0.286\,w + 11.85$
		0.907	$L_c' = -0.276\,w + 14.82$
	oat	0.960	$L_b' = -0.492\,w + 12.84$
		0.947	$L_c' = -0.387\,w + 16.25$
	wheat	0.962	$L_b' = -0.678\,w + 17.26$
		0.898	$L_c' = -0.681\,w + 21.01$
	rye	0.967	$L_b' = -0.736\,w + 18.55$
		0.930	$L_c' = -0.784\,w + 22.63$

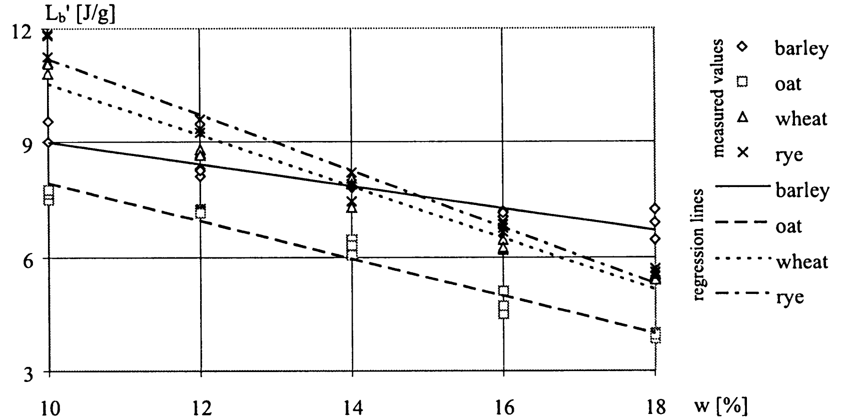

Fig. 5. Relation of specific compression work (L_b') to material moisture (w).

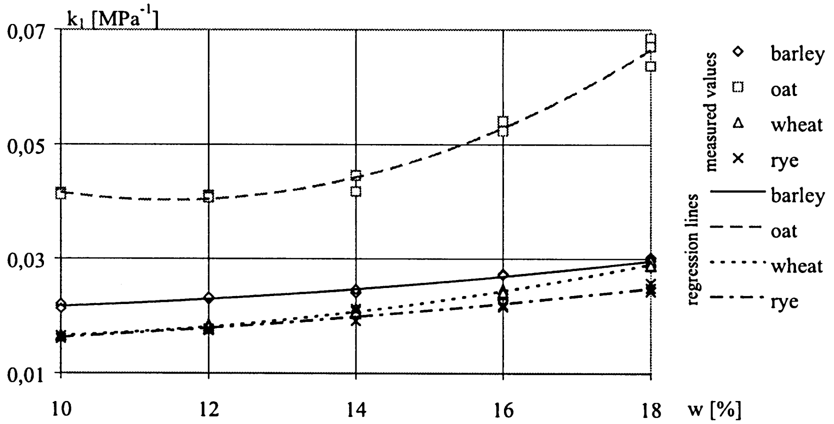

Fig. 6. Relation of coefficient of material ability to densify (k_1) to material moisture (w).

Figure 7 shows the relations of coefficient (k_2) to material moisture level. The highest values were obtained for rye and the lowest for oat. The analysis of the results shows that the coefficient (k_2) decreases with the increase of moisture level in all the studied materials.

As the regression equations have shown (Table 5) relations between k_3 coefficient and moisture are of a similar form and course as the relations for the k_2 coefficient. The highest values of coefficients were obtained for rye and the lowest for oat. The coefficient (k_3) is in direct proportion to the specific work of compression [14]. The higher the value of specific work, the higher the coefficient. What is more the coefficient is also affected by the density in the bulk state and final density of the material during the process of compression.

Analysis of the results shows that with an increase in moisture level the values of coefficients (k_2, k_3) decrease for all the studied materials. The lowest values were obtained for oat, the highest for rye and wheat. And for barley at low moisture levels from 10 to 14% the values of the coefficients were medium, whereas at higher moisture levels they were similar to the values obtained for wheat and rye.

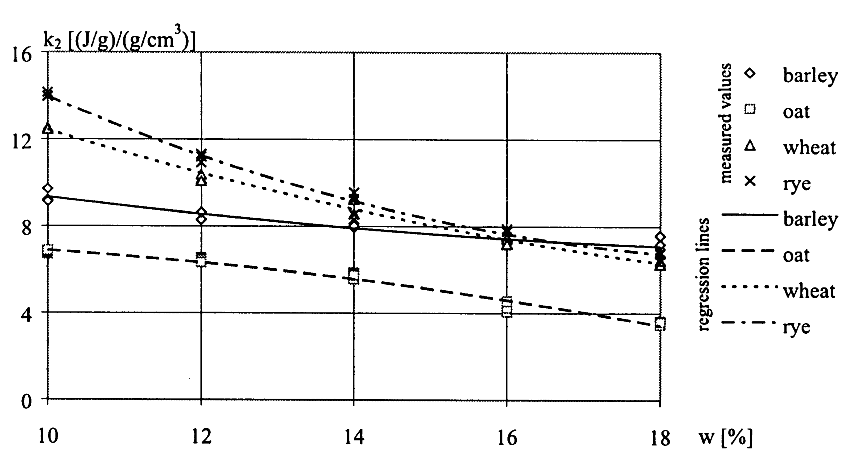

Fig. 7. Relation of coefficient determining the values of the specific compression work releted to the increase in material density (k_2) to material moisture (w).

