Analysis of Internal Fraction Property of Corn Stalk Powder under Triaxial Compression Test

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Keywords: Triaxial compression; Corn stalk powder; Agricultural Material property

Abstract. Corn stalk powder was densified to investigate its internal fraction property using triaxial apparatus in this paper, with the experimental method of quadric regressive orthogonal and central composite design, factors of water content, loading speed and bulk density (which is acquired by changing sample weight due to same volume) were selected to test internal friction coefficient. The mathematic model acquired is help to optimize processing technology as well as predict the corn stalk powder product quality.

Introduction

Knowledge of mechanical properties is useful for the design and development of any processing methods and equipments, and coefficient of internal friction reflects the frictional property and shear stress for granular material, it is regarded as an essential parameter to design storage bin, conveyor and forming machine, etc. corn stalk powder behaves in general particulate feature under compression loading, which facilitates researchers in agricultural engineering to understand mechanical behaviors in forming pellet from stalk with the aid of development in civil engineering, as is well known, the triaxial compression test is by far the most common laboratory test used to measure the mechanical properties of granular soils, which is widely used to measure the internal mechanical property including coefficient of internal friction[1]. It is generally acknowledged that coefficient of friction of agricultural powder be affected mainly be particle size, density (or porosity) and moisture content for the same material. For example, Cho et al. investigated the effect of four different zircon particle sizes on the friction characteristics of brake lining materials, the results showed that the size of the zircon particles played a significant role in the formation of friction film, which was closely related to the friction performance. The lining material with coarse zircon particles generated a stable friction film on the lining surface, which provided excellent friction stability with less lining wear[2]. Schöpfer et al. uses the discrete element method to study the dependence of elasticity, strength and friction angle on porosity and crack density, with performance of a series of triaxial extension and compression test, DEM model results demonstrate that the friction angle decreases (almost) linearly with increasing porosity, and is independent of particle size distribution[3]. Subramanian and Viswanathan put six kind of millet with experiment to study the moisture contents' influence on bulk density, coefficient of static friction and coefficient of internal friction, their work found that both the values of coefficient of static friction and coefficient of internal friction exhibited a linear relationship with moisture content with higher coefficient of fit[4]. The aim of this study is to investigate the impact of moisture content, bulk density and compression speed on the internal friction property of corn stalk powder.

Materials and Methods

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Raw Material

Raw corn stalk is harvested from test plots in Shenyang suburb of Liaoning. After a week of drying by natural sunlight, the material of whole stem then be crushed by the fodder grinder with diameter of sieve-pore of 8 mm, with the strike and grind by high-speed hammer of crusher, the experimental material turn into smashed mixture of powder with a small amount of slight stick and short hard grain. To gain the predetermined moisture content, the drying oven is adopted to get further drier material with water ratio of 12% (wb), which sequentially be used to deal with material with other water ratio, namely 14%, 16%, 18%, 20% , then all material needed be sealed into plastic bags to keep water content constant.

Experimental Equipments

In this study, strain controlled triaxial compression apparatus TSZ30-2.0 of Nanjing Ningxi Corp is applied, which have the axial load range of 0 to 30kN, confining pressure ranges from 0 to 2MPa with digital display, and the size of cylindrical sample in the compression set is of Φ 39.1 by 80 mm.

Electrical scale with type of BL310, rapid infrared moisture meter SFY-20, drying oven as well is employed in this work.

Coding of Factors

The quadric regressive orthogonal and central composite design method is selected to perform trials, as a typical response surface method in statistic; it explores the relationships between several explanatory variables and one or more response variables. Meanwhile, a second-degree polynomial model is easy to estimate and apply, even when little is known about the process [5].

The internal fraction coefficient α is taken as an experimental index in terms of requirement of test, and water content *w*, loading velocity *v* as well as sample weight *m* that represents the initial bulk density in a given sample dimension. The factors is encoded due to request of experiment method, and Z_{0j} , Z_{1j}, Z_{2j} represents the zero, top and down level respectively for factor *j*, while Z_{0j} is the mean value of Z_{1j} and Z_{2j}. Level interval Δ_j is determinated by expression $\Delta_j=(Z_{2j}-Z_{1j})/(2*r)$, where *r* equals to 1.353 through table-lookup, so coding of factor by linear conversion $X_j=(Z_j-Z_{0j})/\Delta_j$, where X_j is the code of Z_j. The entire coding for each factor is list as Table 1.

Table 1. Code and Corresponding Value for Each Factor

Code X_j	Water content Z_1 [%]	Sample weight Z_2 [g]	Loading velocity Z_3 [mm/min]
top asterisk arm（+1.353）	20	24	4.5
top level (+1)	18	22	3.5
zero level (0)	16	20	2.5
down level (-1)	14	18	1.5
down asterisk arm (-1.353)	12	16	0.5
Δ_j	1.478	1.478	0.739

Recording Procedure of Trials

Triaxial consolidated-undrained shear test is implemented in laboratory, one trial is taken for example to demonstrate the recording procedure of test; there are three samples needed with weight of 22±1g, height of 80±0.5mm, diamter of Φ 39.1, water content of 18%. One sample of which be wrapped by rubber layer to avoid water ingress, then it is put on the waterproof plate in inclosed cabinet of triaxial compression apparatus TSZ30-2.0, confining pressure is set to 100, 200 and 300 kPa respectly in one trial, the axial pressure bar advances with loading speed of 3 mm/min until the axial stain reaches 15%, namely 8 mm in deformation. Other trials are did rather similarity with this example.

Axial strain is figure out by

$$\varepsilon=\Sigma\Delta h/h_0\times100\% \quad (1)$$

where, ε is axial strain, ΣΔh is deformation in axial direction in *mm*, and h_0 is initial height of sample in *mm*.

