Calibration of Parameters for Discrete Element Simulation Model for Alfalfa with Different Moisture Contents Based on Angle of Repose Test

Haoyi Wang,[a] Pei Wu,[a,]* Hongkai He,[b] Yanhua Ma,[a] Ku Bu,[c] and Jing Xue [a]

During the simulation analysis of the discrete element method (DEM) for the alfalfa compression process, the input parameters in DEM software had a significant effect on simulation results. To obtain simulation parameters of the alfalfa with different moisture contents, a combination of angle of repose tests and simulation optimization design are presented in this paper. The repose angle of the alfalfa with moisture contents of 2.7%, 13.4%, 19.9%, 33.1%, and 74.5% was measured, and the results were 41.99˚, 38.30˚, 47.47˚, 56.31˚, and 63.09˚, respectively. Inclinometer tests, shear test, and restitution test were performed to evaluate the contact parameters. Taking contact parameters as the calibration object, the Plackett-Burman test was used to screen out which parameters had significant influence on the repose angle. The results of variance analysis showed the surface energy was the most significant parameter in the alfalfa repose angle test for each moisture content. Based on the Box-Behnken test, a second-order regression model of repose angle was obtained and the significance parameters were optimized and calibrated. The parameters calibrated in this paper can provide a reference for other simulations of alfalfa utilization.

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Keywords: Alfalfa; Discrete element method; Repose angle; Parameter calibration

*Contact information: a: College of Mechanical & Electrical Engineering, Inner Mongolia Agricultural University, Hohhot, 010018, P.R. China; b: College of Veterinary Medicine, Inner Mongolia Agricultural University, Hohhot, 010018, P.R. China; c: Institute of Grassland Research of CAAS, Hohhot, 010010, P.R. China; *Corresponding author: jdwupei@163.com*

INTRODUCTION

Alfalfa is a leguminous crop that has abundant crude protein, vitamins, and amino acids (Wang *et al*. 2003). In recent years, alfalfa has become an excellent choice in densified form to feed livestock. Alfalfa pellets are formed by pressing the crushed alfalfa with a compression device in the die to overcome the material deformation resistance and friction between material and the inner wall of the die (Fan *et al*. 2009). Therefore, the research on the pressure in the process of the compression is helpful to reasonably select the compression process parameters. The simulation analysis of discrete element method (DEM) has been applied to the test of soil, powder, and other granular materials, which provides a reference for stress analysis of the alfalfa compression process (Cundall and Strack 1979; Martina *et al*. 2003; Huang *et al*. 2011; Wang *et al*. 2017; Thomas *et al*. 2019). The DEM simulation for alfalfa needs many parameters, including mechanical parameters of alfalfa straw (Poisson ratio and shear modulus) and contact parameters between alfalfa straw and die (Friction and restitution coefficient) (Wang *et al.* 2016; Lu *et al.* 2018). These parameters determine the force, overlap, and displacement of particles in the simulation (DEM Solution 2020).

For biomass material, moisture content is an important mechanical parameter. It not only affects the pressure and product quality in the biomass compression process, but it also affects the contact parameters of the biomass material, especially in the Edinburgh elasto-plastic adhesion (EEPA) or Herts-Mindlin with JKR (Johnson-Kendall-Roberts) contact model. Because the surface energy of the material is determined by moisture content (Luo *et al*. 2018; Xing *et al*. 2020), trying to obtain the accurate simulation parameters is the premise of the DEM research on alfalfa compression with assisted vibration.

The contact parameters of biomass materials can be measured by the repose angle (or angle of repose) test of granular materials. The repose angle represents the characteristics of material flow and friction, which can reflect the comprehensive effect of a material group (Li and Xu 2005). Many researchers have calibrated the contact parameters of materials by DEM based on the repose angle test (Liu *et al.* 2016). Peng *et al*. (2018) directly measured the repose angle of pellet feed by the injected section method and obtained the optimal simulation parameters combination through response surface method. Lee and Park (2019) designed four friction simulation tests to measure the static and rolling friction coefficients of material-material and the static and rolling friction coefficients of material-die respectively. Liu *et al*. (2018) used the cylinder lifting method and MATLAB image processing to obtain the repose angle of wheat.

According to the aforementioned tests, some researchers referred to the range of the material parameters using the Generic EDEM material model database (GEMM) (Li *et al*. 2019), and some researchers calibrated material parameters by physical tests. They calibrated contact parameters of material only for dried material or fixed moisture content. However, there are few studies on physical tests and parameter measurements of comminuted alfalfa material with different moisture content, and on the calibration of the DEM simulation parameters of material based on the measured parameters. Therefore, in this study, a contact parameter measurement test was performed. The maximum and minimum of the measured contact parameters were set as the high level and low level of the Plackett-Burman test. The DEM simulation parameters of alfalfa were calibrated by Plackett-Burman test and Box-Behnken test. Then, the simulation repose angle and physical test repose angle were compared and verified to determine the DEM simulation parameters of alfalfa straw. The results will provide the parameters required for further study of the stress transfer mechanism in the alfalfa compression with assisted vibration using the DEM simulation.

EXPERIMENTAL

Materials

The biomass in this investigation was alfalfa (*Medicago sativa* L.), which was harvested in the suburb of Hohhot (Inner Mongolia, China). The material was dried to moisture contents of approximately 2.7% (dried), 13.4%, 19.9%, and 33.1% by a DHG-9140A drying oven (OLABO Company Ltd., Jinan, China) and then stored in plastic bags. Moisture content of the alfalfa was obtained by calculating the ratio of the water weight contained and the total weight of the raw material according to the GB/T 36055 (2018) standard. Then, when the repose test was conducted, the material was pulverized into small particles using a 9RS-60 feed crumbling machine (Machinery Plant of Inner Mongolia Agriculture University, Hohhot, China), and the impurities were removed. The particle size of the material was measured with the standard sieves according to the GB/T 5917.1 (2008) standard. The height of the alfalfa straw was between 8 and 11 mm. The diameter of the material was between 1.7 and 2.0 mm.

