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RESEARCH ARTICLE

Variation in the Density of a Protein Paste and Ground Feed Grain Mixture under Pressure

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ABSTRACT

The wet fractionation technology for the green biomass of cultivated grasses, developed at the Research Laboratory of Green Feed Concentrates of Don State Technical University, makes it possible to obtain protein paste — a nutritionally complete substitute for animal-derived proteins. To produce dry pelleted feed additives, protein paste is mixed with ground feed grain, followed by pelleting and drying. The determination of the design and operating parameters of pressing equipment requires data on the physicomechanical properties of the processed mixture. The aim of this study was to experimentally determine the dependence of the density of a protein paste and ground feed grain mixture on pressing pressure at different paste moisture contents, particle-size distributions of the ground feed grain, and component mass ratios. Measurements were performed gravimetrically using a compression chamber and an R-10 universal testing machine capable of applying a maximum load of 6,000 kgf. Mixtures with protein paste moisture contents of 63.79% and 89.64% and K_{mix} values ranging from 0.333 to 2 were studied. The dependence of mixture density on pressure was adequately described by regression equations whose coefficients were determined for all compositions studied. The resulting relationships can be used to calculate the energy and load parameters of pressing equipment and to design production lines for pelleting feed mixtures of a specified composition.

INTRODUCTION

The development of energy-efficient technologies for producing plant-based feed additives is an important area of agricultural engineering research. Technologies for the deep processing of the green biomass of cultivated grasses are of particular interest, as they make it possible to obtain protein concentrates with high protein and carotene contents (Dolgov and Proydak, 1990; Dolgov and Popov, 1999). The Research Laboratory of Green Feed Concentrates of Don State Technical University has developed and tested under pilot-scale production conditions a wet fractionation technology that produces a paste-like protein concentrate and dry pelleted feed additives based on it (Osobov et al., 1974).

According to this technology, protein paste is mixed with ground feed grain in specified proportions, after which the feed mixture is pelleted and dried. One of the key stages of pelleting is material compaction in the die channels under the pressure generated by the granulator working element. The magnitude and pattern of pressure application determine not only the energy and load parameters of the process but also the density of the resulting pellets, which, in turn, determines their mechanical strength and the bulk density of the finished product (Lvovsky, 1988; Maltseva, 2025).

Reliable data on the physicomechanical properties of the processed mixture, primarily the dependence of its density on pressing pressure, are required to calculate the design parameters of granulator pressing units and select appropriate compaction conditions. Despite the considerable number of studies devoted to the compaction of various dispersed plant materials (Melnikov et al., 1980; Adler et al., 1976; Dolgov, 1996), data on the behavior of protein paste and ground feed grain mixtures under pressure as a function of paste moisture content, ground feed grain particle-size distribution, and component ratio are virtually absent from the technical literature.

Addressing this gap will not only improve the accuracy of engineering calculations for granulation equipment but also make it possible to predict the quality characteristics of the finished pellets at the process design stage. Therefore, the aim of this study was to experimentally determine the dependence of the density of a protein paste and ground feed grain mixture on pressing pressure at different paste moisture contents, particle-size distributions of the ground feed grain, and component mass ratios, as well as to obtain regression equations suitable for practical use in engineering calculations.

MATERIALS AND METHODS

The development of theoretical models and the determination of the design and technological parameters of working elements for pelleting require a comprehensive study of the physicomechanical properties of a protein paste and ground feed grain mixture. These properties depend on several factors, primarily moisture content, component characteristics, their mass ratio, and temperature. A series of experimental studies of the physicomechanical properties of this mixture was conducted at the Research Laboratory of Green Feed Concentrates, including determination of the dependence of mixture density on pressing pressure.

The physicomechanical characteristics were determined for mixtures of different compositions. The varied parameters were the moisture content of the protein paste, 89.64% and 63.79%; the particle-size distribution of the ground feed grain; and the component mass ratio, K_{mix}, defined as the mass ratio of protein paste to ground feed grain.

