MECHANICAL CHARACTERISTICS OF THE RUBBED MAIZE STRAW DURING SCREW CONVEYING

/

揉碎玉米秸秆螺旋输送过程中的力学特性研究

Wulantuya; Wuyuntana; Wang Hongbo*; Guo Wenbin; Wang Chunguang; Qinglin
College of Mechanical and Electrical Engineering, Inner Mongolia Agricultural University, Hohhot / China
Tel: +86 13739981395; E-mail: wanghb@imau.edu.cn
DOI: https://doi.org/10.35633/inmateh-64-10

Keywords: *rubbed maize straw, mechanical characteristics, screw conveying, experiment*

ABSTRACT

In order to reduce the power consumption of screw conveyor and to improve the productivity, this study investigated such mechanical characteristics of rubbed maize straw as coefficient of sliding friction, angle of repose, internal friction coefficient, cohesion, flow function value and compressible coefficient with respect to its moisture content and density. An experiment was designed and consists of a sliding friction characteristic test-bed, a direct shear apparatus, a self-made device with adjustable density and compression. The results showed that: the coefficient of sliding friction increases with the increase of moisture content and density; the angle of repose and internal friction coefficient each increases with increasing moisture content respectively; there is no significant effect between the moisture content and the cohesion of rubbed maize straw; the flow function value goes up with the increase of the moisture content; also the increase of the moisture content leads to the increased bulk density due to the reduced materials gap and the increased compression coefficient, which makes it hard to compress. The equation of pressure and density was found, and it is suitable for the analysis of compression characteristic of rubbed maize straw. The research results lay a theoretical foundation and a basis for the further study on mechanical properties of maize straw.

摘要

为了减少螺旋输送机的功耗并提高生产率，采用滑动摩擦特性试验台，直切仪、自行研制的密度调节装置和压缩装置试验研究了揉碎玉米秸秆的滑动摩擦系数、休止角、内摩擦系数、粘聚力、流动函数值和可压缩系数等力学特性与含水率、密度之间的关系。结果表明:滑动摩擦系数随着含水率和密度的增加而增大,休止角和内摩擦系数随含水量的增加而增大,含水率对揉碎玉米秸秆粘聚力的影响不显著,流动函数值随含水率的增加而增大,随着含水率的增加物料间的间隙减小、压缩系数增大、堆积密度增大，使物料难以压缩。获得了压强和密度的关系式，该式也适合揉碎玉米秸秆的压缩特性的分析。研究结果可为玉米秸秆力学性能的研究奠定了理论基础。

INTRODUCTION

The rubbing of corn stalks is a processing technology that emerged in China in the 1980s *(Lin Li et al, 1997)*. The straw rubbing process not only separates cellulose, hemicellulose and lignin, but the longer straw silk can prolong its residence time in the rumen of ruminants, which is beneficial to the digestion and absorption for livestock, thus improving both the feed intake of straw and digestibility. Straw rubbing is a simple, efficient and low-cost processing method. The processing efficiency is about 1.2 to 1.5 times that of straw crushing. The rubbed maize straw is a soft, fluffy silk with suitable length and thickness, which can be fed directly, and the feeding rate can reach more than 90%. While it can also be further processed to produce high quality roughage, such as silage, micro-storage, ammoniation, alkalization, briquetting and puffing treatment, etc. (*Tianshu Chu et al, 2016; Cailong Ma et al, 2018; Shuangxia Zhang et al, 2016)*.

The screw conveyor is essential equipment in the treatment of rubbed maize straw. The conveying performance will directly affect the quality and productivity of the processing, and as well affect the performance of screw conveyor. Previous studies have shown that the mechanical properties of rubbed maize straw inevitably affect the working performance of screw conveyor *(Wulantuya et al, 2015; Wulantuya et al, 2016;*

Wulantuya, Lecturer; Wuyuntana, Associate Professor; Hongbo Wang, Associate Professor, Correspondent author; Wenbin Guo, Associate Professor; Chunguang Wang, Professor; Qinglin, Teaching assistant*

