

Article

Investigation of Steel Roller–Material Interaction Based on Frictional Properties of Round Bales

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Abstract

In order to provide a theoretical basis for the monitoring and control of the formation process of round bales, the friction test platform for the rolling formation of round bales was built to study the interaction between steel roll and material in the forming process. The results showed that the torque value of the steel roller at the lowest position (No. 2 steel roll) in the bale chamber was closely related to the forming process of the round bale. According to the change of the torque value, the forming process can be divided into an initial stage, straw core formation stage, compression stage and bale-forming stage. The change of torque value can be used for monitoring the forming process of round bales. During the forming process, materials were subject to sliding friction and rolling friction. From the initial stage to the forming stage, the friction of materials gradually changed from sliding friction to rolling friction, and the surface contacted between the material and the steel roll gradually changed to line contact. The interaction model of steel roll and material was established and verified; the model showed that the maximum error between the theoretical value and the experimental value of the forming density is 13.24% and the minimum error is 0.75%. The forming density of round bales was positively correlated with the mass of material fed per second and negatively correlated with the volume of the bale-forming chamber. The forming density of round bales can be expressed by the tangential force per unit length of No. 2 steel roll under the condition that the moisture content of material, the mass of material fed per second and the volume of the baling chamber were fixed. The model provides a theoretical basis for monitoring and controlling the forming process of round bales.

Keywords: round bale; forming process; steel roll; interaction; friction



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1. Introduction

China has rich grassland and straw resources; making the best of these resources will contribute to the rapid development of animal husbandry [1,2]. The round baler can be used to harvest and bundle the grazing and crop straw timely. The round baler has achieved relatively rapid development owing to the produced round bales of convenient transportation [3,4]. Whether hay harvesting or silage harvesting, appropriate silage density can save harvesting costs [5]; as for silage harvesting, higher bale density can lower the porosity and improve the silage quality [6–9]. Therefore, the forming density decides round bales' quality directly. Moreover, the round bale's density and the motion state of the round

grass bundle inside the baling chamber are closely related. Through the monitoring of the materials enacting the rolling formation process, it is possible to carry out the monitoring and prediction of forming density to then improve the round bales quality.

Because the bale chamber of a round baler is an approximately enclosed space, the real-time monitoring of material motion during the roll-compression bale-forming process remains considerably limited [10–12]. The monitoring of materials in action is generally carried out by making holes on the side wall inside the baling chamber, which is unable to realize the corresponding quantitative expression of the material movement status and bale density [13–15]. The monitoring of the forming density of round grass bales is mostly carried out after the round grass bales are formed. For instance, a force sensor is installed at the contact area between the front and rear compartments of the baling chamber to determine whether the compartment is full—when the material lift the rear compartments after material compartments is filled—making the change of sensor values a determiner of whether the compartment is full; the relative distance between the front and rear compartments can also be converted into the motion of the mechanism through the linkage mechanism, and the forming status of the grass bales in the compartment can be roughly judged by the changes in the position of the mechanism's motion; it can be seen as full when the pressure of the round grass bundle inside the baling chamber acting on the rear compartment reach the set pressure values of the hydraulic cylinder [16–21]. Shang et al. used sensor signals related to tailgate clearance, tailgate position, and full-chamber indication to identify the operating state of the baler and subsequently trigger the net-wrapping and bale-counting processes [22]; Maguire et al. found that the weight of a single square bale can be determined by the peak force of the tension sensor set at the end of the chute [23]; Zawada et al. installed force, displacement, and rotational-speed sensors on a fixed-chamber baler-wrapper to monitor bale compaction, bale diameter, bale mass, and machine overload conditions [24]. Wild et al. determined the static weight of round bales using a weighing system equipped with load cells and strain gauges [25]. In parallel, a variety of techniques have been explored for assessing final bale density, including radar, ultrasonic sensors, microwave technology, near-infrared spectroscopy, gamma-ray, X-ray, and penetrometer-based approaches [14,16,26]. The above studies were conducted only after the completion of the operation; that is, after the material forms a fixed shape, the density of the final formed bale can be measured by sensor technology. There is no quantitative description of whether the material reaches the preset density, and sometimes it needs to be observed manually, which seriously affects the operation efficiency and molding quality. For round bales, the forming process is dynamic and difficult to observe, so there is a lack of methods or theories to monitor the material state during the forming process, which leads to the inability to predict or control the material forming state.

With the development of intelligent sensing technologies for agricultural machinery, considerable progress has been made in the measurement of round-bale density. Yin et al. developed a round-bale weighing system based on the contact pressure on an inclined surface, the platform attitude angle, and the hydraulic cylinder pressure [11]. Wang et al. analyzed the forces acting on the steel rollers and the round bale during the roll-compression process and established a bale-density prediction model based on the radial reaction force of the steel rollers [12]. These studies indirectly estimated bale density using load information obtained from key components of the round baler. Yang et al. investigated the dynamic bale-forming process of a belt-type round baler using a coupled discrete element-multi-body dynamics method, revealing the multiphysics coupling among rigid components, flexible belts, and particulate materials and providing a new modeling approach for understanding complex bale-forming mechanisms [27]. From

a tribological perspective, the steel rollers not only exert normal compressive forces on the material but also transmit tangential driving forces through interfacial friction, thereby enabling the material to continuously tumble, roll, and compact within the bale chamber. Through worm-gear transmission experiments, Bukvić et al. demonstrated that changes in interfacial friction conditions are simultaneously reflected in operating parameters such as mechanical efficiency, vibration, and energy loss, indicating a close relationship between frictional responses and the operating state of mechanical systems [28].