Repose Angle Test

The repose angle was measured following the ISO 4324 (1977) standard. The 5 g alfalfa straw, weighted with a JEB2002 electronic balance (Puchun Measure Instrument Co., Ltd., Shanghai, China), was added to the funnel of the FT-104B repose-angle measuring instrument (Shangyu Prospecting Instrument Factory Ltd., Shangyu, China), and it fell through, as shown in Fig. 1. The material was piled on the base plate, and the formed pile of material was photographed as a front view with a camera. The radius of the alfalfa pile at top and bottom were measured by the scale of the FT-104B repose-angle measuring instrument. The slope of repose angle was measured using the image digitization tool of Origin software (OriginLab, v.2018, Northampton, MA, USA). The tests were repeated five times under five different moisture content conditions. The repose angles that were recorded were the averages of the arctangents of five slopes. The results are shown in Table 1.

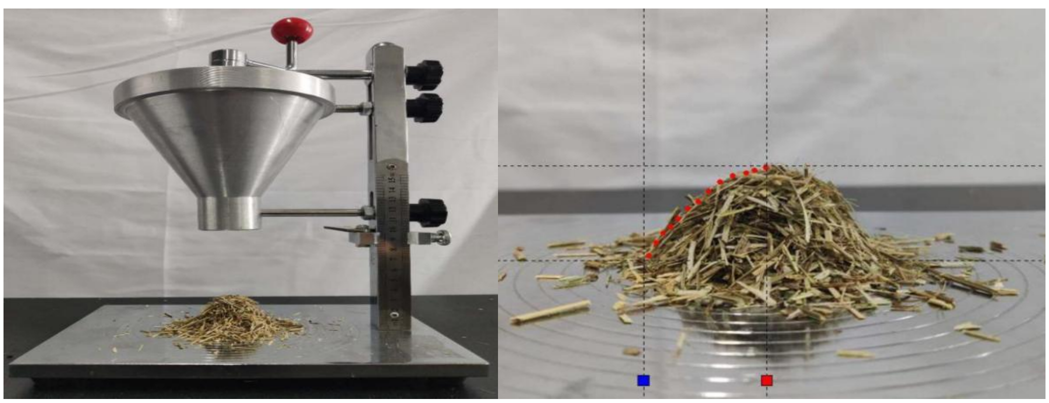

Fig. 1. FT-104B repose angle measuring instrument and close up of pile of material

Table 1. Repose Angle Under Five Moisture Content Conditions

Moisture Content (%)	2.7 (Dry)	13.4	19.9	33.1	74.5 (Fresh)
Slope	0.90	0.79	1.09	1.50	1.97
Repose Angle θ (°)	41.99	38.30	47.47	56.31	63.09

Measurement of Physical Contact Parameters

The contact parameters measured in this test included: the static friction and rolling friction coefficients between alfalfa straws, the static friction and rolling friction coefficients between alfalfa straw and die (steel 45#), the coefficient of restitution, and the shear modulus of alfalfa. The alfalfa straw used in the contact parameter physical test was taken from the middle part of the whole alfalfa straw without stem node, and it was selected and fractured into particles with a diameter of 1.6 to 2.4 mm and a length of 30 mm. The size of the alfalfa particles was measured with a Vernier caliper (accuracy: 0.02 mm, range: 150 mm, Harbin Measuring & Cutting Tool Group Company Ltd., Harbin, China).

Measurement of static friction coefficient

The static friction coefficient was measured using the CNY-1 inclinometer (Chenchi Instrument Company Ltd., Jinan, China). Before the test, the inclinometer was placed horizontally and the test plane was adjusted to zero. As Fig. 2 shows, the steel 45# was pasted to the test plane by a scotch brand tape (3M-CN Company Ltd., Shanghai, China). The alfalfa straw was placed on the steel 45# in the inclined direction and rotated the test plane counterclockwise until the alfalfa straw started to slide, then, the incline angle ϕ_1 (°) was recorded. Thus, the static friction coefficient (μ_1) was obtained from Eq. 1:

$$\mu_1 = \tan \phi_1 \quad (1)$$

For each moisture content condition, the test was repeated 10 times. When the static friction coefficient between alfalfa straw and alfalfa straw was measured, the steel 45# was replaced with alfalfa straw, and the aforementioned process was repeated. The results are shown in Table 2.

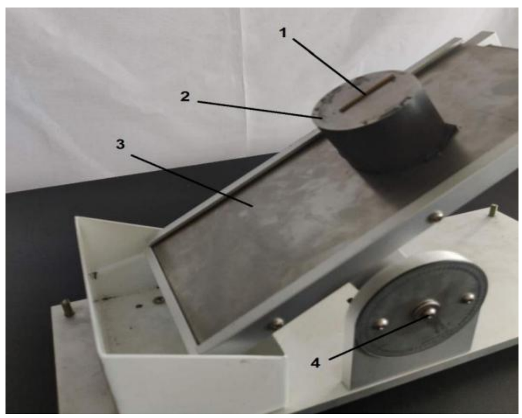

Fig. 2. Measurement of static friction coefficient between alfalfa straw and steel 45#: 1: Alfalfa straw; 2: Steel 45# plane; 3: Test plane of inclinometer; 4: Pointer

Table 2. Static Friction Coefficient (μ_1) under Five Moisture Content Conditions

Moisture Content (%)	2.7	13.4	19.9	33.1	74.5
μ_1 (Alfalfa-Steel)	0.67 to 0.93	0.57 to 0.84	0.49 to 0.9	0.53 to 0.78	0.50 to 0.80
μ_1 (Alfalfa-Alfalfa)	0.55 to 0.90	0.36 to 0.63	0.38 to 0.75	0.45 to 0.70	0.36 to 0.60

Measurement of rolling friction coefficient

The measurement of rolling friction coefficient was conducted also on the CNY-1 inclinometer. Before the test, the inclinometer was placed horizontally, and the pointer of test plane was adjusted to the ‘0’ mark. As Fig. 3 shows, the steel 45# was pasted to the test plane by scotch tape. The alfalfa straw was placed on the steel 45#, which is vertical to the inclined direction, and then the test plane was rotated counterclockwise until the alfalfa straw started to slide (Liu *et al*. 2018). Then, the incline angle ϕ_2 (°) was recorded. Thus, the rolling friction coefficient (μ_2) was obtained from Eq. 2:

$$\mu_2 = \tan \phi_2 \quad (2)$$

For each moisture content condition, the test was repeated 10 times. When the rolling friction coefficient between alfalfa straw and alfalfa straw was measured, the steel 45# was replaced with alfalfa straw and the aforementioned process was repeated. The test was repeated 10 times under each moisture content conditions. Although the rolling friction coefficient could not be accurately obtained through the above test method, it provides a range of selection of the rolling friction coefficient in the simulation. The results are shown in Table 3.