Wulantuya et al, 2020). While there have been few studies on the mechanical properties of rubbed maize straw, similar research on rice straw, crushed straw and soybean stalk is common *(Chevanan et al, 2009).* Shinners et al. studied the effects on the sliding friction coefficient of stalks and static friction coefficient of chopped grasses with regard to water content, pressure, relative velocity and material type of straw *(Shinners et a, 1991; Joseph et al, 2008; Kakitis et al, 2005)*. Larsson et al *(2010)* studied the influence of moisture content and pressure on the dynamic friction coefficient of straw, and established a model to analyse its influence. Phani et al. *(2010)* studied the variation of friction coefficient of crushed straw of barley, rapeseed, oat and wheat respectively, with untreated raw and through steam explosion. Yishui Tian et al. studied the fluidity by Carr index evaluation method assuming a straw with a length of 5-30mm as a bulk with a large particle size distribution *(Yishui Tian et al, 2011; Zonglu Yao et al, 2012)*. Xin Fang et al. *(2012)* made a self-made bevelling instrument and researched the effects of moisture content on the sliding friction between finely shredded soybean straw and different materials. Haitao Chen et al. *(2013)* studied the flow dynamics characteristics of straw materials following refining treatment, which detailed the internal friction angle, cohesion and flow function values of rice straw.

The mechanical properties of straw materials refer to the friction, flow and compression characteristics, in which friction is expressed by sliding friction angle, rolling stability angle, angle of repose and internal friction angle, flow by internal friction angle, cohesion, flow function value representation, compression expressed in terms of compressibility coefficients *(Yuming Guo et al, 2005)*.

In this study the test was conducted to obtain the mechanical characteristics and corresponding parameters of rubbed maize straw by using a direct shear apparatus, sliding friction characteristic test-bed, self-made adjustable density device and compression device. The moisture content and density of rubbed maize straw has an effect on its mechanical characteristics, and the influence law was obtained. This data provides the necessary theoretical basis and technical basis for the design and optimization of rubbed maize straw conveying machinery.

MATERIALS AND METHODS

Materials

The maize straw was obtained from the suburbs of Hohhot, China and was rubbed using a 9R-40 type rubber *(Designed and manufactured by Inner Mongolia Agricultural University)*. Rubbed maize straw was less than 180 mm long and 2-8 mm wide, as shown in Fig.1. The moisture content of the rubbed maize straw was tested by moisture meter *(Hebi Electronic Research Institute Co., Ltd. DYSF-8000W automatic moisture analyser, Henan, China)*. The initial average moisture content of the straw was 15.76%. According to the test requirements, each of the ground straws was conditioned to moisture contents of 22.36%, 31.82%, 42.27%, and 52.87% *(w.b)* by adding appropriate amounts of distilled water to the samples contained in Ziploc bags and stored in a cool room at 4℃ for 24 h. The calculation formula for the moisture content of the material was shown in Eq. 1 below. The mechanical properties test was performed after the moisture content of the straw was uniform.

$$M = \frac{m_1 - m_2}{m_1} \times 100\% \quad (1)$$

where: M is wet basis moisture content, m_1 is the mass of fresh materials, m_2 is the mass of dry materials.

Fig. 1 - Test samples

Devices

The experimental devices were a test-bed for sliding friction characteristics, a self-made density-adjustable device, a direct shear test apparatus, and a compression device, as shown in Fig.2- Fig.5. Besides, there was also a iHP-2K push-pull force meter produced by Yueqing Aidebao Instrument Co., Ltd. The balance scales produced by Beijing Fums Technology Development Co., Ltd. has an accuracy of 0.01g and a measuring range of 6 kg.

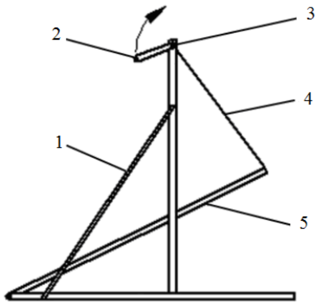


Fig. 2 - Sliding friction characteristic test-bed
1 – Studdle; 2 – Handle; 3 – Winding shaft; 4 – Rope; 5 – Sideling plane