Based on the above studies, existing methods can estimate bale mass or density indirectly using measurements obtained from auxiliary components. However, the evolution of the tangential frictional interaction between the steel roller and the material during the roll-compression bale-forming process, as well as the relationships between tangential force, the round-bale formation state, and bale density, have not yet been systematically investigated. Therefore, this study focused on a steel roller-type round baler and established a friction-force test platform for the round bale roll-compression process. The torque variation of the roller located at the lowest position in the bale chamber was measured during bale formation, and the relationship between roller torque and the different bale-forming stages was analyzed. In combination with the variation in friction acting on the material, the evolution of the steel roller-material interaction throughout the roll-compression bale-forming process was investigated. On this basis, the tangential force per unit length of the lowest-positioned roller was obtained from the roller torque-balance relationship. A steel roller-material interaction model was then established and validated using the experimental data to identify and predict the round bale formation state, thereby providing a theoretical basis for the prediction and regulation of the round bale roll-compression process.

2. Analysis of Interaction Between Steel Roll and Material

2.1. Analysis of the Material Rolling Process

During the rolling and forming process of the steel roller round baler, the material is mainly subjected to frictional force F along the tangential direction of the steel roller and the extrusion force N pointing to the axis of the round bale. Among them, the friction force makes the material enter the baling chamber from the feeding inlet and rotate, and the squeezing force compresses the rotated material, thus forming the final round bale. However, at the initial moment when the material enters the baling chamber, as shown in Figure 1a, the material at this time is not fully formed and is mainly loose, so the material at this stage is mainly affected by friction. The squeezing effect is not obvious; As the material gradually fills the baling chamber, as shown in Figure 1b, the material begins to be subject to the squeezing force, eventually forming a round bale.

It can be seen that the friction force of the material plays a major role in the material rolling formation. At the same time, the friction of materials is closely related to the quality of materials in the baling room. Therefore, the interaction relationship between the steel roller and the material friction vice is studied, and the state of the material in the rolling process is reflected through the change of the friction force of the material during the rolling process.

2.2. Analysis of Contact Interaction Between Steel Roll and Material

The friction is related to the material and positive pressure of the friction pair, the friction pair of the round bale is steel roller and material, the positive pressure is related to

the quality of the round bale, and the quality of the round bale is related to the bale density and the volume of the baling chamber. Therefore, the friction force on the material is

$$F = f(h, \rho, S) \quad (1)$$

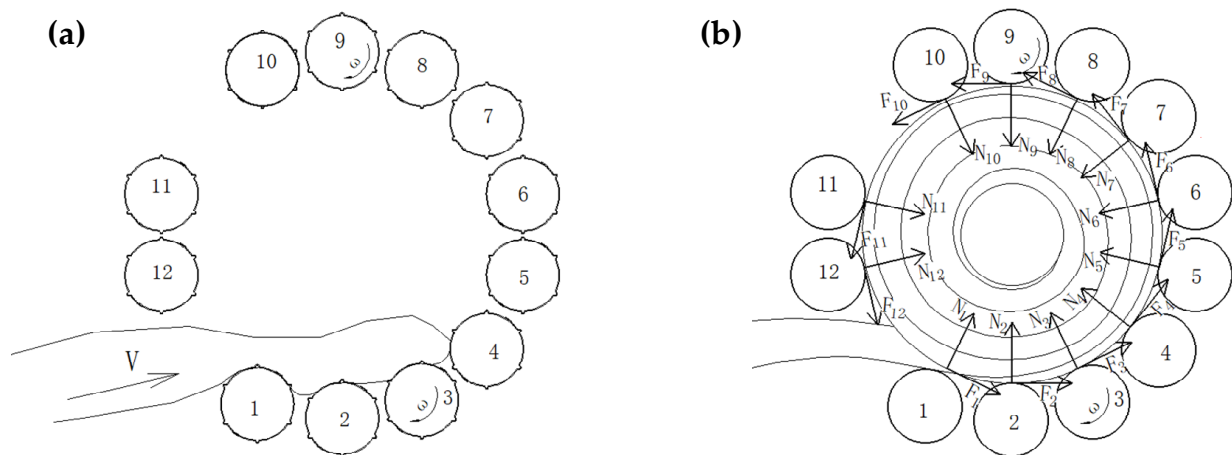


Figure 1. Force analysis of bales in rotary compression. (a) Initial material; (b) The material is fully packed in the baling chamber.

Here, h is a comprehensive coefficient that integrates the friction properties of the steel roll–material pair and the compaction characteristics of straw. In the subsequent quantitative modeling, the physical effect of h will be further decomposed and quantified into experimentally fitted parameters combined with the material feeding rate so as to establish a calculable quantitative relationship between measured friction force and bale density. ρ is the maximum final density of round bales. S is the volume of the baling chamber.

It can be seen that in order to realize the monitoring of the density of the round bale rolling formation process, it is necessary to measure the friction force of the materials in the rolling formation process, the coefficient related to the friction pair material and the volume of the baling chamber.

In order to analyze the friction force of materials, the steel rolls in the baling chamber are numbered counterclockwise in sequence (Figure 1). According to the structure of the baling chamber, the No. 2 steel roller is located at the lowest position in the baling chamber. Therefore, during the rolling formation process, the No. 2 steel roller always makes contact with the material; that is, the change of friction between the No. 2 steel roller and the material can reflect the rolling formation process of the material.

To simplify the analysis, it is assumed that the materials in the bundling chamber are evenly distributed along the axial direction of the steel roller; that is, the materials are in uniform contact with the surface of the steel roller. At the same time, the frictional force F'_2 per unit length experienced by the second steel roller and the frictional force F_2 per unit length experienced by the material at the position of the second steel roller are mutual forces, with the direction along the tangent line of the steel roller and parallel to the side wall of the baling chamber, as shown in Figure 2.