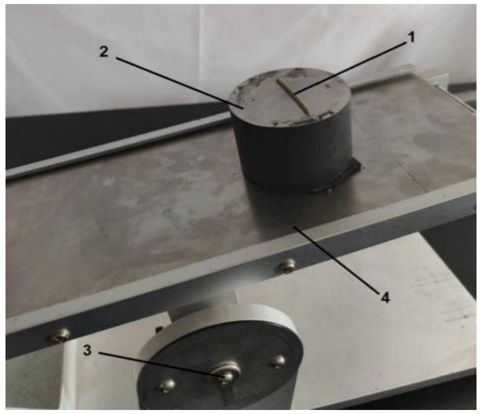

Fig. 3. Measurement of rolling friction coefficient between alfalfa straw and steel 45#: 1: Alfalfa straw; 2: Steel 45# plane; 3: Pointer; 4: Test plane of inclinometer

Table 3. Rolling Friction Coefficient (μ_2) under Five Moisture Content Conditions

Moisture Content (%)	2.7	13.4	19.9	33.1	74.5
μ_2 (Alfalfa-Steel)	0.19 to 0.36	0.19 to 0.38	0.09 to 0.36	0.12 to 0.30	0.12 to 0.29
μ_2 (Alfalfa-Alfalfa)	0.14 to 0.25	0.16 to 0.31	0.12 to 0.36	0.14 to 0.29	0.12 to 0.30

Measurement of restitution coefficient

The restitution coefficient represents the ability of the object to recover to its original state after collision. It is defined as the ratio of the normal velocity of the object after collision to the normal velocity before the collision (Lu *et al.* 2016; Zhang *et al.* 2017). The measurement of restitution coefficient is shown in Fig. 4a. The falling and rebound track of alfalfa was photographed by a high-speed camera (PCO.dimax S, China Ltd., Suzhou, China), and the video was recorded with software PCO.Camware (PCO China Ltd., V3.16/64bit, Suzhou, China) and analyzed with software Tema (Image Systems Ltd., V3.4-005, Linköping, Sweden). To reduce the impact of air resistance on the falling speed of alfalfa straw, the falling distance of alfalfa straw should be small. However, if the falling distance is too small, the effect of alfalfa straw collision rebound will not be obvious. To ensure the high-speed camera can clearly shoot and record the rebound height data, alfalfa straw should have a certain speed in the collision. Therefore, the alfalfa straw should have a certain falling height. After several attempts, the falling height was determined as 355 mm.

The high-speed camera was placed facing the test board and 1 m away from it. Its horizontal placement was maintained using a tripod. To capture the track of alfalfa straw by high-speed camera, three reference points were needed to be set on the test board for recording the track of falling, collision, and rebound, and the distance between the two reference points should be larger than or equal to the movement range of alfalfa straw.

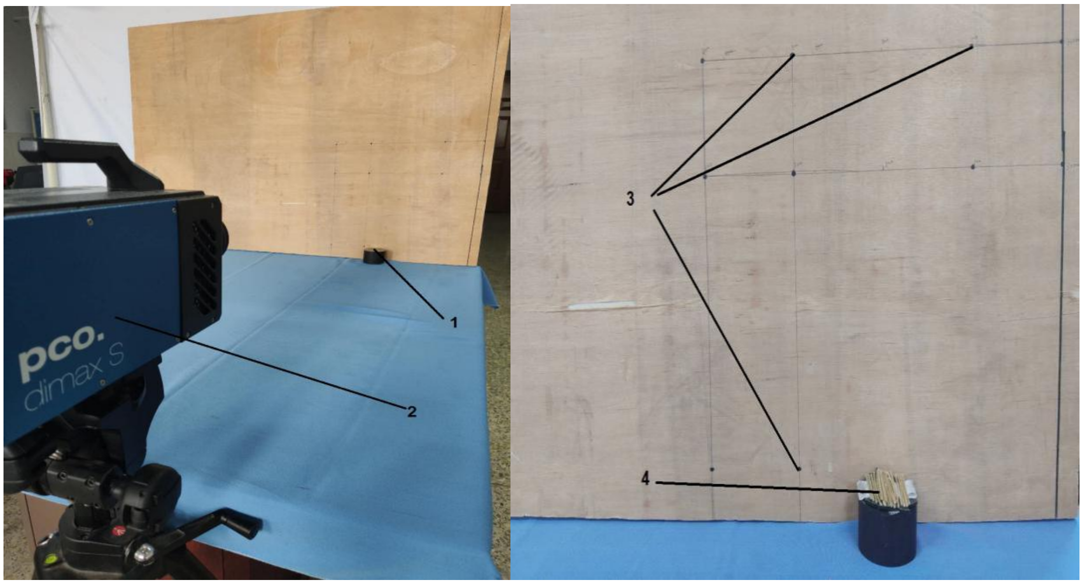

Fig. 4. Measurement of restitution coefficient; 4a: 1: Steel 45# plane; 2: High-speed camera; 4b: 3: Reference points; 4: Alfalfa straw row

During the test, a single alfalfa straw piece fell freely from 355 mm height to collide with the alfalfa straw row. To ensure enough contact area, the alfalfa straw row was composed of alfalfa straw without stem nodes and with length of 60 mm and diameter of approximately 2 mm, as shown in Fig. 4b. Once the alfalfa straw and the alfalfa straw row collided, the alfalfa straw would bounce up quickly. The whole process of alfalfa straw movement was photographed in real time by the high-speed camera, and the pictures were stored in the computer. When the test for measuring the restitution coefficient between alfalfa straw and steel 45# was over, the alfalfa straw row was removed, and the alfalfa - steel 45# restitution coefficient testing process were the same as above.

