



RESEARCH ARTICLE

Experimental Study of the Rheological Properties of a Mixture of Protein Paste and Ground Feed Grain

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ARTICLE INFO	ABSTRACT
Received: JUNE 05, 2026 Accepted: JUNE 22, 2026	Wet fractionation of the green biomass of cultivated grasses makes it possible to obtain protein paste, a complete substitute for animal-derived proteins in livestock and poultry diets. To produce dry pelleted feed additives, protein paste is mixed with ground feed grain, followed by pelleting of the resulting mixture. The determination of the design and operating parameters of pelleting equipment requires data on the rheological properties of the processed material. The aim of this study was to experimentally determine the rheological characteristics of a mixture of protein paste and ground feed grain, specifically the dependence of shear stress and apparent viscosity on the moisture content, composition, and temperature of the mixture. Measurements were performed using a rotational viscometer over a shear rate range of 1.8–27 s ⁻¹ . The varied parameters were the moisture content of the protein paste, 63.79% and 89.64%, the particle-size distribution of the ground feed grain, and the mass ratio of the components. It was established that the rheological behavior of the mixture is adequately described by the Bingham viscoplastic model. The apparent viscosity of the mixture was found to increase with decreasing moisture content, increasing proportion of ground feed grain, and decreasing temperature. The resulting quantitative relationships can be used to calculate the energy and force parameters of pressing equipment and to select appropriate pelleting conditions for feed mixtures of a specified composition.
Keywords Protein paste Ground feed grain Rheological properties Apparent viscosity Shear stress Pelleting Feed production Shvedov–Bingham model	
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INTRODUCTION

One of the key challenges facing modern agriculture is providing livestock and poultry production with nutritionally complete feed proteins. Traditionally, animal-derived components such as fish meal and meat-and-bone meal have been used as protein sources, but their production involves high economic costs and a number of sanitary and hygienic restrictions. An alternative approach that has been actively developed in recent decades is the production of plant protein concentrates from the green biomass of cultivated grasses using wet fractionation technologies (Dolgov and Proydak, 1990; Dolgov and Popov, 1999).

The Problem Research Laboratory of Green Feed Concentrates at Don State Technical University has developed a technology for producing a paste-like protein concentrate from the leaf-and-stem biomass of alfalfa and other cultivated grasses. After appropriate processing, this concentrate can serve as a nutritionally complete substitute for animal-derived proteins in livestock and poultry diets (Dolgov and Proydak, 1990; Dolgov and Popov, 1999). The process includes grinding the raw material, separating it into a solid fraction, or press cake, and a liquid fraction, or green juice, chemical coagulation of the juice, and subsequent separation of the coagulate into protein paste and brown juice. To produce dry pelleted feed additives, the protein paste is mixed with ground feed grain in specified proportions, after which the resulting feed mixture is pelleted and dried to the required moisture content.

Despite significant progress in the development of technologies for producing protein concentrates, issues related to the design of equipment for pelleting feed mixtures based on protein paste and ground feed grain remain insufficiently studied. In particular, reliable data on the rheological properties of the processed material are required to substantiate the design parameters of screw granulators and to establish rational operating conditions. Rheological characteristics such as yield shear stress and apparent viscosity determine the behavior of the mixture as it flows through the pelletizer channels and directly affect process energy consumption and pellet quality (Machikhin, 1990; Lvovsky, 1988; Melnikov et al., 1980).

An analysis of the scientific and technical literature shows that the rheological properties of plant pastes and their mixtures with grain components have been studied only to a limited extent. Existing studies (Adler et al., 1976; Ivanova et al., 1981) focus primarily on the rheology of pure plant juices or pastes without fillers, whereas data on the behavior of mixtures of protein paste and ground feed grain as a function of moisture content, composition, and temperature are virtually absent from the available literature. Addressing this gap is a necessary step toward developing a scientifically sound method for calculating pelleting equipment.

The aim of this study was to experimentally determine the rheological characteristics of a mixture of protein paste and ground feed grain, specifically the dependences of shear stress and apparent viscosity on shear rate, mixture moisture content, component ratio, and temperature. The resulting data are intended for use in developing engineering methods for calculating screw granulators and selecting process conditions for pelleting feed mixtures of a specified composition.