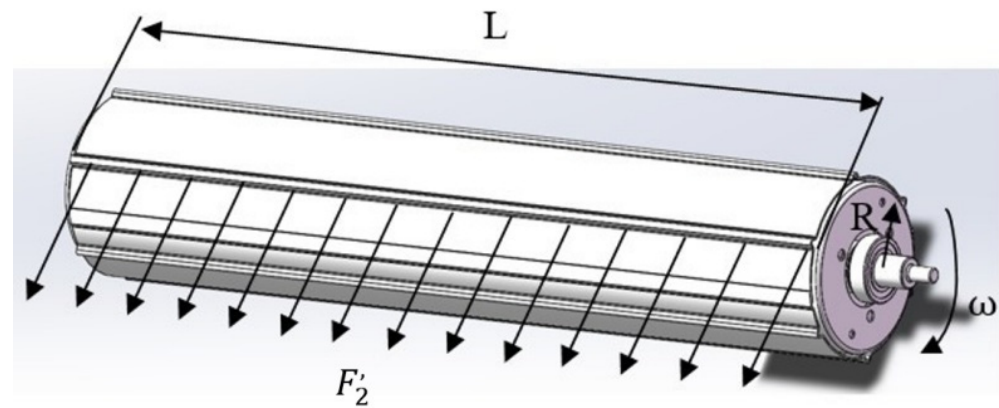


Figure 2. Schematic diagram of friction force on No. 2 steel roll.

It needs to be clarified that this is an idealized simplification. In practical operation, asymmetric feeding, uneven material accumulation and manufacturing tolerances will break axial uniformity and produce non-uniform contact pressure along the roller. This assumption facilitates the establishment of an analytical model and helps reveal the fundamental material–roller interaction mechanism under relatively steady working conditions matching the experimental setup. Nevertheless, obvious prediction deviations may emerge under eccentric feeding, heavy loads and long-term asymmetric wear, where axial non-uniformity cannot be neglected. In addition, the model adopts constant contact conditions, including fixed contact geometry and invariant contact stiffness. In real engineering scenarios, contact range and contact pressure evolve dynamically owing to load fluctuations, variations in material compaction and structural elastic deformation. Therefore, the proposed model is more applicable to stable operating conditions.

At this time, the torque generated by the material of the No. 2 steel roller is determined by the following Formula (2):

$$M_2 = F'_2 LR \quad (2)$$

M_2 is the torque applied by the material to the No. 2 steel roller during the rolling formation process, N·m.

F'_2 is the friction force of the material on the No. 2 steel roller during the rolling formation process, N.

L is the contact width between steel roll and grass material, $L = 0.7$ m.

R is the radius of steel roller, $R = 0.075$ m.

When the round baler is in operation, the torque of the No. 2 steel roller is shown in the following Formula (3):

$$M = M_2 + M'_2 \quad (3)$$

M is the torque of the No. 2 steel roll during the rolling formation process, N·m.

M'_2 is the torque of the No. 2 steel roll when it is idling (not in contact with material) N·m.

M and M'_2 can be measured by the torque sensor set on the shaft of No. 2 steel roll. Therefore, through Formulas (2) and (3), the friction force F'_2 per unit length of the No. 2 steel roller caused by the material during the round bale forming process can be calculated as shown in Formula (4):

$$F'_2 = F_2 = \frac{M_2}{LR} = \frac{M - M'_2}{LR} \quad (4)$$

The friction force per unit length generated by the material on the No. 2 steel roll is a function of h , ρ and S . In order to monitor the rolling formation process and predict the

forming density of round bales, it is necessary to measure the torque of the No. 2 steel roller and the parameter h related to the friction pair material.

3. Materials and Methods

3.1. Design and Construction of Friction Test Platform

In order to measure the torque of the No. 2 steel roller, the friction test device of the No. 2 steel roller was designed. As shown in Figure 3, it includes the diaphragm coupling, No. 1 steel roll power output shaft, No. 2 steel roll power input shaft, torque sensor II (JN-DN type, 0–50 N·m; Bengbu Sensor System Engineering Co., Ltd., Bengbu, China), sprocket II, sprocket I and support frame, etc.