Assuming that alfalfa straw was only affected by gravity in the falling process, the normal velocity of alfalfa straw before collision can be obtained by the kinetic energy theorem:

$$v_1 = \sqrt{2gh_1} \tag{3}$$

The normal velocity after collision can be expressed as Eq. 4:

$$v_2 = \sqrt{2gh_2} \tag{4}$$

From the definition of the restitution coefficient, the result can be calculated using Eq. 5,

$$e = \frac{v_2}{v_1} = \sqrt{\frac{h_2}{h_1}} \tag{5}$$

where e is restitution coefficient, v_1 (m/s) is the normal velocity before collision, v_2 (m/s) is the normal velocity after collision, h_1 (mm) is the falling height before collision, and h_2 (mm) is the rebound height.

The falling height before collision was 355 mm, and the rebound height was recorded by the high-speed camera. Thus, the restitution coefficient of alfalfa straw under different moisture contents could be calculated, as shown in Table 4.

Table 4. Restitution Coefficient (*e*) Under Five Moisture Content Conditions

Moisture Content (%)	2.7	13.4	19.9	33.1	74.5
e (Alfalfa-Steel)	0.18 to 0.39	0.20 to 0.39	0.20 to 0.38	0.10 to 0.20	0.10 to 0.18
e (Alfalfa-Alfalfa)	0.12 to 0.18	0.16 to 0.34	0.12 to 0.22	0.10 to 0.29	0.08 to 0.13

Measurement of shear modulus

The shear modulus represents the shear resistance of a material. The parameter of shear modulus in simulation software will affect the result of compressive force in compression process. In addition, the material with different moisture contents has different shear resistance. The diameter of each alfalfa straw was measured with a Vernier caliper (accuracy: 0.02 mm and range: 150 mm, Harbin Measuring & Cutting Tool Group Company Ltd., Harbin, China), and the shear modulus of alfalfa straw was measured using the TMS-Pro texture analyzer (Food Technology Corporation Ltd., Sterling, VA, USA) as shown in Fig. 5. Then, the alfalfa straw was put on the test table and cut using the cutter of the texture analyzer. At each moisture content condition, the test was repeated 9 times. The data of shear force and displacement was recorded on the computer, and the shear modulus of alfalfa straw was calculated with Eq. 6,

$$G_s = F_m / S_a / \tau \qquad (6)$$

where G_s (MPa) is the shear modulus, F_m (N) is the maximum shear force, S_a (mm^2) is the cross-section area of alfalfa straw, and τ (rad) is the shear strain. The results are shown in Table 5.

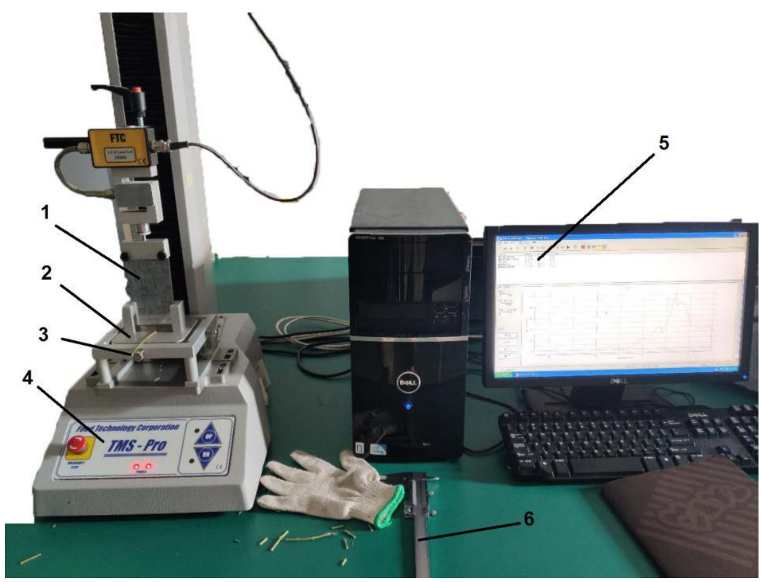

Fig. 5. Measurement of the shear modulus: 1: Cutter; 2: Test table; 3: Alfalfa straw; 4: Texture analyzer; 5: Computer; 6: Vernier caliper

Table 5. Shear Modulus under Five Moisture Content Conditions

Moisture Content (%)	2.7	13.4	19.9	33.1	74.5
Shear Modulus (MPa)	26.7 to 43.1	30.8 to 54.1	18.9 to 31.9	29.0 to 40.1	17.1 to 34.5

Due to limitations of test condition, the range of Poisson's ratio and surface energy was referred to the GEMM database. The Poisson's ratio of the alfalfa straw is 0.2 to 0.4, and the range of surface energy under different moisture content conditions are shown in Table 6.

Table 6. Surface Energy under Five Moisture Content Conditions

Moisture Content (%)	2.7	13.4	19.9	33.1	74.5
Surface Energy (J/m^2)	0 to 7	3.5 to 10.5	7 to 14	7 to 16	10 to 26

After the measurement of alfalfa physical parameters, the calibration of simulation parameters would be performed. The test design was performed using Minitab 19 software (Minitab LLC, Philadelphia, PA, USA). For the alfalfa straw with average diameter of 2 mm and average length of 10 mm, the nine basic spheres with a radius of 1 mm were combined to establish the discrete element mode by the strip model of EDEM software (DEM Solutions Ltd., v.2018, Edinburgh, UK). The simulation model of repose angle test was built according to the actual repose angle measuring instrument. A particle factory was established at the upper mouth of the funnel. The alfalfa straw model was generated after 4.5 s falling at 6 g/s rate. The alfalfa straw pile was formed on the base plate, as shown in Fig. 6. The EEPA (Edinburgh elastic plastic adhesion model) contact model and Hertz-Mindlin (no slip) contact model were used in alfalfa-alfalfa and alfalfa-steel, respectively.