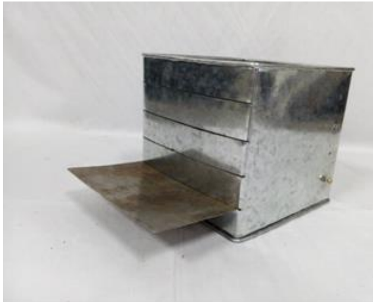


Fig. 3 - The density controller

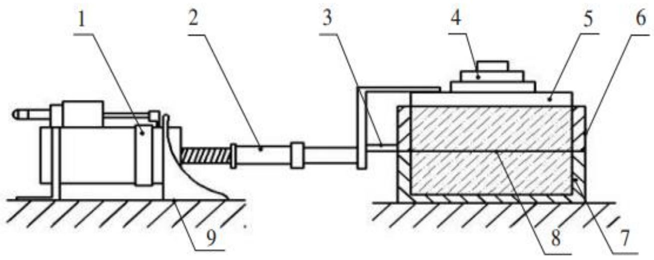


Fig. 4 - Direct shear test apparatus
1 – Load device; 2 – Dynamometer; 3 – Load pole; 4 – Compaction load; 5 – Cap; 6 – Shear cell; 7 – Base; 8 – Shear plane; 9 – Bottom plane

Fig. 5 - Material compression test unit

Experimental Methods

The mechanical properties of rubbed maize straw are subject to many factors. The friction characteristic is mainly related to such factors as moisture content and density. The moisture content will affect the flow characteristics as well as the compression characteristics of rubbed maize straw. The selected experimental factors and levels are shown in Table 1. Each test was replicated 10 times, and the results were averaged.

Table 1

Test factors and levels

Moisture Content [%]	Density [kg/m^3]
15.76	76.8
22.36	96
31.82	128
42.27	192
52.87	384

Method for sliding friction coefficient determination

Five groups of rubbed maize stalks with different moisture contents were taken as test materials. 1.2 kg of rubbed maize stalks were placed in the density controller for each test, and the volume of the material was changed by inserting plates to different positions so as to obtain five different densities. The sliding friction coefficient test was carried out at different densities respectively.

Method for determining the angle of repose

Determination of the angle of repose of rubbed maize straw with five different moisture contents by the tilt method.

Method for measuring internal friction angle, cohesion force and flow function value

Determination of the angle of repose of rubbed maize straw with five different moisture contents by the tilt method. Set the pre-compacting positive load to 200 kPa, then at 200, 150, 100, 50 kPa. Direct shearing is carried out step by step under positive load conditions of 4 grades. This method refers to GB/T4934.1-2008 for specific operation procedures, which is a China National Standard Test Method.

Excel 2003 software was used, the positive load value as the x-axis, and the corresponding shear load value as the y-axis. The scatter diagram was plotted and the trend line was added, linear regression equation was fitted. This trend line is the Moire envelope, and the regression equation can be regarded as the expression of the Moire envelope, expressed by the formula (2), and then the internal friction angle and the value of cohesion were obtained.

$$\tau = c + \sigma \tan\varphi \tag{2}$$

where:

τ is the shear stress; c is the unitary cohesion; σ is the normal stress, φ is the internal friction angle.

Under certain pre-compaction conditions, the flow function value of rubbed maize straw was obtained by formulas (3), (4) and (5).

$$FF = \frac{\sigma_1}{\sigma_c} \tag{3}$$

where:

σ_1 is the maximum main stress; σ_c is the unconfined yield stress.

$$\sigma_c = \frac{2c(1+\sin\varphi)}{\cos\varphi} \tag{4}$$

$$\sigma_1 = \left(\frac{A-\sqrt{A^2\sin^2\varphi - {\tau_0}^2\cos^2\varphi}}{\cos^2\varphi}\right)\times(1+\sin\varphi)-\left(\frac{c}{\tan\varphi}\right) \tag{5}$$

where:

$A=\sigma_0+c/\tan\varphi$; σ_0 is the maximum normal stress corresponding to the pre-compacting load;

τ_0 is the shear stress corresponding to the maximum normal stress.

Method for determining coefficient of compressibility

The rubbed maize straw is a soft, loose viscoelastic body with a large random shape and size. In order to improve the measurement accuracy, 20 samples were taken and filled at each moisture content without any pre-compaction. The box body is weighed and then the bulk density of the material is calculated. The formula is as follows:

$$\rho_a = \frac{M - m_X}{V_X} \tag{6}$$

where:

ρ_a is the bulk density of material;

M is the total mass of materials and cabinets;

m_X is the mass of the cabinet;

V_X is the volume of the box.