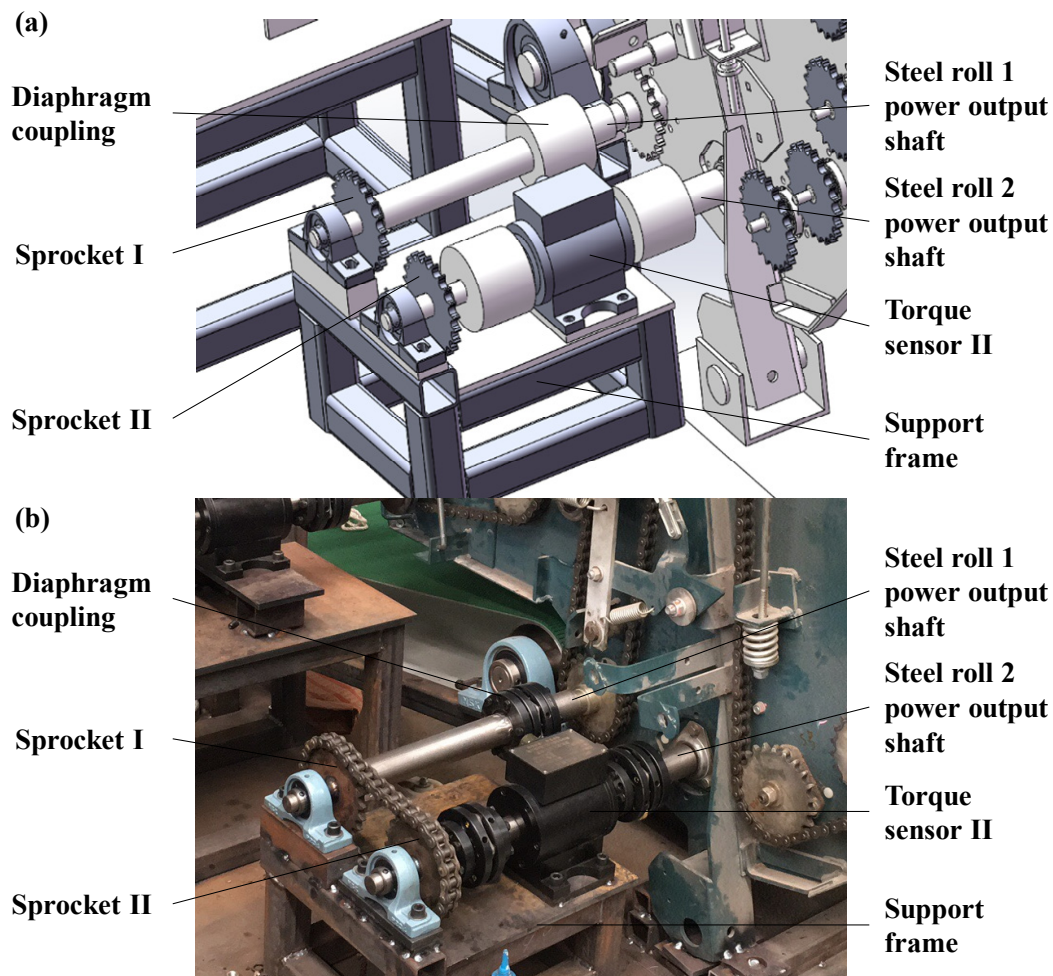


Figure 3. Friction testing device for steel roller No. 2. (a) schematic diagram; (b) photograph of the physical device.

At the same time, the torque value at the power input shaft of the baling chamber can also reflect the overall stress of the materials in the baling chamber during the rolling process, so it is also necessary to measure the torque change at the power input shaft of the baling chamber.

To sum up, in order to realize the monitoring of the material movement state and the prediction of the round bale density in the forming process, the round bale material state monitoring platform (Figure 4) was designed to study the forming state of the material and the round bale forming density in the round bale rolling formation process.

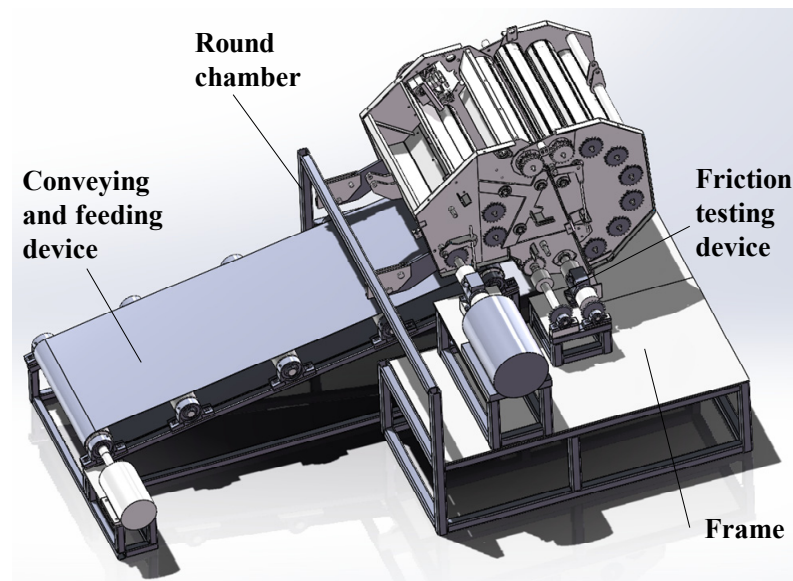


Figure 4. Material status monitoring platform for round bales.

The round bale material condition monitoring platform mainly includes a conveying and feeding device, baling chamber, frame and friction testing device. During the test, the materials are sent into the baling chamber by the conveying and feeding device, and the materials are rolled and formed in the baling chamber. The friction test device and the baling chamber are fixed on the frame.

The baling chamber test system assembly designed based on the above scheme is shown in Figure 5. During the test, the motor III connected with the No. 1 steel roller provides power for the baling chamber and the test device. The motor III drives the steel rollers in the baling chamber to rotate through the diaphragm coupling and the dynamic torque sensor I (JN-DN type, 0~200 N·m, Bengbu Sensor System Engineering Co., Ltd., Bengbu, China) and measures the sum of the torque of all steel rollers in the baling chamber through the dynamic torque sensor I. Under the action of motor III, the No. 1 steel roller rotates. Because the No. 1 steel roller is connected to the corresponding sprocket by a spline shaft, the power output shaft of the No. 1 steel roller is made in the form of a spline sleeve and matched with the No. 1 steel roller so as to transmit the power from the sprocket I to the sprocket II through the chain. At the same time, the torque sensor II is set between the sprocket II and the No. 2 steel roller power input shaft so as to detect the change in the torque value of the No. 2 steel roller.

3.2. Test Materials

Bare oats planted in the Chabei Administrative Area, Zhangbei County, Zhangjiakou City, Hebei Province (41°28' N, 115°0' E, 1370 m above sea level) were used as the test materials.

Since the moisture content of materials is one of the important factors [29,30] that directly affect the friction characteristics of materials, it is of great significance to study the tribological behavior of materials with different water content in the rolling process. Therefore, the single-factor method was adopted for the test with the moisture content of the material as the factor. According to the sensory determination method, the mowed and harvested naked oats were dried in the field under natural conditions. When their moisture content decreased to about 70%, 40% and 10%, respectively, they were collected and transported back to the laboratory for bench testing, a comprehensive preliminary investigation and literature research on the operating parameters of the circular baler on

the market [30]. The material feeding speed V_1 during the design test was 2.3 m/s. The linear speed of the steel roll V_2 was 1.7 m/s.



Figure 5. Bale chamber test system assembly.

Before the test, the dynamic torque tester and frequency converter shall be zeroed in sequence. At the beginning of the test, first turn on the motor of the round baler and the conveyor, and keep the round baler and conveyor idling for 20 s to eliminate the influence of the starting torque of the device. After the torque value is stable, record the idling torque of the baler—consistent idle torque values were maintained across all tests to guarantee reliable torque acquisition—and then evenly place the naked oats on the conveyor belt so that the naked oats can be fed into the baling room at a uniform speed under the action of the conveyor.