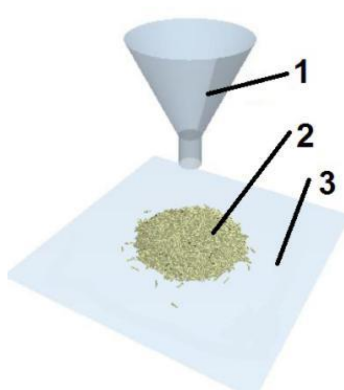

Fig. 6. Simulation model of repose angle: 1: Funnel; 2: Alfalfa straw pile; 3: Base plate

RESULTS AND DISCUSSION

Plackett-Burman Test

There are many parameter inputs in discrete element simulation. To obtain the determined parameters as soon as possible, the Plackett-Burman test was designed to select the parameters that have significant influence (P value < 0.05 in the analysis of variance). The 9 uncertain parameters previously mentioned were selected for the Plackett-Burman test. Each parameter took 2 levels that were coded +1 and -1. The list of parameters is shown in Table 7.

Table 7. List of Plackett-Burman Test Parameters

Moisture Content (%)		2.7		13.4		19.9		33.1		74.5	
Parameters	Code	-1	+1	-1	+1	-1	+1	-1	+1	-1	+1
Poisson's Ratio	X_1	0.2	0.4	0.2	0.4	0.2	0.4	0.2	0.4	0.2	0.4
Shear Modulus (MPa)	X_2	26.7	43.1	30.8	54.1	18.9	31.9	29.0	40.1	17.1	34.5
Surface Energy (J/m^2)	X_3	0	7	3.5	10.5	7	14	7	16	10	26
Alfalfa-steel Static Friction Coefficient	X_4	0.67	0.93	0.57	0.84	0.49	0.90	0.53	0.78	0.50	0.80
Alfalfa-alfalfa Static Friction Coefficient	X_5	0.55	0.90	0.36	0.63	0.38	0.75	0.45	0.70	0.36	0.60
Alfalfa-steel Rolling Friction Coefficient	X_6	0.19	0.36	0.19	0.38	0.09	0.36	0.12	0.30	0.12	0.29
Alfalfa-alfalfa Rolling Friction Coefficient	X_7	0.14	0.25	0.16	0.31	0.12	0.36	0.14	0.29	0.12	0.30
Alfalfa-steel Restitution Coefficient	X_8	0.18	0.39	0.20	0.39	0.20	0.38	0.10	0.20	0.10	0.18
Alfalfa-alfalfa Restitution Coefficient	X_9	0.12	0.18	0.16	0.34	0.12	0.22	0.10	0.29	0.08	0.13

In the test, the central point was set to 0, and the test was conducted 13 times under each moisture content condition. As shown in Fig. 7, using the angle measuring tool in the EDEM software measured the repose angle at +X and +Y direction twice, and the average value was calculated as the simulated repose angle. The results are shown in Table 8.

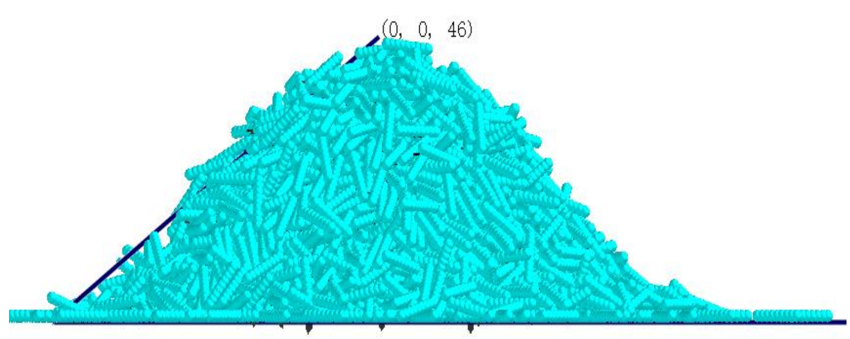

Fig. 7. Discrete-element model pile for the alfalfa straw

Table 8. Design and Results of Plackett-Burman Test

Code										Repose Angle (°)				
No.	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	2.7%	13.4%	19.9%	33.1%	74.5%
1	0	0	0	0	0	0	0	0	0	52.98	48.45	57.99	44.02	53.52
2	-1	-1	1	1	1	-1	1	1	-1	63.78	58.95	74.36	58.02	72.61
3	-1	-1	-1	1	1	1	-1	1	1	35.72	34.11	47.14	37.60	55.57
4	1	1	-1	1	1	-1	1	-1	-1	35.51	37.37	47.49	40.36	48.88
5	1	1	-1	1	-1	-1	-1	1	1	31.85	39.50	37.13	30.47	35.93
6	1	-1	-1	-1	1	1	1	-1	1	38.52	36.68	45.50	38.88	46.74
7	-1	1	1	-1	1	-1	-1	-1	1	61.53	62.26	56.87	46.63	63.62
8	1	-1	1	-1	-1	-1	1	1	1	63.66	59.54	57.44	48.59	70.79
9	-1	1	-1	-1	-1	1	1	1	-1	35.54	34.88	47.88	39.46	43.26
10	1	1	1	-1	1	1	-1	1	-1	52.20	61.94	48.68	35.25	74.53
11	-1	-1	-1	-1	-1	-1	-1	-1	-1	36.08	33.44	51.56	42.71	61.03
12	1	-1	1	1	1	-1	-1	-1	-1	62.35	53.43	59.19	51.50	75.97
13	-1	1	1	1	-1	1	1	-1	1	63.78	56.50	61.34	65.58	76.84

Nomenclature

Adj SS: Adjust sum of square. The sum of squares represents a measure of variation or dispersion of the mean distance. The calculation method is the sum of the squares of the difference from the mean. The adjust sum of square does not depend on the order in which the factors are entered into the model.