MATERIALS AND METHODS

The development of theoretical models and the substantiation of the design and technological parameters of working elements for pelleting require a comprehensive study of the physicomechanical and rheological properties of a mixture of protein paste and ground feed grain. These properties depend on several factors, the main ones being moisture content, component characteristics, their mass ratio, and temperature. A series of experimental studies of the rheological characteristics of this mixture was conducted at The Research Laboratory of Green Feed Concentrates (Adler et al., 1976; Machikhin, 1990; Eirich et al., 1962).

The structural and mechanical properties of the mixture describe the behavior of the material under external forces. Depending on the direction of the applied load, shear, compression, or tensile deformations occur in the material. When studying complex heterogeneous systems, including the mixture under investigation, shear deformation caused by tangential stresses is the most informative type of deformation. Measuring tensile and compressive deformations in materials of this type involves considerable methodological difficulties. The key characteristics of such media are yield shear stress and viscosity, including plastic and apparent viscosity. Shear properties are determined using instruments that record the resistance of the material to the relative displacement of its layers (Machikhin, 1990; Gorbатов, 1979; Dyakonov, 1989).

The deformation behavior of the mixture is determined by the state of its structure and is described by a flow curve, or rheogram, which establishes the relationship between stress and shear rate. The dependence of apparent viscosity on stress or shear rate is a key characteristic of the structural and mechanical properties of dispersed systems. Apparent viscosity reflects the equilibrium between structural breakdown and recovery processes in steady flow.

The aim of this study was to determine the rheological properties of a mixture of protein paste and ground feed grain.

The research program included determining:

- The dependence of shear stress on shear rate;
- The dependence of apparent viscosity on moisture content, temperature, and shear rate.

The rheological characteristics were measured using a rotational viscometer equipped with two types of measuring systems: cylinder-in-cylinder and cone-and-plate. The material under investigation was placed in the gap between the measuring elements, after which one of them was set in rotational motion while the shear rate and shear stress were recorded.

The experiments were conducted using 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 (Rudoy et al., 2025; Rudoy et al., 2023; Rudoy et al., 2021).

Protein paste with a moisture content of 89.64% was produced at the experimental facility of the Problem 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 liquid, or green juice, and solid, or plant press cake, fractions 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% 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 content values of the feed mixture 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 of statistical analysis and the development of empirical relationships (Melnikov et al., 1980; Ivanova et al., 1981; Shelest, 1988).

Before loading into the viscometer, the mixture was thoroughly mixed and conditioned under a pressure of 0.8–1.1 MPa for 3 min to achieve greater homogeneity and a more uniform distribution of moisture between the components. All measurements were performed in triplicate.

RESULTS AND DISCUSSION

Based on the experimental results, rheograms were constructed — plots of shear stress versus shear rate, $\tau = f(\dot{\gamma})$ (Figures 1 and 2).

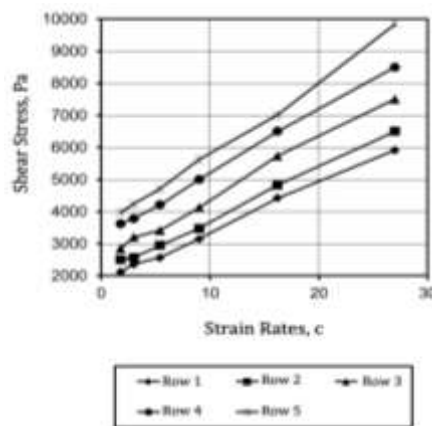


Figure 1: Shear Stress versus Shear Rate

($W_p = 89.64\%$; ground feed grain < 1 mm; series:

1 - $K_{mix} = 1$; 2 - $K_{mix} = 0.666$; 3 - $K_{mix} = 0.5$; 4 - $K_{mix} = 0.4$; 5 - $K_{mix} = 0.333$)

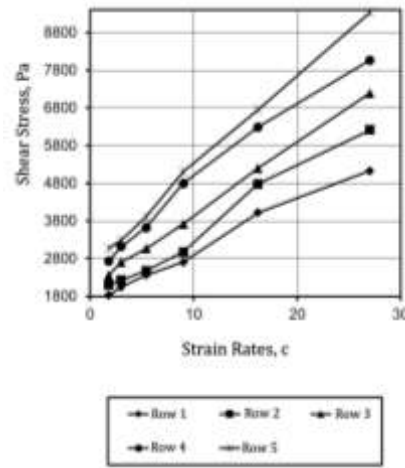


Figure 2: Shear Stress versus Shear Rate

($W_p = 89.64\%$; ground feed grain 1–2 mm; series:

1 – $K_{mix} = 1$; 2 – $K_{mix} = 0.666$; 3 – $K_{mix} = 0.5$; 4 – $K_{mix} = 0.4$; 5 – $K_{mix} = 0.333$)

The apparent viscosity was calculated from the rheograms using the following equation:

$$\eta_{\text{app}} = \tau / \dot{\gamma}$$

Table 2 presents selected experimental results and the corresponding calculated values of apparent viscosity.

Table 2: Mean Shear Stress and Apparent Viscosity of Protein Paste and Ground Feed Grain Mixtures of Different Compositions

Mixture composition	Shear rate $\dot{\gamma}$, s^{-1}	Shear stress τ , Pa	Apparent viscosity η_{app} , Pa·s	Calculated shear stress τ_c , Pa
1	2	3	4	5
$W_p = 89.64\%$, ground feed grain < 1 mm, $K_{mix} = 1$	1.8	2123.5	1179.4	2111.74
	3.0	2359.6	786.3	2294.45
	5.4	2569.1	475.7	2659.87
	9.0	3147.0	349.6	3208.01
	16.2	4418.2	272.7	4304.26
	27	5911.7	218.9	5948.65
$K_{mix} = 0.666$	1.8	2497.2	1387.2	2401.33
	3.0	2571.9	857.0	2596.98
	5.4	2950.3	546.3	2988.28
	9.0	3474.1	386.1	3575.24
	16.2	4829.0	298.1	4749.14
	27	6500.8	240.7	6509.99
$K_{mix} = 0.5$	1,8	2850.3	1583.3	2865.25
	3,0	3201.2	1067.3	3089.17
	5,4	3415.0	632.4	3537.01
	9,0	4119.7	457.6	4208.76
	16,2	5733.2	353.8	5552.26
	27	7502.9	277.8	7567.52
$K_{mix} = 0.4$	1.8	3618.3	2010.0	3574.22
	3.0	3787.4	1263.3	3810.68

Mixture composition	Shear rate $\dot{\gamma}$, s^{-1}	Shear stress τ , Pa	Apparent viscosity η_{app} , Pa·s	Calculated shear stress τ_c , Pa
	5.4	4209.9	779.4	4283.59
	9.0	5001.8	555.6	4992.96
	16.2	6498.1	401.1	6411.70
	27	8500.6	314.8	8539.82
$K_{mix} = 0.333$	1.8	3971.4	2206.1	3914.19
	3.0	4233.5	1411.9	4190.97
	5.4	4709.5	972.0	4744.55
	9.0	5618.5	624.2	5574.91
	16.2	7009.6	432.6	7235.63
	27	9847.1	364.7	9726.72
$W_p = 89.64\%$, ground feed grain 1–2 mm, $K_{mix} = 1$	1.8	1828.5	1015.5	1869.31
	3.0	2049.4	683.4	2029.39
	5.4	2366.0	438.1	2349.53
	9.0	2705.1	300.6	2829.74
	16.2	4018.9	248.0	3790.18
	27	5133.7	190.1	5230.82
$K_{mix} = 0.666$	1.8	2097.3	1165.0	1985.97
	3.0	2228.9	742.6	2192.06
	5.4	2482.1	459.6	2604.26
	9.0	2974.6	330.4	3222.55
	16.2	4779.8	295.0	4459.13
	27	6218.3	230.3	6314.01
$K_{mix} = 0.5$	1.8	2359.2	1310.6	2397.64
	3.0	2705.4	901.7	2626.76
	5.4	3063.8	567.2	3085.00
	9.0	3715.8	412.8	3772.36
	16.2	5203.1	321.1	5147.07
	27	7193.5	266.4	7209.15
$K_{mix} = 0.4$	1.8	2733.3	1518.3	2938.52
	3.0	3115.9	1038.3	3194.33
	5.4	3622.5	670.7	3705.95
	9.0	4798.0	533.1	4473.38
	16.2	6291.4	388.3	6008.25
	27	8072.7	298.9	8310.54
$K_{mix} = 0.333$	1.8	3073.6	1707.2	3084.40
	3.0	3287.7	1095.7	3385.69
	5.4	3906.7	723.3	3988.28
	9.0	5103.9	567.0	4892.15
	16.2	6759.1	417.2	6699.91
	27	9344.7	346.1	9411.54

The graphical relationships between apparent viscosity and shear rate are presented in Figures 3 and 4, while the relationships between viscosity and mixture moisture content are shown in Figures 5 and 6.