Protein paste with a moisture content of 89.64% was produced at the experimental facility of the Research Laboratory of Green Feed Concentrates at the educational and experimental site of Don State Technical University. First-cut alfalfa at the budding to early flowering stage was used as the raw material. The green biomass was ground using an IZM-10A unit and separated into a liquid fraction, or green juice, and a solid fraction, or plant press cake, by mechanical dewatering in a VPO-20 screw press with a reinforced screw chamber. Chemical coagulation of the green juice was carried out by adding a mixture of coagulant and preservative consisting of 0.4% of a concentrate of low-molecular-weight acids, based on the juice mass, and 0.5% formaldehyde. The coagulate was separated into protein paste and brown juice by settling for 36 h in a flotation-type separator.

Protein paste with a moisture content of 63.79% was obtained by prolonged settling for 144 h followed by partial mechanical dewatering in an upgraded NOGSh-type centrifuge. The paste moisture content was determined using the standard method in accordance with GOST 13496.3-80.

Ground feed grain with a moisture content of 12.3% was produced from barley by grinding it in a DKU-2 hammer mill followed by sieving through screens with aperture sizes of 1, 2, and 3 mm.

The protein paste and ground feed grain were mixed at mass ratios of 1:0.5, 1:1, 1:1.5, 1:2, 1:2.5, and 1:3, corresponding to K_{mix} values of 2, 1, 0.666, 0.5, 0.4, and 0.333, respectively. The calculated moisture contents of the feed mixtures are presented in Table 1.

Table 1: Calculated Moisture Content of Feed Mixtures

	W_p = 89.64%					W_p = 63.79%				
K_{mix}	1	0.666	0.5	0.4	0.333	2	1	0.666	0.5	0.4
W_{mix}, %	51.16	43.40	38.25	34.56	31.76	46.74	38.17	33.01	29.58	27.12

The experimental data were processed using standard methods (Lvovsky, 1988; Melnikov and Aleshkin, 1980; Adler et al., 1976), as well as engineering calculation methods implemented using programmable calculators (Dyakonov, 1989; Shelest, 1988).

The mixture density was determined gravimetrically using the following relationship

$$\rho = \frac{G}{V},$$

where G is the mass of the material and V is the volume of the material.

Measurements were performed at different pressures generated using an R-10 universal testing machine (Figure 1). The equipment operated in compression mode and provided a maximum load of 6,000 kgf.

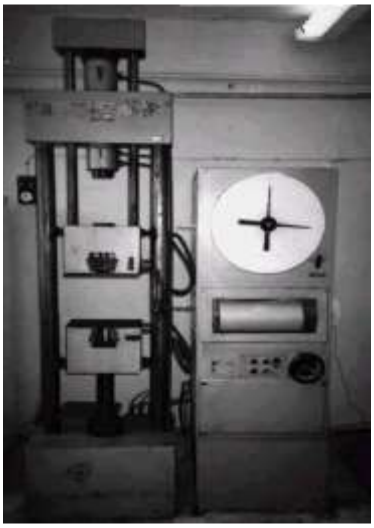

Figure 1: General View of the R-10 Universal Testing Machine

Figure 2: General View of the Compression Chamber

The experiments were performed in the following sequence

The material was loaded into a special compression chamber (Figure 2) designed as a cylinder with an internal diameter of 0.1 m, inside which a rod with a brass piston moved under the applied force, the chamber mass was known in advance.

The compression chamber was installed in the R-10 universal testing machine

The mixture was compressed until the specified pressure was reached in the compression chamber

The pressure value and rod displacement were recorded

The compression chamber containing the mixture was weighed

Mixtures with an initial protein paste moisture content of 89.64% were studied at K_{mix} values of 1 0.5, and 0.333, while mixtures with a moisture content of 63.79% were studied at K_{mix} values of 2 1, and 0.5. The material mass was calculated as the difference between the total mass and the mass of the compression chamber. The material volume was taken as equal to the internal chamber volume after compression. Pressure was calculated as the ratio of the load generated by the testing machine to the cross-sectional area of the compression chamber piston.

RESULTS AND DISCUSSION

The experiments were performed in triplicate. Selected experimental results for mixture density as a function of pressure are presented in Table 2.