Adj MS: Adjust mean square. The mean square is calculated by dividing the adjust sum of square by the degrees of freedom.

F-value: Variance ratio. The value of dividing the variance of the two groups of samples.

P-value: P-value refers to the probability that the statistical summary is the same as the actual observation data in a probability model, or even greater.

The results are shown in Table 9. For all moisture contents, the factor X_3 (surface energy) was the most significant. When the moisture content was 19.9%, X_1 (Poisson's ratio), X_2 (shear modulus), X_7 (alfalfa-alfalfa rolling friction coefficient), as well as X_9 (alfalfa-alfalfa restitution coefficient) were the significant factors, while X_7 (alfalfa-alfalfa rolling friction coefficient), X_1 (Poisson's ratio), X_8 (alfalfa-steel restitution coefficient), and X_4 (alfalfa-steel static friction coefficient) were the significant factors when the moisture content was 33.1%.

Table 9. ANOVA of Plackett-Burman Test

Moisture Content 2.7%					
Symbol	Degree of Freedom	Adj SS	Adj MS	F-Value	P-Value
Linear Term	9	2093.88	232.65	51.02	0.019
X_1	1	12.69	12.69	2.78	0.237
X_2	1	32.34	32.34	7.09	0.117
X_3 **	1	1978.39	1978.39	433.88	0.002
X_4	1	2.48	2.48	0.54	0.537
X_5	1	3.00	3.00	0.66	0.502
X_6	1	1.54	1.54	0.34	0.620
X_7	1	36.96	36.96	8.11	0.104

X_8	1	18.80	18.80	4.12	0.179
X_9	1	7.68	7.68	1.68	0.324
Moisture Content 13.4%					
Symbol	Degree of Freedom	Adj SS	Adj MS	F-Value	P-Value
Linear Term	9	1635.26	181.70	117.17	0.008
X_1	1	5.77	5.77	3.72	0.194
X_2	1	22.14	22.14	14.28	0.063
X_3 **	1	1555.87	1555.87	1003.35	0.001
X_4	1	6.57	6.57	4.24	0.176
X_5	1	16.38	16.38	10.56	0.083
X_6	1	15.23	15.23	9.82	0.088
X_7	1	0.05	0.05	0.03	0.876
X_8	1	7.11	7.11	4.59	0.165
X_9	1	6.13	6.13	3.96	0.185
Moisture Content 19.9%					
Symbol	Degree of Freedom	Adj SS	Adj MS	F Value	P Value
Linear Term	9	1009.05	112.117	53.59	0.018
X_1 *	1	155.66	155.664	74.40	0.013
X_2 *	1	103.84	103.841	49.63	0.020
X_3 **	1	542.44	542.439	259.27	0.004
X_4	1	30.78	30.784	14.71	0.062
X_5	1	3.00	3.000	1.43	0.354
X_6	1	20.33	20.332	9.72	0.089
X_7 *	1	95.99	95.994	45.88	0.021
X_8	1	8.04	8.036	3.84	0.189
X_9 *	1	48.96	48.965	23.40	0.040
Moisture Content 33.1%					
Symbol	Degree of Freedom	Adj SS	Adj MS	F Value	P Value
Linear Term	9	1098.66	122.073	40.61	0.024
X_1 *	1	168.38	168.375	56.01	0.017
X_2	1	31.85	31.850	10.59	0.083
X_3 **	1	482.47	482.474	160.49	0.006
X_4 *	1	85.39	85.387	28.40	0.033
X_5	1	38.77	38.772	12.90	0.070
X_6	1	0.19	0.185	0.06	0.827
X_7 *	1	181.97	181.974	60.53	0.016
X_8 *	1	109.63	109.626	36.47	0.026
X_9	1	0.02	0.017	0.01	0.947
Moisture Content 74.5%					
Symbol	Degree of Freedom	Adj SS	Adj MS	F Value	P Value
Linear Term	9	2003.34	222.59	2.10	0.364
X_1	1	33.63	33.63	0.32	0.630
X_2	1	131.01	131.01	1.24	0.382
X_3 *	1	1702.89	1702.89	16.07	0.057
X_4	1	2.83	2.83	0.03	0.885
X_5	1	0.29	0.29	0.00	0.963
X_6	1	33.50	33.50	0.32	0.631
X_7	1	4.73	4.73	0.04	0.852
X_8	1	34.65	34.65	0.33	0.625
X_9	1	59.81	59.81	0.56	0.531
Note: ** shows the factor is very significant ($P < 0.01$), * shows the factor is significant ($P < 0.05$);					

Steepest Climbing Test

The significant parameters obtained from Plackett-Burman test could be used in steepest climbing test to approach the optimal area. Each of significant parameters was gradually increased according to the step size to obtain the repose angle. Other parameters were mean value. The results are shown in Table 10.

Table 10. Results of Steepest Climbing Test

Moisture Content 19.9%							
No.	X_3 (J/m^2)	X_1	X_2 (MPa)	X_7	X_9	Repose Angle (°)	Relative Error (%)
1	7.00	0.20	18.30	0.12	0.120	40.50	14.68
2	8.75	0.25	22.15	0.18	0.145	46.67	1.69
3	10.50	0.30	25.40	0.24	0.170	48.52	2.21
4	12.25	0.35	28.65	0.30	0.195	50.14	5.62
5	14.00	0.40	31.90	0.36	0.220	53.50	12.70
Moisture Content 33.1%							
No.	X_3 (J/m^2)	X_7	X_1	X_8	X_4	Repose Angle (°)	Relative Error (%)
1	8	0.14	0.20	0.100	0.120	40.50	28.08
2	10	0.18	0.25	0.125	0.145	43.19	23.30
3	12	0.22	0.30	0.150	0.170	49.67	11.97
4	14	0.26	0.35	0.175	0.195	52.64	6.52
5	16	0.30	0.40	0.200	0.220	64.08	13.80

From the results of the steepest climbing test, because the surface energy was the only significant factor, the optimal value could be obtained when the moisture content was 2.7%, 13.4%, or 74.5%. The optimal values were 4.38, 3.50, and 18.00 J/ m^2 respectively. For other moisture content conditions, not only surface energy, but also other factors were significant. When moisture contents were 19.9 % and 33.1 %, the relative error decreased first and then increased.