The measurement of the material density was repeated 10 times for each sample and the result was averaged. Finally, the average of the density obtained from the repeated test of 20 samples with the same moisture content averaged as the final density.

Five groups of rubbed maize straw with different moisture contents were taken as test materials, and 20 samples were taken from each group. The mold filled and the upper template covered without any pre-compaction. The push-pull force gauge *(HP-2K type)* applies different pressures *(during the screw conveying process, the pressure of the rubbed maize straw is 30-200 N)* and the distance between the upper surface of upper template and the upper edge of mold under different pressures were measured to calculate the volume of the material. Then the material density corresponding to each pressure value is calculated. The experimental data was analysed using MATLAB 2014 *(Math Works, Natick, MA, USA)*.

RESULTS AND DISCUSSION

Effects of moisture content and density on the sliding friction coefficient

Fig.6 shows the relation between moisture content and sliding friction coefficient of rubbed maize straw with different densities. Take five different densities from 76.8 kg/m³ to 384 kg/m³ and observe the result when the moisture content of the material varies from 15.76% to 52.87%. It is obvious that the sliding friction coefficient of rubbed maize straw is gradually increasing with the increase of moisture content. Many related studies have shown that the friction coefficient is related to the material, smoothness and humidity of the contacting objects and is subject to moisture content. The main reason is that as the moisture content increases, a thin liquid film was formed on the contact surface *(by adsorption or deposition)* and thus generating a meniscus force around the surface and consequently increased frictional force. Therefore, when sliding occurs, both the sliding friction angle and the friction coefficient increase. In addition, as the moisture content increases, the material is more likely to adhere to the contact surface, resulting in increased resistance to frictional sliding between the material and the steel sheet.

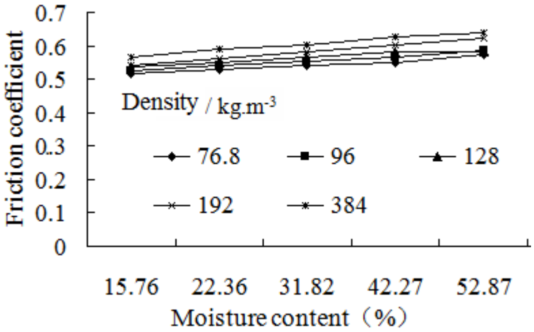


Fig. 6 - Relation between moisture content and friction coefficient

By the mathematical statistics analysis software MATLAB, the relation between the moisture content of the material and the friction coefficient was obtained, as shown in Table 2.

Table 2

Functional relation between moisture content and friction coefficient

Density [kg/m³]	Moisture Content [%]	Fitting Equation	R^2
76.8	15.76～52.87	$y = 0.0015x + 0.4918$	0.9391
96	15.76～52.87	$y = 0.0017x + 0.4977$	0.9934
128	15.76～52.87	$y = 0.0018x + 0.507$	0.996
192	15.76～52.87	$y = 0.0022x + 0.5102$	0.9878
384	15.76～52.87	$y = 0.002x + 0.5401$	0.9778

Note: y is the sliding friction coefficient, x, is the moisture content.

Fig.7 shows the relation between density and friction coefficient at different moisture content values. With the moisture content changing from 15.76%-52.87%, the sliding friction coefficient between the material and the steel plate increased with the material density in the range of 77.8-384kg/m³. The main reason for this effect is that the rubbed maize straw is soft and fluffy, and there is gap between them. For a certain amount of materials, increasing density squeezes the gap between them so that the area of contact surface between material and steel plate increases. As a result, increasing adhesion leads to increasing friction coefficient.

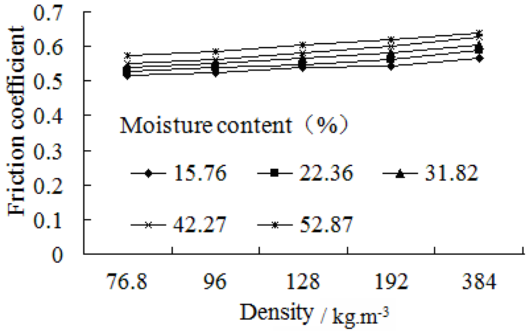


Fig. 7 - Relation between density and friction coefficient

Through the mathematical analysis by MATLAB, the relation between the density of the material and the friction coefficient was obtained, as shown in Table 3.