Table 5. Regression equations of the relation of coefficients (k_1), (k_2) and (k_3) to material moisture (w) and the values of determination coefficients (R^2)

Coefficient	Material	R^2	Regression equation
k_1	barley	0.973	$k_1 = 0.000035\,w^2 + 0.0179$
	oat	0.985	$k_1 = 0.0006\,w^2 - 0.014\,w + 0.121$
	wheat	0.993	$k_1 = 0.0001\,w^2 - 0.0021\,w + 0.024$
	rye	0.957	$k_1 = 0.000038\,w^2 + 0.0123$
k_2	barley	0.919	$k_2 = 0.0189\,w^2 - 0.8109\,w + 15.559$
	oat	0.968	$k_2 = -0.015\,w^2 + 8.505$
	wheat	0.988	$k_2 = 0.0376\,w^2 - 1.8186\,w + 26.861$
	rye	0.992	$k_2 = 0.0754\,w^2 - 3.0166\,w + 36.593$
k_3	barley	0.937	$k_3 = 0.0258\,w^2 - 0.9866\,w + 19.269$
	oat	0.939	$k_3 = -0.0117\,w^2 + 11.50$
	wheat	0.980	$k_3 = 0.0697\,w^2 - 2.6923\,w + 35.934$
	rye	0.990	$k_3 = 0.1147\,w^2 - 4.1221\,w + 47.313$

Evaluation of the quality of agglomerates obtained

The quality of the obtained agglomerates was determined with respect to their resistance to compression (σ_n) and with the use of the coefficient of shape preservation (k_4). Table 6 shows the regression equations describing relations of resistance to compression and coefficient of shape preservation to material moisture level and the values of coefficients of determination R^2.

The resistance of barley wheat and rye agglomerates increased with the increase in material moisture level from 10 to about 14-16% (differently for individual cereals), whereas in the moisture range from 16 to 18% the resistance decreases. The resistance of oat agglomerates decreases with the increase in moisture level. The highest resistance was noted for the oat agglomerate (7.29-4.98 MPa) and the lowest for the rye agglomerate (0.35-1.16 MPa).

Figure 8 shows the relation of the coefficient of shape preservation to moisture level. A significant influence on the coefficient of shape preservation was exerted by the compression pressure and agglomerate resistance to compression [12]. The results of the studies show that the coefficient of shape preservation varies differently for specific materials with the increase in moisture level (Fig. 8). The values of this coefficient range from 0.002 to 0.085. The highest values were obtained for oat (0.062-0.083) and the lowest for rye (0.002-0.011).

CONCLUSIONS

The studies carried out on some chosen cereals allow for drawing the following conclusions:

1. The densities in the bulk state and in the shaken up state for specific materials do not show uniform tendencies for either increasing or decreasing with changes in moisture level. The angles of repose and slide as well as the coefficient of internal friction change with the increase in material moisture level. The character of these changes is different for the different varieties studied.

2. An increase in material moisture level causes a decrease in compression pressure and in specific compression and pressure work. The highest values of compression parameters were obtained for wheat and rye, and the lowest for oat.

3. An increase in moisture level has a positive clearly effect on material granulability. Oat has the best granulability (the highest values of k_1 and the lowest of k_2 and k_3). Wheat and rye have similar quality of granulability.

4. Material moisture level affects differently the quality of agglomerates determined in terms of resistance to compression and of shape preservation coefficient. This results from different chemical composition of the studied cereals.

Table 6. Regression equations of the relation of agglomerate's resistance (σ_n) and coefficient (k_4) to material moisture (w) and the values of determination coefficients (R^2)

Parameter	Material	R^2	Regression equation
Agglomerate resistance	barley	0.919	$\sigma_n = -0.0863\ w^2 + 2.557\ w - 16.61$
	oat	0.931	$\sigma_n = -0.0013\ w^2 - 0.2026\ w + 9.145$
	wheat	0.879	$\sigma_n = -0.0325\ w^2 + 1.072\ w - 7.214$
	rye	0.821	$\sigma_n = -0.0306\ w^2 + 0.901\ w - 5.618$
Coefficient k_4	barley	0.910	$k_4 = -\ 0.0007\ w^2 + 0.021\ w - 0.1385$
	oat	0.823	$k_4 = 0.0005\ w^2 - 0.0131\ w + 0.146$
	wheat	0.931	$k_4 = -\ 0.0002\ w^2 + 0.0067\ w - 0.049$
	rye	0.813	$k_4 = -\ 0.0002\ w^2 + 0.0072\ w - 0.0464$

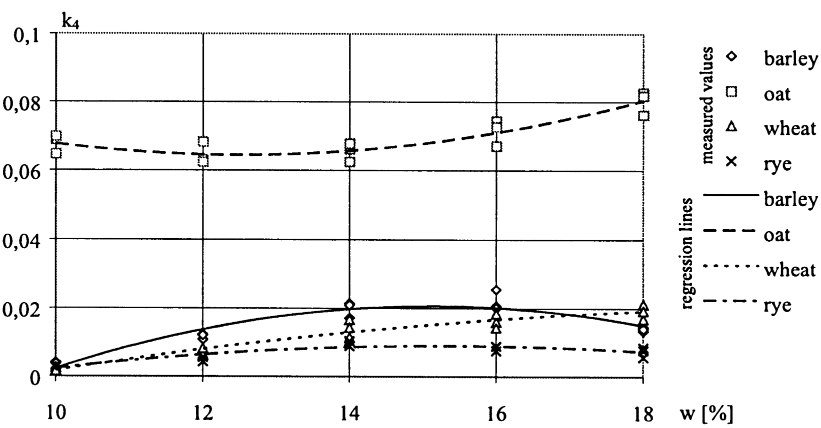

Fig. 8. Relation of coefficient of shape preservation (k_4) to material moisture (w).

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