During the test, the test system starts to work, and the sensor collects the output torque of the motor of the round hay bale device and the torque value at the No. 2 steel roller and records them in the computer using the dynamic torque tester and the upper computer software. After the bare oats are filled into the baling chamber, the formed round bales will lift the bin door of the baling chamber and open it at a certain angle. The bin door will drive the linkage mechanism to observe whether the baling process is completed through the marks on the linkage mechanism. If the marking position is reached, the conveyor will stop feeding, and then the test will stop after the forming device test system continues to run for about 5 s. The round bales are bundled and unloaded in the baling chamber. Weigh and record round bales on a platform scale (Yingheng YHC-LA8, 0~150 kg; Dongyang Yingheng Intelligent Equipment Co., Ltd., Dongyang, China). One rolling formation process has been completed. During the test, the measurement interval of the dynamic torsion tester is 0.1 s. At the same time, the GoPro motion camera is installed at the top of the feeding inlet of the baling chamber, which is used to take pictures of the movement of materials in the baling chamber during the test.

To provide a systematic description of the measuring equipment, experimental conditions, and testing procedures, the main instruments and their models, measuring ranges, and accuracies, as well as the test material, moisture content conditions, and experimental procedures, are summarized in Table 1.

Table 1. Summary of measuring equipment, experimental conditions and testing regimes.

Category	Item	Details
Measuring equipment	Torque sensor I	Model: JN-DN; Measuring range: 0~200 N·m; Accuracy: $\pm 0.5\%$ FS;
	Torque sensor II	Model: JN-DN; Measuring range: 0~50 N·m; Accuracy: $\pm 0.5\%$ FS;
	Platform scale	Model: Yingheng YHC-LA8; Range: 0–150 kg;
	Drying oven	Model: TY101-0A; Function: Determine material moisture content via oven-drying method
Experimental conditions	Test material	Naked oat
	Material moisture contents	74.30%, 63.40%, 47.70%, 14.80%
	Material feeding speed	2.3 m/s
	Steel roller line speed	1.7 m/s
	Steel roller size	Radius: 0.075 m; contact width between steel roller and grass material, L = 0.7 m
	Operation mode	Continuous feeding and rolling formation
	Pretreatment	Raw material uniformly prepared to target moisture in advance
Testing regimes	Pre-test operation	Each group runs idle for 20 s to record baseline idle torque
	Data acquisition	Real-time torque data recorded during baling; Baling density measured after forming; Moisture tested by sampling

4. Result and Analysis

4.1. Analysis of Rolling Formation Process

According to the characteristics of different motion states of the material rolling formation process, the material rolling formation process is divided into four stages, as shown in Figure 6. At the initial stage, as shown in Figure 6a, the materials are fed into the baling chamber under the action of the materials moving along the direction of steel roll 1, steel roll 2 and steel roll 3 under the action of the steel roll, and they gradually accumulate. With the increasing number of feeding materials, the materials enter the baling chamber together with the subsequently fed materials for crimping. At the stage of straw core formation, as the material fed into the baling chamber is continuously thrown back under the action of friction, and then again as the newly fed material is fed into the baling chamber, so repeatedly, the loose straw core is gradually formed. As shown in Figure 6b, the straw core and the subsequently fed material roll intermittently under the action of friction. In the compression stage, as shown in Figure 6c, the straw core formed in the previous stage will continue to be rolled together with the material fed subsequently; on the whole, it can realize continuous rolling and gradually form a relatively dense bale, showing the initial shape of round bale. In the bale forming stage, as shown in Figure 6d, the round bale shape gradually forms and is compacted with the subsequent feeding of materials, and finally fills the entire baling chamber.

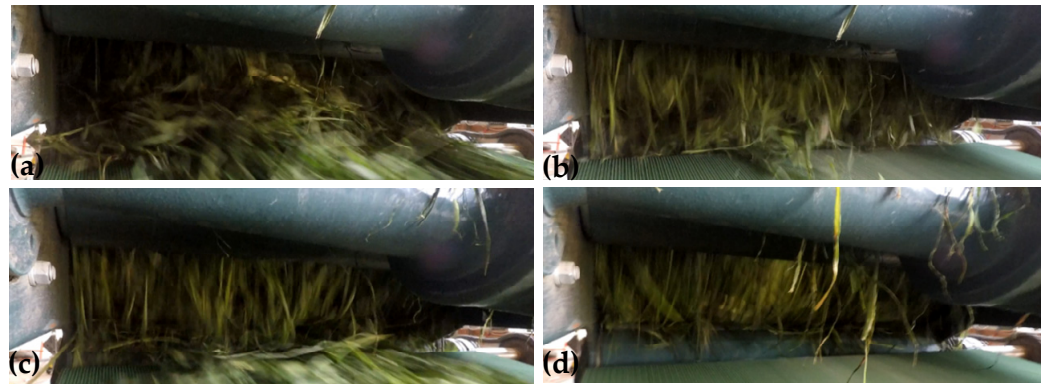


Figure 6. Forming process of naked oats. (a) Initial stage; (b) Grass core formation stage; (c) Compression stage; (d) The bale-forming stage.

According to the change of torque values in the rolling formation process and the characteristics of material movement in the captured image, the change of torque values in the rolling formation process of naked oats is divided into the initial stage, the core-forming stage, the compression stage and the bale-forming stage. Take the roll forming process of naked oats with a moisture content of 14.8% as an example, as shown in Figure 7. Since the idle torque of the device is measured during the test and the influence of the starting torque is excluded, the time 20~30 s before the test is not included in the roll forming process. At the initial stage, the material is fed into the baling chamber under the action of the conveying device and gradually contacts with the steel roller to generate friction. During this process, the motor output torque (M') and M are slowly increasing with the feeding of the material. At the stage of straw core formation, with the increase of feed materials, the friction force on the steel roll increases; M' and M both start to rise, but the fluctuation is small and the increase is gentle. In the compression stage, with the continuous increase of feeding materials, M' and M rapidly increases, but the torque value fluctuates greatly, which is due to straw core formed in this stage and the subsequent feeding materials being in a continuous rolling state in the baling chamber, and the materials are compressed by the steel roller. Finally, in the forming stage, as the material gradually fills the baling chamber, M' and M reach their peak values and decrease slightly. After the torque reaches the peak value, the material stops feeding, while the forming device test system continues to operate. Under the friction of the steel roller in the baling chamber, a part of the material falls from the baling chamber, causing the quality of round bales to decline, which makes the torque value slightly decrease after reaching the peak value.