Table 2: Experimental Results for the Dependence of the Density of a Protein Paste and Ground Feed Grain Mixture on Pressure

Mixture Composition	Mean Density, kg/m^3, at the Corresponding Pressure, MPa (Piston Rod Load in the Compression Chamber, tf, in Parentheses)				
	0.625(0.5)	1.25(1)	1.875(1.5)	2.5(2)	3.125(2.5)
W_p = 63.79%, ground feed grain < 1 mm, K_{mix} = 2	930.78	1050.76	1340.78	1372.15	1371.78
K_{mix} = 1	947.96	1130.46	1347.44	1390.96	1394.45
K_{mix} = 0.5	970.04	1350.90	1401.34	1479.33	1487.08
W_p = 63.79%, ground feed grain 1–2 mm, K_{mix} = 2	867.25	1053.16	1303.09	1300.65	1326.63
K_{mix} = 1	899.73	1157.84	1347.15	1390.74	1399.03
K_{mix} = 0.5	904.01	1117.33	1401.30	1409.67	1423.77
W_p = 63.79%, ground feed grain 2–3 mm, K_{mix} = 2	830.46	1034.73	1203.44	1300.49	1288.42
K_{mix} = 1	861.61	1015.55	1247.29	1320.31	1377.19
K_{mix} = 0.5	905.88	1076.85	1201.73	1389.27	1401.84

Figures 3–5 show mixture density as a function of pressure for different mixture compositions. Figure 6 shows the dependence of mixture density on the particle-size distribution of the ground feed grain at different pressures.

Statistical analysis of the experimental data showed that the dependence of the density of the protein paste and ground feed grain mixture on pressure can be described by a regression equation of the following form:

$$\rho = \rho_0 + a \ln (P + 1). \quad (1)$$

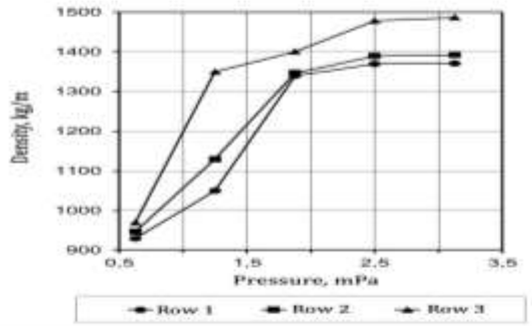

Figure 3: Mixture Density versus Pressure

(series 1 — K_{mix} = 2; series 2 — K_{mix} = 1; series 3 — K_{mix} = 0.5; W_p = 63.79%; ground feed grain particle size < 1 mm)

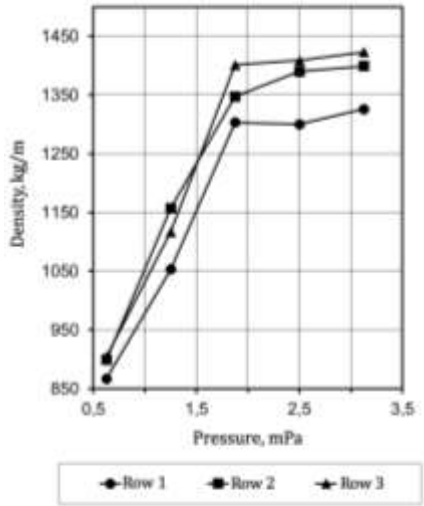

Figure 4: Mixture Density versus Pressure

(series 1 — K_{mix} = 2; series 2 — K_{mix} = 1; series 3 — K_{mix} = 0.5; W_p = 63.79%; ground feed grain particle size 1–2 mm)

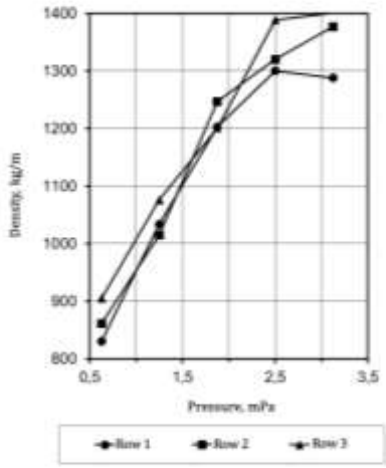

Figure 5: Mixture Density versus Pressure

(series 1 — K_{mix} = 2; series 2 — K_{mix} = 1; series 3 — K_{mix} = 0.5; W_p = 63.79%; ground feed grain particle size 2–3 mm)