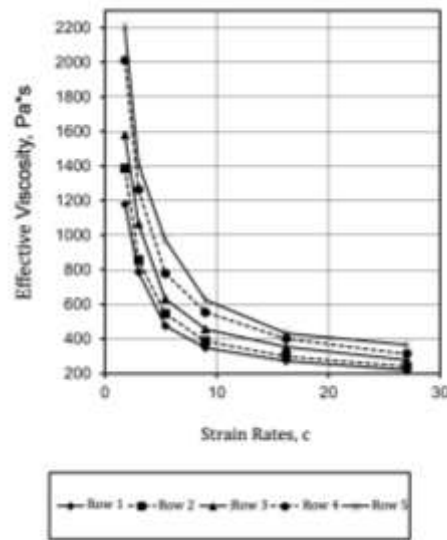


Figure 3: Apparent Viscosity versus Shear Rate

($W_p = 89.64\%$; ground feed grain < 1 mm; series: 1 - $K_{mix} = 1$; 2 - $K_{mix} = 0.666$; 3 - $K_{mix} = 0.5$; 4 - $K_{mix} = 0.4$; 5 - $K_{mix} = 0.333$)

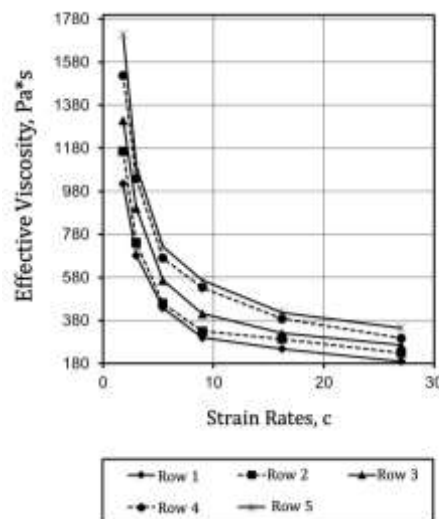


Figure 4: Apparent Viscosity versus Shear Rate

($W_p = 89.64\%$; ground feed grain 1–2 mm; series: 1 - $K_{mix} = 1$; 2 - $K_{mix} = 0.666$; 3 - $K_{mix} = 0.5$; 4 - $K_{mix} = 0.4$; 5 - $K_{mix} = 0.333$)

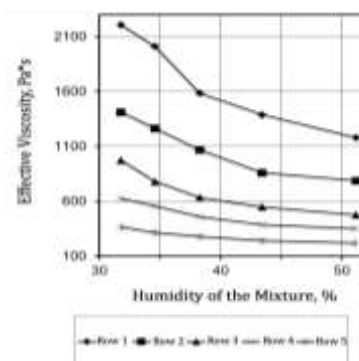


Figure 5: Apparent Viscosity versus Mixture Moisture Content

($W_p = 89.64\%$; ground feed grain < 1 mm; series: 1 – $\dot{\gamma} = 1.8 \text{ s}^{-1}$; 2 – $\dot{\gamma} = 3.0 \text{ s}^{-1}$; 3 – $\dot{\gamma} = 5.4 \text{ s}^{-1}$; 4 – $\dot{\gamma} = 9.0 \text{ s}^{-1}$; 5 – $\dot{\gamma} = 27 \text{ s}^{-1}$)