Thus, in the initial stage, the materials are mainly subject to sliding friction in the baling chamber; the material starts to roll intermittently until, in the forming stage, the material rolls continuously. It can be seen from this that from the formation stage of the straw core to the forming stage, there is rolling friction between the material and the steel roll, specifically the rolling with sliding—that is, the tangential velocity on the contact surface of the round bale and the steel roll is not equal, and the rolling is accompanied by sliding [31,32]. At the same time, from the initial stage to the forming stage of the material, the shape of the bale gradually changes from the irregular and loose stacking state to the regular round bale shape—that is, during the rolling formation process, the contact between the material and the steel roller gradually changes from the surface contact to the line contact.

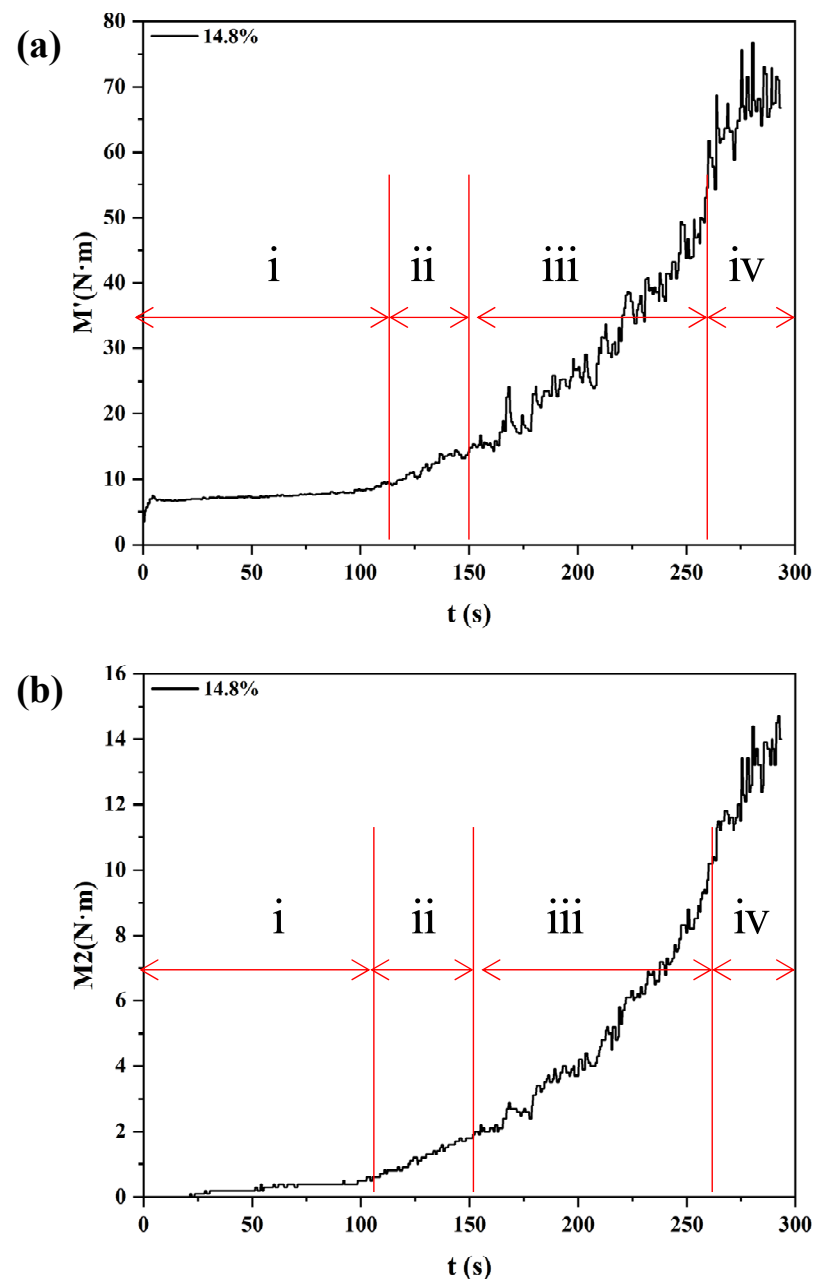


Figure 7. Variation curve of torque with time during rolling process of naked oat with moisture content of 14.8% (a) Motor output torque (b) Motor output torque No. 2 steel roller torque. (a) i. Initial stage ii. Grass core formation stage iii. Compression stage iv. Bale-forming stage.

The transition of friction behavior throughout the four forming stages dominates the variation of measured torque. In the initial stage, loose materials merely form sporadic contact with steel rollers, and sliding friction prevails. Only a small proportion of friction force contributes to material transport, leading to slow and mild torque growth. During the straw core formation stage, continuous feeding creates a rotating loose core. Mixed rolling–sliding contact occurs between materials and rollers. Inter-fiber interlocking gradually develops, which steadily increases interfacial friction and brings gentle torque rising with low fluctuation. In the compression stage, the straw core continuously accumulates thickness. Contact area and compaction degree increase sharply. Intense rolling–sliding friction between the bale core and steel rollers generates rapidly rising torque; the periodic rearrangement of internal materials causes obvious torque fluctuation. In the final bale forming stage, the bale shape is basically stabilized. The contact state gradually transfers

toward line contact. When the bale fills the baling chamber, material overflow leads to slight torque decline after reaching the peak.