Table 3

Functional relation between density and friction coefficient

Moisture Content [%]	Density [kg/m³]	Fitting Equation	R^2
15.76	76.8～384	$y = 0.002x + 0.5104$	0.9583
22.36	76.8～384	$y = 0.002x + 0.5182$	0.9651
31.82	76.8～384	$y = 0.002x + 0.534$	0.8544
42.27	76.8～384	$y = 0.002x + 0.5433$	0.8778
52.87	76.8～384	$y = 0.002x + 0.5717$	0.8838

Note: y is the sliding friction coefficient, x, is the density.

Effect of moisture content on the angle of repose

Fig.8 shows the relation between moisture content and the angle of repose. It can be seen from Fig.8 that as the moisture content increased, the angle of repose for the rubbed maize straw increased. The reason is that after the moisture content increases, the surface of the rubbed maize straw is wet, and the viscosity between the materials is increased, which making it easier to pile up, and its scattering and fluidity are obviously weakened.

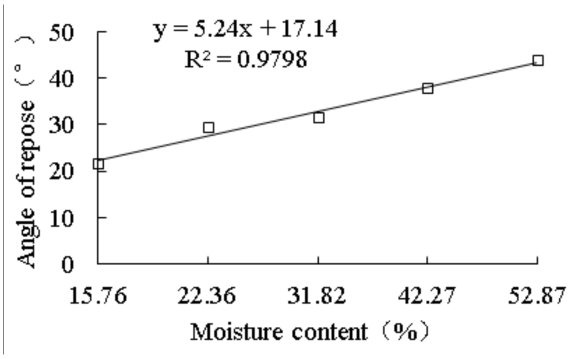


Fig. 8 - Angle of repose of materials under different moisture content

Effect of moisture content on the flow characteristics

As shown in Fig.9, with the increase of moisture content, the internal friction coefficient increased, which was consistent with the previous test results. The internal friction coefficient is one of the indicators for measuring the interaction force between materials. For rubbed maize straw, the internal friction coefficient is one of the main causes for material compression and aggregation. As the moisture content increases, the adhesion force between materials increases, resulting in an increase in internal frictional resistance.

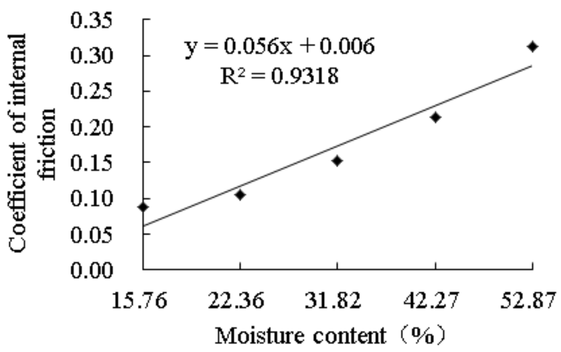


Fig. 9 - Internal friction coefficient of materials under different moisture content

As shown in Fig.10, with the increase of moisture content, the cohesion of the rubbed maize straw fluctuates, and the flow function value increases steadily. Under the conditions of this study, the moisture content is not the main factor affecting cohesion of rubbed maize straw. There are few studies on the relation between moisture content and cohesion. Some research showed that the physical and compression properties of the material are the main factors affecting the cohesion.

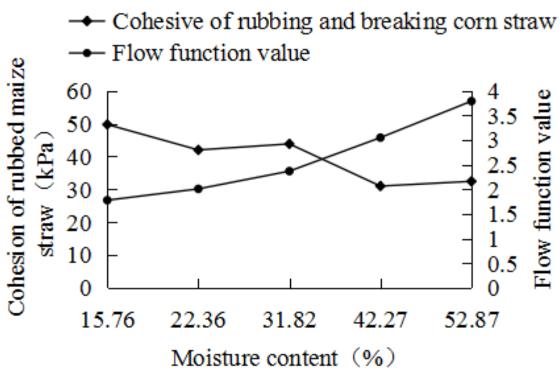
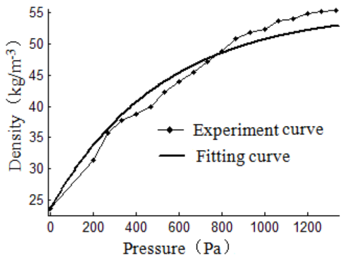