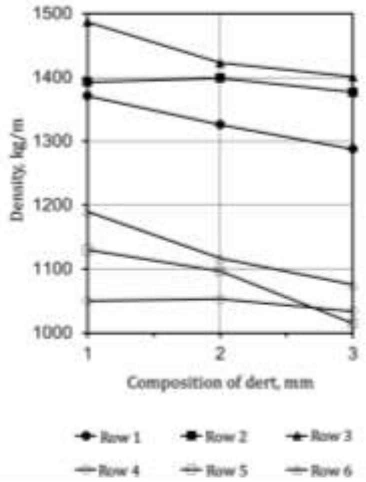

Figure 6: Mixture Density versus Ground Feed Grain Particle-Size Distribution

(series 1, 2, and 3 — P = 3.125 MPa; series 4, 5, and 6 — P = 1.25 MPa; W_p = 63.79%; series 1 and 4 — K_{mix} = 2; series 2 and 5 — K_{mix} = 1; series 3 and 6 — K_{mix} = 0.5)

Table 3 presents the mixture density values calculated using the regression equations.

The coefficients of the regression equations were obtained by the least-squares method, with evaluation of the pairwise correlation coefficient (Lvovsky, 1988).

Table 3: Mixture Density Values Calculated Using the Regression Equations

Mixture Composition	Mean Density, kg/m³, at the Corresponding Pressure, MPa (Piston Rod Load in the Compression Chamber, tf, in Parentheses)				
	0.625(0.5)	1.25(1)	1.875(1.5)	2.5(2)	3.125(2.5)
W_p = 63.79%, ground feed grain < 1 mm, K_{mix} = 2	934.9354	1109.0509	1240.2023	1345.4511	1433.3606
K_{mix} = 1	973.50724	1141.6205	1268.2507	1369.8713	1454.7502
K_{mix} = 0.5	1060.9255	1234.2947	1364.8839	1469.6816	1557.2142
W_p = 63.79%, ground feed grain 1–2 mm, K_{mix} = 2	898.11708	1068.4816	1196.8077	1299.7891	1385.8048
K_{mix} = 1	949.4585	1130.6454	1267.1233	1376.6467	1468.1264
K_{mix} = 0.5	940.23787	1134.9824	1281.6726	1399.3912	1497.7161
W_p = 63.79%, ground feed grain 2–3 mm, K_{mix} = 2	857.36088	1028.9521	1158.2021	1261.9251	1348.56
K_{mix} = 1	860.11751	1050.6735	1194.2086	1309.3953	1405.6054
K_{mix} = 0.5	900.0827	1084.6406	1223.6577	1335.2188	1428.4005

The adequacy of the resulting regression equations was assessed using Fisher's F-test (Lvovsky, 1988; Ivanova et al., 1981).

Comparison of the calculated F-values with the critical values indicates that the proposed regression equations adequately describe the dependence of the density of the protein paste and ground feed grain mixture on pressure at the 5% or 10% significance level, depending on the mixture composition.

Regression Equation (1) can also be expressed in exponential form.

$$P = e^{b(\rho - \rho_0)} - 1, \qquad (2)$$

where b = 1/a.

The empirical relationships represented by Equations (1) and (2) are consistent with the results reported for the compression of various plant materials by Dolgov (1996) and other authors, including Rudoy and Saakyan (2023).

CONCLUSION

The experimental studies established quantitative relationships between the density of a protein paste and ground feed grain mixture and pressing pressure at different paste moisture contents, particle-size distributions of the ground feed grain, and component mass ratios. The resulting relationships were adequately described by regression equations at the 5% or 10% significance level, depending on the mixture composition. Mixture density was found to increase with pressing pressure, while the pattern of density increase depends on the initial moisture content of the protein paste and the proportion of ground feed grain in the mixture. The regression equations and their coefficients can be used in engineering calculations for the design of pressing and granulation equipment, as well as in the development of process regulations for the production of dry pelleted feed additives based on protein paste. Practical application of the results will make it possible to select appropriate compaction conditions for feed mixtures of different compositions, thereby improving the efficiency of the pelleting process and the quality of the finished product.

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