At the same time, it can be seen from Figure 7 that the torque fluctuation of the No. 2 steel roller is relatively small compared with the output torque of the motor during the coiling process. This is because the No. 2 steel roller always contacts the material during the coiling process, while the steel rollers at other positions in the baling chamber gradually contact with the material in the subsequent time. At the same time, with the increase of the material in the baling chamber, the bale rolls continuously in the baling chamber, causing the fluctuation of M' . Therefore, the analysis of the torque value of the No. 2 steel roll can more accurately reflect the movement and change of the material.

To sum up, in the process of material rolling and forming, the torque value of the No. 2 steel roller continuously changes with time because the material in the baling chamber increases with time; therefore, this further verifies that the torque value of the No. 2 steel roller can reflect the movement state of the material in the baling chamber during the rolling and forming process—that is, the change of the torque value of No. 2 steel roller can be used to monitor the movement of the material in the baling chamber. The unmeasurable material movement state of the round bale crimping process is converted into the quantifiable torque value of the No. 2 steel roller, which provides a method for realizing the monitoring of the round bale crimping process.

4.2. Analysis of Theoretical Model of Forming Density

From the above analysis, it can be seen that the change of torque value of the No. 2 steel roll fully reveals the rolling process of materials. In order to further reveal the relationship between the rolling density of round bales and the torque of the No. 2 steel roll, the variation of tangential force per unit length of No. 2 steel roll with time was studied. By measuring the idle torque of the rolling formation device test bench during the test, the measured idle torque value of the forming device is $M_3 = 6.8 \text{ N}\cdot\text{m}$. The idling torque value of the No. 2 steel roll is $M_2 = 0.2 \text{ N}\cdot\text{m}$. According to Formula (4), the tangential force per unit length of the material in the rolling formation process (F_2), the curve of F_2 and the time t in the rolling formation process were calculated, which is shown in Figure 8.

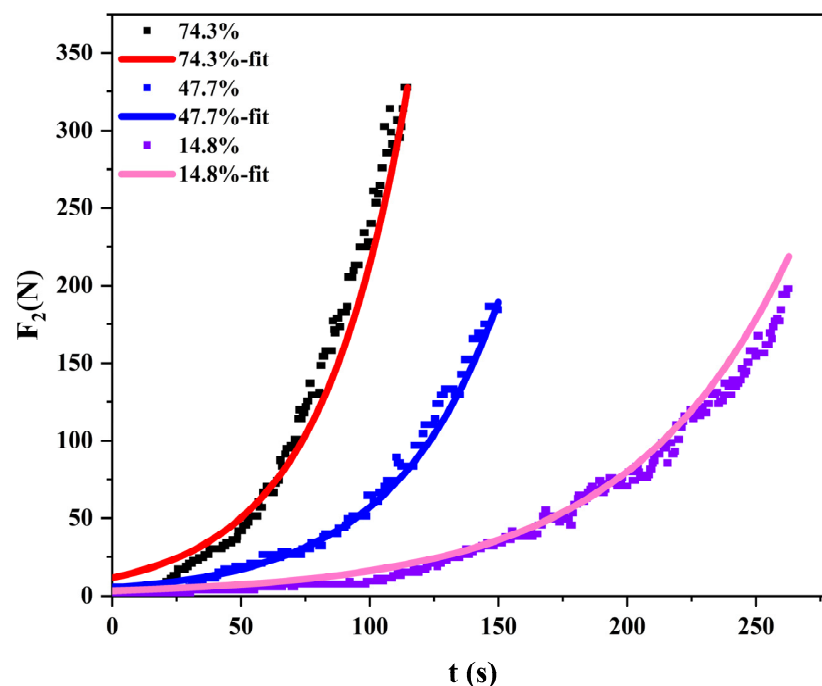


Figure 8. The law of F_2 changing with t in the rolling process.

Through analysis, the tangential force per unit length of No. 2 steel roll increases exponentially with the time of rolling during the rolling process of naked oats. According to the relationship of mutual forces, the tangential force per unit length of material increases exponentially with time t . The fitting equation is shown in Equation (5):

$$F_2 = Ee^{kt} \quad (5)$$

t (unit: s) is the rolling formation process time;

E and k are equation fitting coefficients.

The exponential rising trend of F_2 can be explained by the physical evolution during material rolling compaction. With the increase of rolling time, continuous compaction enlarges the effective contact area between the naked oats and steel roller and strengthens interlocking friction among plant fibers. The increment of friction resistance is positively related to the instantaneous resistance, which leads to an exponential evolutionary characteristic. Therefore, $F_2 = Ee^{kt}$ is a semi-empirical equation, which is identified from experimental data and supported by the compaction and friction evolution mechanism. This correlation applies within the test conditions adopted in this work.

Raw torque data were acquired continuously by the proprietary supporting software provided by the sensor manufacturer. Curve fitting and coefficient identification for the F_2 - t exponential model and forming density model were implemented in MATLAB R2024b (MathWorks, Natick, MA, USA). The built-in Curve Fitting Toolbox was utilized for analysis, and the software was used under an academic license.

The fitting coefficient of the curve equation of the change of materials F_2 with different water content with time t in the rolling process is shown in Table 2.

Table 2. Table of fitting coefficients of F_2 - t equation in rolling process with different moisture content.

Moisture Content (%)	E (N)	k (s ⁻¹)	R ²
74.30	11.767	0.029	0.98
47.70	5.181	0.024	0.98
14.80	3.267	0.016	0.99

Note to the table: the water content is the actual water content of the test. Samples were taken during the test and tested after the test. The design water content is 70%, 40% and 10%, respectively (all are moisture content on wet basis).