Fig. 10 - Flow characteristic of materials under different moisture content

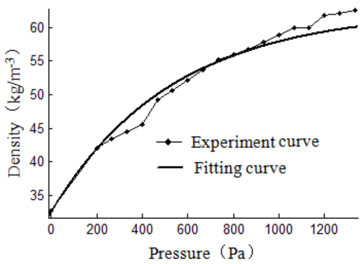
Effect of moisture content on the compressibility

In deriving the mathematical model of the productivity and power consumption of the screw conveyor, the relation between pressure and density is used, which involves the compressible coefficient C_o of the material, so it is necessary to study this coefficient *(Wulantuya et al, 2020)*.

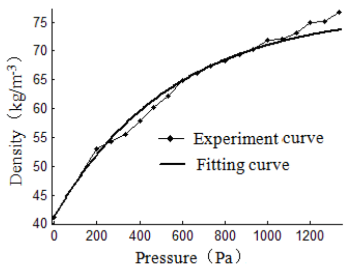
The following relation exists between the pressure and density of the material. The bulk density of the materials with five different moisture contents and the density values of the materials under different pressures are substituted into the above formula respectively to obtain a function of density and pressure, and the function is further combined with the test curve to obtain the compressibility factor of rubbed maize straw. The compression test curves of rubbed maize straw under five moisture contents are shown in Fig.11.



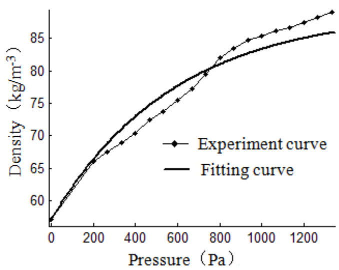
(a) Moisture content 15.76%



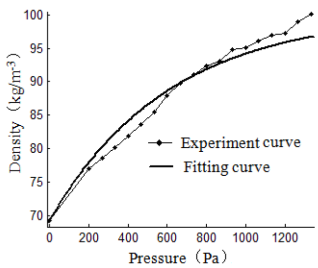
(b) Moisture content 22.36%



(c) Moisture content 31.82%



(d) Moisture content 42.27%



(e) Moisture content 52.87%

Fig. 11 - Relation between density and pressure under different moisture content

The equations and compressibility values for different moisture contents are shown in Table 4.

Table 4

Equation and the value of C_0 under different moisture content

Moisture Content[%]	Fitting Equation	C_0
15.76	$y = 55.27 - (55.27 - 23.73) \cdot e^{-C_0 x}$	0.001929
22.36	$y = 62.51 - (62.51 - 32.85) \cdot e^{-C_0 x}$	0.001865
31.82	$y = 76.82 - (76.82 - 41.23) \cdot e^{-C_0 x}$	0.001812
42.27	$y = 89.06 - (89.06 - 57.2) \cdot e^{-C_0 x}$	0.001713
52.87	$y = 100.12 - (100.12 - 69.4) \cdot e^{-C_0 x}$	0.001639

The compression coefficient C_o is a characteristic parameter of the material itself, which reflects the difficulty of compressing the material, and is related to the type of material, the size of the particle, and the moisture content. According to the relevant literature, the greater the compression coefficient, the easier the material is compacted, and the smaller the compressible coefficient, the harder it is to compact the material *(Canjun Huang, 2013)*.

From Table 4 and the results of the bulk density test, it is known that as the moisture content increases, the bulk density of the rubbed maize straw increases, the gap between the materials becomes smaller, the compressibility coefficient decreases, and the material is not easily compressed, which is in accordance with the rules above. The relation between pressure and density is as follows. It is also suitable for the analysis of the compressive properties of rubbed maize straw.

$$\rho = \rho_m - (\rho_m - \rho_a) \cdot e^{-C_0 P} \tag{7}$$

where:

$A = \sigma_0 + c/\tan\varphi$;

σ_0 is the maximum normal stress corresponding to the pre-compacting load;

τ_0 is the shear stress corresponding to the maximum normal stress

CONCLUSIONS

After analysing the influence of the moisture content on coefficient of sliding friction, the results showed that when the density of the rubbed maize straw was 77.8 to 384 kg/m^3 and the moisture content of the material was in the range of 15.76% to 52.87%, as the moisture content increased, the coefficient of sliding friction increased gradually. Through the analysis of MATLAB, the relation between the moisture content of the material and the friction coefficient was obtained. The fitting coefficient of determination was greater than 0.97.