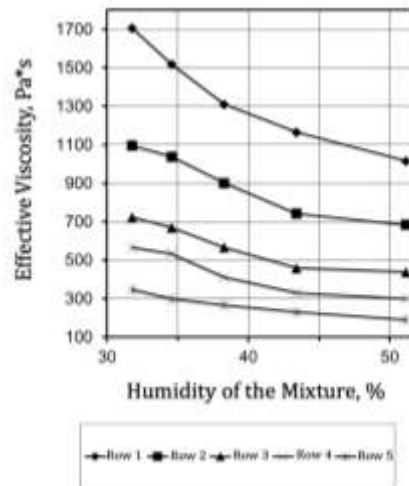


Figure 6: Apparent Viscosity versus Mixture Moisture Content

($W_p = 89.64\%$; ground feed grain 1–2 mm; series: 1 – $\dot{\gamma} = 1.8 \text{ s}^{-1}$; 2 – $\dot{\gamma} = 3.0 \text{ s}^{-1}$; 3 – $\dot{\gamma} = 5.4 \text{ s}^{-1}$; 4 – $\dot{\gamma} = 9.0 \text{ s}^{-1}$; 5 – $\dot{\gamma} = 27 \text{ s}^{-1}$)

The relationships between shear stress and shear rate presented in Figures 1 and 2 are practically linear over the range $\dot{\gamma} = 1.8\text{--}27 \text{ s}^{-1}$. Extrapolation of the obtained straight lines to $\dot{\gamma} = 0$ makes it possible to determine the intercept on the shear stress axis corresponding to the yield shear stress τ_0 . This parameter characterizes the plastic properties of the material under study. At shear stresses $\tau < \tau_0$, no residual deformation occurs in the material, and after the load is removed, the structure is fully restored. At $\tau > \tau_0$, flow occurs, and the material behaves similarly to a Newtonian fluid under the effective shear stress $\tau - \tau_0$. Thus, the rheological behavior of the mixture of protein paste and ground feed grain can be described by the Shvedov–Bingham viscoplastic model (Ivanova et al., 1981; Rudoy et al., 2023; Machikhin, 1990):

$$\tau = \tau_0 + \eta_{pl}\dot{\gamma},$$

where η_{pl} is the plastic, or Bingham, viscosity.

The yield shear stress τ_0 and plastic viscosity η_{pl} were calculated by the least-squares method using computational methods (Gorbatov, 1979; Rudoy et al., 2021), together with the corresponding correlation coefficients r . The shear stress values calculated from the resulting regression equations are presented in Table 2.

The adequacy of the resulting regression equations was assessed using Fisher’s F-test (Ivanova et al., 1981; Melnikov et al., 1980). Comparison of the calculated F-values with the tabulated values indicates that the proposed equations adequately describe the dependence of shear stress on shear rate at the 1% significance level.

Figure 7 shows the dependence of apparent viscosity on temperature for two shear rates, $\dot{\gamma} = 3.0 \text{ s}^{-1}$ and 9.0 s^{-1} , and two feed mixture moisture contents, 31.76% and 38.25%, which, at a paste moisture content of $W_p = 89.64\%$, correspond to $K_{mix} = 0.333$ and 0.5.

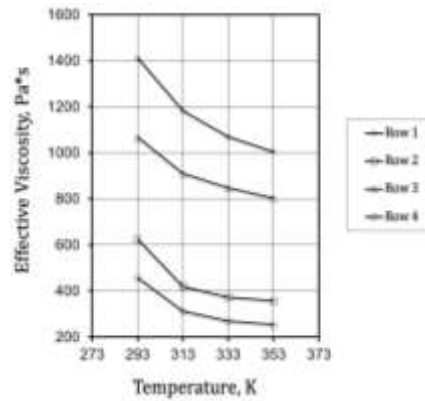


Figure 7: Apparent Viscosity versus Temperature

($W_p = 89.64\%$; ground feed grain < 1 mm; series: 1 – $K_{mix} = 0.333, \dot{\gamma} = 3.0 \text{ s}^{-1}$; 2 – $K_{mix} = 0.333, \dot{\gamma} = 9.0 \text{ s}^{-1}$; 3 – $K_{mix} = 0.5, \dot{\gamma} = 3.0 \text{ s}^{-1}$; 4 – $K_{mix} = 0.5, \dot{\gamma} = 9.0 \text{ s}^{-1}$)

The experimental data on the dependence of apparent viscosity on temperature are presented in Table 3.