At the same time, there is the following relationship between the time consumption of the rolling formation process:

$$t = \frac{m_1}{m_0} \quad (6)$$

m_1 is the final mass of round bale, kg;

$m_1 = \rho S$, $S = 0.1979 \text{ m}^3$;

m_0 is the quality of material fed per second, kg;

Combine Formulas (5) and (6), then

$$F_2 = Ee^{k\frac{m_1}{m_0}} = Ee^{k\frac{\rho S}{m_0}} \quad (7)$$

The theoretical model of forming density is as follows:

$$\rho = \frac{m_0}{kS} \ln \frac{F_2}{E} \quad (8)$$

According to the test, the final tangential force per unit length of No. 2 steel roll is F_2 and the maximum value is $F_{2\max}$. In order to further verify the proposed theoretical model

of molding density, baling validation tests were carried out under four discrete moisture levels: 74.30%, 63.40%, 47.70% and 14.80%.

Restricted by experimental conditions, it is difficult to perform repeated parallel tests under identical moisture content. Raw materials were prepared uniformly in advance. During the waiting period between trials, spare materials exposed to ambient surroundings continuously lose moisture, resulting in gradual moisture decay. Even materials prepared with the same initial moisture content will experience moisture drift before being fed into the baling chamber. An additional intermediate moisture condition of 63.40% was therefore supplemented to evaluate model performance over a broader moisture range. The relative error between theoretical density and measured density under each working condition is calculated and listed in Table 3.

Table 3. Test results of compression molding of naked oat with different moisture content.

Moisture Content (%)	Test Density (kg/m ³)	Theoretical Density (kg/m ³)	F _{2max} (N)	m ₀ (kg/s)	Error (%)
74.30	323.40	280.59	373.33	0.56	13.24
63.40	308.08	274.62	354.25	0.47	10.86
47.70	286.51	265.09	329.52	0.36	7.47
14.80	195.09	196.56	270.47	0.14	0.75

Note to the table: the water content is the actual water content of the test. Samples are taken during the test and tested after the test. The design water content is 70%, 40% and 10%, respectively (all are moisture content on wet basis).

As shown in Table 3, the test value and theoretical value have the same trend. Under the same conditions, with the increased moisture content of the material, the final forming density of naked oats gradually increases, and the maximum values of F₂ and F_{2max} in the rolling process also increase. The theoretical value of the final forming density of round bales calculated by the theoretical model of forming density is close to the experimental value; this is due to the fluctuation of the quality of the material fed per second (m₀) within a certain range during the test, the loss of moisture in the material, the change of moisture content and other factors as the test progresses.

Many existing studies on round baler forming density adopt empirical models directly linking final density with feed rate or compression force, while few studies characterize density evolution via intermediate friction parameters between material and rollers.

Compared with previous density models, the proposed model establishes a quantitative relationship between forming density and roller tangential force. It provides a feasible way to monitor real-time bale formation state using measurable torque signals, instead of only predicting final density under fixed working parameters.

It can be seen that, for materials with different moisture content, the final forming density of round bales and F_{2max} in the rolling formation process meet the theoretical model of forming density. The forming density of round bales is related to the moisture content of the material, the mass of the material fed per second, the volume of the baling chamber and the tangential force per unit length of the No. 2 steel roll. Specifically, it is positively related to the mass of the material fed per second and negatively related to the volume of the baling chamber. Under the condition that the moisture content of the material, the mass of the material fed per second and the volume of the baling chamber are fixed—that is, the same materials are harvested and the operating parameters of the round baler are fixed—the forming density of the round bales can be expressed by the tangential force per unit length of the No. 2 steel roller.

5. Conclusions

In this paper, naked oats were used as the experimental materials through the friction test platform, which was designed to carry out the material rolling formation test, collect the torque value of the steel roll during the rolling formation process, then obtain and verify the interaction model of steel roll and material. The main conclusions are as follows:

- (1) A monitoring platform for the material condition of round bales was designed that mainly includes the conveying and feeding device, the baling chamber, the frame and the friction testing device. The friction testing system of crimping can collect the torque changes in the process of crimping, which provides a basis for the study of the crimping mechanism.
- (2) The rolling formation process is divided into an initial stage, straw core-forming stage, compression stage and bale-forming stage. During the rolling formation process, the material is subject to the joint action of sliding friction and rolling friction. From the initial stage to the forming stage, the friction of the material is gradually changed from sliding friction to rolling friction, and the contact between the material and the steel roll is gradually changed from surface contact to line contact.
- (3) The change of the torque value of the No. 2 steel roll corresponds to the movement of the material in the baling chamber, which is used to monitor the movement of the material. This method converts the unmeasurable material movement state of the round bale crimping process into the quantifiable change of the torque value of the No. 2 steel roller, providing a method for monitoring the material state of the round bale crimping process.
- (4) The theoretical model $\rho = \frac{m_0}{kS} \ln \frac{F_2}{E}$ of forming density was established and verified. The test shows that the model can better predict the forming density of round bales with different moisture content. The maximum error between the theoretical value and the experimental value is 13.24%, and the minimum error is 0.75%. The model shows that the forming density of round bales is related to the moisture content of the material, the mass of the material fed per second, the volume of the baling chamber and the tangential force per unit length of the No. 2 steel roll. Under the condition that the moisture content of the material, the mass of the material fed per second and the volume of the baling chamber are fixed—that is, the same materials are harvested and the operating parameters of the round baler are fixed—the forming density of the round bales can be expressed by the tangential force per unit length of the No. 2 steel roller. The model provides a theoretical basis for monitoring and controlling the forming density of round bales.
- (5) This study converted the material motion state, which is difficult to observe directly within the enclosed bale chamber, into the continuously measurable torque signal of steel roller No. 2, thereby providing an engineering-feasible monitoring variable for identifying the round-bale roll–compression formation stages and estimating bale density. Real-time closed-loop control and multi-condition field validation have not yet been conducted in this study. Future research will investigate the effects of different crop materials, steel roller structures, operating speeds, and round baler configurations on the model parameters and prediction accuracy, thereby promoting the intelligent monitoring and automatic control of the round-bale roll–compression forming process.

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