After analysing the influence of the density on friction coefficient, the results showed that when the moisture content of the material was 15.76% to 52.87%, the density of the material was in the range of 77.8 to 384 kg/m^3, as the density increased, the coefficient of sliding friction increased gradually. Through the analysis of MATLAB, the relation between the moisture content of the material and the friction coefficient was obtained. The fitting coefficient of determination was greater than 0.97.

After analysing the influence of the moisture content of rubbed maize straw on angle of repose, the results showed that as the moisture content increased, the angle of repose increased.

After analysing the influence of the moisture content on internal friction coefficient, cohesion and flow function value, the results showed that with the increase of moisture content, the internal friction coefficient increased, the cohesion fluctuated and the flow function value increased too.

After analysing the influence of the moisture content of rubbed maize straw on the compression coefficient, the result showed that with the increase of the moisture content, the bulk density increased due to the decrease of materials gap and the compression coefficient, resulting in smaller compressibility. The equation of pressure and density, is suitable for the analysis of compression character of rubbed maize straw.

ACKNOWLEDGEMENT

The research was supported by the Inner Mongolia Natural Science Foundation (No. 2020BS05022) and the High-level Talent Introduction Fund Project of Inner Mongolia Agricultural University (205-206050).

REFERENCES

[1] Canjun Huang, (2013), *Study on continuous explosion mechanism and technology of discarded biomass spiral booster (废弃生物质螺旋增压式连续闪爆过程机理及技术研究),* PhD Thesis, South China University of Technology, Guangzhou/China;

[2] Chevanan, N., Womac, A.R., Bitra, V.S.R., Yoder, D.C., Sokhansanj, S., (2009), Flowability parameters for chopped switchgrass, wheat straw and corn stover, *Powder Technology*, Vol.193, no.1, ISSN 00325910, pp.79-86, Elsevier, Lausanne/Switzerland;

[3] Cailong Ma, (2018), *Improved Design of 9RS-2 Straw Kneading Machine (9RS-2 型秸秆揉丝机的改进设计)*, MSc Thesis, Gansu Agricultural University, Lanzhou/China;

[4] Enchen Jiang, Leiming Xiong, Mingfeng Wang, Xulin Su, Xinhui Guo, Chuang Zhao, (2014), Development of biomass pyrolysis volatiles fractional condenser, *Journal of Northeast Agricultural University*, Vol.45, no.5, ISSN 10059369, pp.110-115, Heilongjiang/China;

[5] Haitao Chen, Ying Zhang, Zhenhua Huang, Xin Fang, Lixia LI, (2013), Effect of different moisture contents on flowability parameters of chopped rice straw (含水率对水稻秸秆流动力学特性的影响), *Journal of Northeast Agricultural University,* Vol.44, no.11, ISSN 10059369, pp.90-94, Heilongjiang/China;

[6] Joseph, S.t., (2008), Friction coefficients of chopped forages, *American Society of Agricultural and Biological Engineer*, Vol.26, no.9, pp.1-2, ASABE/U.S.A.;

[7] Kakitis, A., Nulle. I., (2005), Friction of chopped straw, *AGRIS*, Vol.113, no.16, pp.98-107, AGRIS/U.S.A.;

[8] Lingxin Geng, Lijuan Zhang, Qingxiang Shi, Chang'an Ni, Feng Jing, (2011), Parameters optimization of long-straws vertical cutting table based on double helix mechanism, *Transactions of the Chinese Society for Agricultural Machinery*, Vol.42, no.s1, ISSN 10001298, pp.10-13, Beijing/China;

[9] Lin Li, Mingshao Yang, Chuanguang Wang, Weifeng Liu, Qiurong Zhao, (1997), The manufacture & testing of 9R-40 rubber (9R-40 型揉碎机的研制与试验)*, Journal of Inner Mongolia Institute of Agriculture & Animal Husbandry*, Vol.18, no.3, ISSN 10093575, pp.69-74, Inner Mongolia /China;