Table 3: Dependence of the Apparent Viscosity of a Protein Paste and Ground Feed Grain Mixture on Temperature

Mixture Composition	Temperature T, K (°C)	Apparent Viscosity η_{app} , Pa·s	Calculated Apparent Viscosity Values
$W_p = 89.64\%$; ground feed grain < 1 mm; $K_{mix} = 0.333$; $\dot{\gamma} = 3.0 \text{ s}^{-1}$	293 (20)	1411.9	1377.65
	313 (40)	1182.7	1225.37
	333 (60)	1070.0	1091.38
	353 (80)	1004.2	972.58
$W_p = 89.64\%$; ground feed grain < 1 mm; $K_{mix} = 0.333$; $\dot{\gamma} = 9.0 \text{ s}^{-1}$	293 (20)	624.2	579.06
	313 (40)	419.5	480.64
	333 (60)	372.1	394.04
	353 (80)	356.1	317.25
$W_p = 89.64\%$; ground feed grain < 1 mm; $K_{mix} = 0.5$; $\dot{\gamma} = 3.0 \text{ s}^{-1}$	293 (20)	1067.3	1041.81
	313 (40)	909.8	944.11
	333 (60)	847.5	858.14
	353 (80)	803.6	781.92
$W_p = 89.64\%$; ground feed grain < 1 mm; $K_{mix} = 0.5$; $\dot{\gamma} = 9.0 \text{ s}^{-1}$	293 (20)	457.6	426.95
	313 (40)	311.2	351.53
	333 (60)	269.4	285.17
	353 (80)	253.7	226.33

The dependence of apparent viscosity on temperature was approximated using a hyperbolic equation of the form $y = a/x + b$. The calculated values of coefficients a and b and the pairwise correlation coefficient for different mixture compositions and shear rates are presented in Table 4. The calculated values of apparent viscosity at different temperatures are presented in Table 3.

The adequacy of the resulting regression equations was assessed using Fisher’s F-test (Rudoy et al., 2025; Melnikov et al., 1980). Comparison of the calculated F-values with the tabulated values presented in Table 4 shows that the hyperbolic function adequately describes the dependence of apparent viscosity on temperature at the 10% significance level.

Table 4: Results of the Statistical Processing of Experimental Data and Calculated Regression Coefficients Describing the Dependence of Mixture Apparent Viscosity on Temperature

Mixture Composition	b	a	r	F	$F_{r(v_1, v_2, f)}$ $v_1 = n-1$ $v_2 = n-2$	Significance Level f, %
$W_p = 89.64\%$; ground feed grain < 1 mm; $K_{mix} = 0.333$;	-1005.514	698268.42	0.9765415	22.56	19.164	5

$\dot{\gamma} = 3.0 \text{ s}^{-1}$						
$W_p = 89.64\%$; ground feed grain < 1 mm; $K_{mix} = 0.333$; $\dot{\gamma} = 9.0 \text{ s}^{-1}$	-961.2582	451314.59	0.9110962	15.98	9.1618	10
$W_p = 89.64\%$; ground feed grain < 1 mm; $K_{mix} = 0.5$; $\dot{\gamma} = 3.0 \text{ s}^{-1}$	-487.2078	448003.55	0.9690822	21.13	19.164	5
$W_p = 89.64\%$; ground feed grain < 1 mm; $K_{mix} = 0.5$; $\dot{\gamma} = 9.0 \text{ s}^{-1}$	-753.3815	345839.16	0.9296316	17.55	9.1618	10

CONCLUSION

The experimental studies showed that the rheological behavior of the mixture of protein paste and ground feed grain over the shear rate range $\dot{\gamma} = 1.8\text{--}27 \text{ s}^{-1}$ is adequately described by the Shvedov-Bingham viscoplastic model, as evidenced by the linear relationships between shear stress and shear rate and the high values of the pairwise correlation coefficients for the obtained regression equations. It was established that the apparent viscosity of the mixture consistently increases with decreasing moisture content, increasing proportion of ground feed grain, corresponding to a decrease in K_{mix} , and decreasing temperature. Quantitatively, these relationships are approximated by a hyperbolic function, the parameters of which were determined for the investigated compositions. The resulting rheological characteristics and analytical relationships can be used to develop engineering methods for calculating the energy and force parameters of pelleting equipment and can also be applied in the design of production lines for dry pelleted feed additives based on protein paste. Practical implementation of the results will make it possible to select appropriate pelleting conditions for feed mixtures of different compositions and moisture contents, thereby improving the production efficiency of nutritionally complete substitutes for animal-derived proteins for livestock and poultry.

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