Box-Behnken Test

To reduce the level range of the parameters, when the moisture content was 19.9%, No. 3 was determined as the intermediate level (0), whereas No. 4 and No. 2 levels were determined as the high level (+1) and low level (-1), respectively. Finally, when the moisture content was 33.1%, No. 4 was determined as the intermediate level (0), and the No. 5 and No. 3 levels were determined as the high level (+1) and low level (-1), respectively. For the other parameters the mean values were also used. The results of the Box-Behnken test, designed by Minitab 19 software, are shown in Table 11.

Regression analyses for the test results in Table 11 were performed using Minitab 19 software, and the results are shown in Table 12.

Table 11. Scheme and Results of the Box-Behnken Test

	Test Factors					Moisture Content 19.9%	Moisture Content 33.1%
No.	$X_3(X_3)$	$X_1(X_7)$	$X_2(X_1)$	$X_7(X_8)$	$X_9(X_4)$	Repose Angle θ (°)	Repose Angle θ (°)
1	0	1	0	0	-1	51.13	60.73
2	1	0	1	0	0	57.49	58.53
3	0	-1	0	0	1	50.48	61.27
4	-1	-1	0	0	0	45.11	56.83
5	0	-1	0	1	0	52.35	61.47
6	1	0	0	0	-1	50.81	61.92
7	0	0	1	0	1	52.95	53.11
8	0	0	0	1	-1	53.66	58.62
9	0	0	0	0	0	49.95	56.31
10	0	0	-1	0	-1	52.28	56.81
11	0	0	0	0	0	50.00	55.82
12	-1	0	-1	0	0	48.68	54.63
13	0	0	1	0	-1	51.49	59.84
14	0	0	0	0	0	50.96	58.42
15	0	1	0	0	1	49.16	57.36
16	1	-1	0	0	0	55.37	60.37
17	0	0	0	1	1	51.68	56.39
18	0	0	0	0	0	50.26	58.58
19	0	1	0	1	0	53.60	59.00
20	0	-1	0	-1	0	50.55	56.13
21	0	1	1	0	0	47.42	58.94
22	1	0	-1	0	0	53.23	60.51
23	-1	0	0	1	0	48.22	56.94
24	0	0	-1	1	0	51.21	58.35
25	1	0	0	-1	0	55.66	64.57
26	0	0	0	-1	1	50.75	60.93
27	0	0	0	0	0	49.97	56.27
28	-1	0	1	0	0	47.37	55.48
29	0	-1	1	0	0	52.39	55.71
30	0	0	-1	0	1	51.59	58.45
31	-1	0	0	-1	0	45.06	55.56
32	-1	0	0	0	1	45.06	53.58
33	0	0	1	-1	0	48.67	56.86
34	-1	0	0	0	-1	46.85	55.17
35	0	1	0	-1	0	49.31	61.18
36	0	0	1	1	0	51.38	58.09
37	0	0	-1	-1	0	48.04	59.79
38	0	1	-1	0	0	50.91	57.68
39	0	-1	0	0	-1	52.40	56.74
40	0	0	0	0	0	51.17	58.55
41	-1	1	0	0	0	47.11	57.88
42	0	0	0	-1	-1	47.44	58.94
43	1	0	0	0	1	55.76	62.88
44	1	0	0	1	0	51.89	59.93
45	1	1	0	0	0	51.72	62.42
46	0	-1	-1	0	0	48.89	57.29

Table 12. Analysis of Variance of Box-Behnken Test

Moisture Content 19.9%					
Symbol	Degree of Freedom	Adj SS	Adj MS	F-Value	P-Value
Model	15	301.323	20.088	12.46	< 0.001
Linear Term	5	240.158	48.032	29.79	< 0.001
X_3**	1	213.671	213.671	132.52	< 0.001
X_1	1	3.222	3.222	2.00	0.168
X_2	1	1.010	1.010	0.63	0.435
X_7**	1	22.137	22.137	13.73	0.001
X_9	1	0.117	0.117	0.07	0.789
Interactive Term	10	61.166	6.117	3.79	0.002
X_3*X_1	1	7.981	7.981	4.95	0.034
X_3*X_2	1	7.756	7.756	4.81	0.036
X_3*X_7 *	1	12.006	12.006	7.45	0.011
X_3*X_9 *	1	11.357	11.357	7.04	0.013
X_1*X_2 *	1	12.215	12.215	7.58	0.010
X_1*X_7	1	1.550	1.550	0.96	0.335
X_1*X_9	1	0.001	0.001	0.00	0.984
X_2*X_7	1	0.148	0.148	0.09	0.764
X_2*X_9	1	1.156	1.156	0.72	0.404
X_7*X_9 *	1	6.996	6.996	4.34	0.046
R^2 = 86.17%; R^2_{adj} = 79.25%; R^2_{pred} = 62.85%;					
Moisture Content 33.1%					
Symbol	Degree of Freedom	Adj SS	Adj MS	F-Value	P-Value
Model	20	240.634	12.032	7.86	< 0.001
Linear Term	5	138.529	27.706	18.11	< 0.001
X_3**	1	126.900	126.900	82.95	< 0.001
X_7	1	5.499	5.499	3.59	0.070
X_1	1	3.019	3.019	1.97	0.172
X_8	1	1.671	1.671	1.09	0.306
X_4	1	1.440	1.440	0.94	0.341
Square Term	5	33.663	6.733	4.40	0.005
X_3*X_3	1	4.942	4.942	3.23	0.084
X_7*X_7 *	1	9.976	9.976	6.52	0.017
X_1*X_1	1	3.976	3.976	2.60	0.119
X_8*X_8 **	1	12.883	12.883	8.42	0.008
X_4*X_4	1	1.266	1.266	0.83	0.372
Interactive Term	10	68.443	6.844	4.47	0.001
X_3*X_7	1	0.250	0.250	0.16	0.689
X_3*X_1	1	2.002	2.002	1.31	0.263
X_3*X_8 *	1	9.060	9.060	5.92	0.022
X_3*X_4	1	1.626	1.626	1.06	0.312
X_7*X_1	1	2.016	2.016	1.32	0.262
X_7*X_8 **	1	14.138	14.138	9.24	0.005
X_7*X_4 **	1	15.602	15.602	10.20	0.004
X_1*X_8	1	1.782	1.782	1.17	0.291
X_1*X_4 **	1	17.514	17.514	11.45	0.002
X_8*X_4	1	4.452	4.452	2.91	0.100
R^2 = 86.29%; R^2_{adj} = 75.32%; R^2_{pred} = 53.12%;					