[10] Larsson, S.H., (2010), Kinematic wall friction properties of reed canary grass powder at high and low normal stresses, *Powder Technology*, Vol.198, no.1, ISSN 00325910, pp.108-113, Elsevier, Lausanne/Switzerland;

[11] Phani, A., Lope, T., Greg, S., (2010), Physical and Frictional properties of non-treated and steam exploded barley, canola, oat and wheat straw grinds, *Powder Technology*, Vol.201, no.3, ISSN 00325910, pp.230-241, Elsevier, Lausanne/Switzerland;

[12] Ran Li, Wei Long, (2014), Fuel delivery system layout design of grey straw biomass power plant (灰色秸秆生物质电厂燃料输送系统布置设计), *Jilin Electric Power*, Vol.42, no.3, ISSN 10095306, pp.55-56, Jilin/China;

[13] Shinners, K.J., Koegel, R.G., Lehman, L.L., (1991), Friction coefficient of alfalfa, *Transactions of the ASABE*, Vol.34, no.1, pp.33-37, ASABE/U.S.A.;

[14] Shuangxia Zhang, Qiang Xu, (2016), Study of 9ZS－4 forage grass crushing machine and its design (9ZS-4 饲草揉碎机的研究设计), *Machine Building & Automation*, Vol.45, no.5, ISSN 16715276, pp.147-149, Nanjing/China;

[15] Tianshu Chu, Zengling Yang, Lujia Han, (2016), Analysis on satisfied degree and advantage degree of agricultural crop straw feed utilization in China, *Transactions of the Chinese Society of Agricultural Engineering,* Vol.32, no.22, pp.1-9, Beijing/China;

[16] Wulantuya, Chunguang Wang, Shaohua Qi, Jianguo Yan, Jinlian Wang, (2015), Test and analysis of performance of screw conveyor for rubbing and breaking corn straw, *Transactions of the Chinese Society of Agricultural Engineering*, Vol.31, no.21, ISSN 10026819, pp.51-59, Beijing/China;

[17] Wulantuya, Chunguang Wang, Shaohua Qi, Xiaorong Wang, Haichao Wang, Jinlian Wang, (2016), Theoretical model analysis and test of screw conveyor for rubbing and breaking corn straw, *Transactions of the Chinese Society of Agricultural Engineering*, Vol.32, no.22, ISSN 10026819, pp.18-26, Beijing/China;

[18] Wulantuya, Hongbo Wang, Chunguang Wang, Qinglin, (2020), Theoretical analysis and experimental study on the process of conveying agricultural fibre materials by screw conveyors, *Engenharia Agrícola*, vol.40, no.5, pp.589-594, ISSN 18094430, Jaboticabal/Brazil;

[19] Xin Fang, Haitao Chen, Zhenhua Huang, Lixia Li, (2012), Sliding friction characteristic of different moisture content of soybean stalk with different materials (不同含水率大豆秸秆与不同材料间滑动摩擦特性的研究), *Soybean Science*, Vol.31, no.5, ISSN 10009841, pp.838-841, Beijing/China;

[20] Yishui Tian, Zonglu Yao, Shuangping Ouyang, Lixin Zhao, Haibo Meng, Shulin Hou, (2011), Physical and chemical characterization of biomass crushed straw (切碎农作物秸秆理化特性试验), *Transactions of the Chinese Society for Agricultural Machinery*, Vol.42, no.9, ISSN 1000-1298, pp.124-128,145, Beijing/China;

[21] Yuming Guo, Hongmei Yuan, Decong Zheng, (2005). A review on application and development of agricultural material mechanics (农业工程科技创新与建设现代农业—2005 年中国农业工程学会学术年会论文集第一分册), *Proceedings of the annual conference of Chinese society of agricultural engineering*, pp.426-461, Guangzhou/China;

[22] Zonglu Yao, Shuangping Ouyang, Haibo Meng, Lixin Zhao, Yishui Tian, (2012), Flow characterization of biomass particle straw (颗粒状秸秆物料流动特性试验), *Transactions of the Chinese Society for Agricultural Machinery*, Vol.43, no.7, ISSN 10001298, pp.112-116, Beijing/China.