The average cross area of sample is acquired by

$$A=A_0/(1-\varepsilon) \quad (2)$$

where, A is the average cross area in cm^2, A_0 is the initial cross area in cm^2.

Principal stress difference is

$$\sigma_1-\sigma_3=CR/A*10=CR(1-\varepsilon)*10 \quad (3)$$

where, σ_1 and σ_3 is the first and third principal stress in *kPa*, C is the calibration coefficient in N/0.01*mm* and R is the indication of dynamometer in 0.01*mm*.

Results

There are several methods are usually suggested to get internal friction value, moment method is the basic and the most common way based on the experiment data, but the due to ignoring of variation in one set and obvious experimental error for insufficient number of trials; plotting method is considered easy to introduce artificial error; and regressive method in p-q coordinate plane that put all test point in the same coordinate system, then solution is done according to failure principal stress trajectory and failure envelop, the last is the major way to organize triaxial test data, in this paper, we choose this method to calculate internal friction coefficient *f*.

The related equations about regressive method in p-q coordinate plane are listed as follows:

$$q=C+D*p \quad (4)$$

where, C and D are coefficient in Eq. 4

$$C=c*\cos\varphi \quad (5)$$

$$D=\sin\varphi \quad (6)$$

c is the cohesion index and φ is the angle of internal friction, then

$$f=\tan\varphi=\tan(\sin^{-1}D) \quad (7)$$

$$c=C/\cos(\sin^{-1}D) \quad (8)$$

In conventional triaxial test, σ_1 and σ_3 instead of p and q are measured directly, so linear regression of σ_1-σ_3 is carried out firstly

$$\sigma_1=A+B\sigma_3=2c*\tan(\varphi/2+\pi/4)+\sigma_3\tan^2(\varphi/2+\pi/4) \quad (9)$$

then, the value of *f* can be acquired by

$$f=\tan\varphi=\tan(2\arctan B^{0.5}-\pi/2) \quad (10)$$

As shown in table 2, seventeen sets of trials totally in this experiment are completed and internal friction coefficient *f* is computed through Eq. 4 to Eq. 10.

Table 2. Internal friction coeffcient f determinated and corresponding trial

trial No.	water content [%]	sample weight [g]	*loading velocity [mm/min]*	internal friction coefficient	trial No.	water content [%]	sample weight [g]	loading velocity [mm/min]	internal friction coefficient
1	14	18	*1.5*	0.55	10	20	20	2.5	0.46
2	14	18	*3.5*	0.48	11	16	16	2.5	0.54
3	14	22	*1.5*	0.49	12	16	24	2.5	0.55
4	14	22	*3.5*	0.53	13	16	20	0.5	0.53
5	18	18	*1.5*	0.51	14	16	20	4.5	0.42
6	18	18	*3.5*	0.45	15	16	20	2.5	0.57
7	18	22	*1.5*	0.43	16	16	20	2.5	0.58
8	18	22	*3.5*	0.31	17	16	20	2.5	0.57
9	12	20	*2.5*	0.55					

Conclusion and Discussion

Linear regression is done based on the data from table 3 and principal of the quadric regressive orthogonal and central composite design, the expression is

$$Y=C_0+C_1X1+C_2X2+C_3X3+C_4X1X2+C_5X1X3+C_6X2X3+C_7X1X1+C_8X2X2+C_9X3X3 \quad (11)$$

C_0 to C_9 is the coefficient to be fitted, and X1 to X3 presents the variable of water content, sample weight and loading velocity respectively. Analysis of Variance (ANOVA) is executed to test the significance of Eq. 11, and the value of F-criterion is 7.53, probability that greater than F value is

0.0072(<0.01), which indicates that the regressive model is highly significant; meanwhile the R-Square is 0.91.

The value for each parameter in model is shown in table 3. In accordance with the criterion in statistics, significant value that less than 0.01 is in highly significant level, greater than 0.01 and less than 0.05 at the same time is seen as in significant level, otherwise the factors will be regarded as insignificant to target index will be rejected in the model.

The final mathematical model used to describe the relation between objective variable (internal friction coefficient) and factors is as Eq. 12.

$$Y=0.573+0.039X1+0.019X2+0.030X3-0.019X1X3 -0.037X1^2-0.014X2^2-0.053X3^2 \quad (12)$$

Table 3. Parematers Estimated in Model

Parameters	Value estimated	Standard. Error	t value	Significance	95.0% Confidence Interval for B	
					Lower Bound	Upper Bound
C_0	0.573	0.017	34.105	0	0.533	0.612
C_1	0.039	0.009	4.155	0.004	0.017	0.062
C_2	0.019	0.009	1.996	0.046	-0.003	0.041
C_3	0.030	0.009	3.126	0.017	0.007	0.052
C_4	-0.027	0.011	-2.317	0.054	-0.054	0.001
C_5	-0.019	0.011	-1.617	0.049	-0.046	0.009
C_6	0.008	0.011	0.678	0.198	-0.019	0.035
C_7	-0.037	0.012	-2.958	0.021	-0.067	-0.007
C_8	-0.014	0.012	-1.144	0.040	-0.044	0.015
C_9	-0.053	0.012	-4.269	0.004	-0.083	-0.024

Based on the above model, it shows that water content, sample weight and loading velocity has an typical influencing rule according with quadratic equation within a certain range, this is helpful to optimize technological conditions and predict product quality of stalk powder.

Acknowledgements

This work was financially supported by Shenyang Agricultural University Young Teachers' Scientific Research Funds (grant No.:20111017), and scientific research project of Ministry of Education of Liaoning province (grant No.:L2012232), and the Twelfth Five-Year Rural Areas National Science and Technology Plan subject (grant No.:2011BAD20B09-10).

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