From the Table 12, it can be seen the P value of the model was less than 0.001 when the moisture content was 19.9%, which showed a very significant model and significant factors of X_3, X_7, X_3*X_7, X_3*X_9, and X_1*X_2. Thus, the regression equation can be written as:

$$\theta = 50.603 + 3.654X_3 - 0.449X_1 + 0.251X_2 + 1.176X_7 + 0.086X_9 - 1.412X_3*X_1 + 1.393X_3*X_2 - 1.732X_3*X_7 + 1.685X_3*X_9 - 1.747X_1*X_2 + 0.622X_1*X_7 - 0.013X_1*X_9 - 0.193X_2*X_7 + 0.537X_2*X_9 - 1.323X_7*X_9 \quad (7)$$

The optimization of the regression model Eq. 7 was performed with the tested repose angle value of 47.47° and obtained: X_3 = 8.75 J/m^2, X_1 = 0.35, X_2 = 22.26 MPa, X_7 = 0.18, and X_9 = 0.154.

According to the analysis of variance (ANOVA) result, when the moisture content was 33.1%, the model was significant, and the fitting is good. The regression equation can be written as:

$$\theta = 57.325 + 2.816X_3 + 0.586X_7 - 0.434X_1 - 0.323X_8 - 0.300X_4 + 0.752X_3^2 + 1.069X_7^2 - 0.675X_1^2 + 1.215X_8^2 + 0.381X_4^2 + 0.250X_3*X_7 - 0.707X_3*X_1 - 1.505X_3*X_8 + 0.638X_3*X_4 + 0.710X_7*X_1 - 1.880X_7*X_8 - 1.975X_7*X_4 + 0.668X_1*X_8 - 2.093X_1*X_4 - 1.055X_8*X_4 \quad (8)$$

The optimization of the regression model Eq. 8 was performed with the repose angle test value of 56.31° as the target value. The results were: X_3 =12.52 J/m^2, X_7 = 0.23, X_1 = 0.31, X_8 = 0.153, and X_4 = 0.725

Verification of the Optimal Parameters in Simulation

To verify whether the optimal parameters meet the simulation test results, the aforementioned parameters were input to the EDEM software to do the simulation with the discrete element model for pile of alfalfa straw. The repose angle was also measured at +X and +Y direction twice by software's angle measuring tool and the averaged value was calculated. For each moisture content the test was repeated three times. The results are shown in Table 13.

Table 13. Results of the Verification Test

Moisture Content (%)	2.7	13.4	19.9	33.1	74.5
Repose Angle (°) 1	45.41	38.29	51.90	55.58	62.90
Repose Angle (°) 2	41.38	39.67	48.23	56.02	63.75
Repose Angle (°) 3	41.19	38.82	47.86	58.34	64.75
Mean Value	42.66	38.93	49.33	56.65	63.80
Relative Error (%)	1.60	1.64	3.92	0.60	1.13

Student's t test was performed on 5 groups of data, and the results showed that there was no significant difference between the mean value and the target value in these 5 groups. This demonstrated that the simulated parameters were credible. Through the above tests, the DEM simulation parameters of alfalfa straw under different moisture content conditions were calibrated, as shown in Table 14.

Table 14. Calibrated Values of Each Parameters

Moisture Content (%)	2.7	13.4	19.9	33.1	74.5
Poisson's Ratio	0.30	0.30	0.35	0.31	0.30
Shear Modulus (MPa)	34.90	42.50	22.26	34.60	25.80
Surface Energy (J/m^2)	4.38	3.50	8.75	12.52	18.00
Alfalfa-Steel Static Friction Coefficient	0.800	0.700	0.700	0.725	0.650
Alfalfa-alfalfa Static Friction Coefficient	0.725	0.500	0.570	0.585	0.480
Alfalfa-steel Rolling Friction Coefficient	0.275	0.290	0.225	0.210	0.205
Alfalfa-alfalfa Rolling Friction Coefficient	0.195	0.240	0.180	0.230	0.210
Alfalfa-steel Restitution Coefficient	0.285	0.300	0.290	0.153	0.140
Alfalfa-alfalfa Restitution Coefficient	0.150	0.250	0.154	0.195	0.105

CONCLUSIONS

1. Based on the physical test results of alfalfa straw contact parameters, the ranges of contact parameters were measured with different moisture contents. These ranges were with reference to the Plackett-Burman test. The Plackett-Burman test was carried out and find out that the significant parameters were different with various moisture content. Moreover, the surface energy was the most significant factor in the repose angle test, regardless of the moisture content.
2. The Box-Behnken test was used to obtain the second-order regression model of repose angle. Then, the optimal value of each significant parameters under different moisture contents was calibrated.
3. Student's t test was used to verify the correctness of the optimized parameters, which showed that there was no significant difference between the simulated repose angle and the physical tested value. It was feasible to calibrate the discrete element method (DEM) simulation parameters by using the aforementioned optimization tests, and the optimal parameters can be obtained easily.

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