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Effects of wet storage on compression molding of sawdust and mechanism analysis

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Abstract. This study investigated the effects of wet storage on characteristics of compression molded sawdust, molding energy consumption and combustion characteristics during 13 days' storage. Results showed that the hemicellulose content of sawdust decreased following the wet storage time, while the surface porosities increased. After wet storage for 5 days, a large number of orderly small holes were observed on the surface of sawdust. During the wet storage period, the compression ratio energy consumption decreased as a whole, and reached the lowest level when stored for 5 days which was 19.82% lower than that of raw materials. The water resistance of molded sawdust was significantly improved from 3 days of wet storage, and there was no significant change for the bulk density, drop resistance, and radial compressive strength. Comparing with the material, the ignition temperature and burnout temperature of treated sawdust decreased significantly, and the flammability index, comprehensive combustion characteristic index and combustion stability discriminant index all showed an obvious increasing trend. The lowest ignition temperature was found for the sawdust stored for 5 days. The mechanism of wet storage was further analyzed combining with the physicochemical properties.

1. Introduction

The production of biomass briquette fuel has increased rapidly in China. According to the Chinese 13th Five-Year Plan for Biomass Energy Development, the annual utilization of biomass briquette fuel will reach 30 million tons by 2020 in China [1]. Compared with raw material of biomass, briquette fuel has the advantages of small volume, high density, high combustion efficiency etc., which is a high-quality environmental friendly fuel that can replace conventional fossil fuels [2, 3].

At present, sawdust is one of the main raw material for biomass briquette in China. It is mostly molded by roll-die extrusion molding technology which is popular for high productivity, no external heating and good formability. However, there are some bottleneck problems in the production of biomass briquette fuel, such as high energy consumption and short life of key components. The energy consumption of the molding fuel production line is mainly concentrated in the raw material pulverization and compression molding process, in which the compression molding energy consumption accounts for more than 60% of total energy consumption [4, 5]. Literature analysis showed that researches on biomass briquette fuel mainly focused on two aspects, one was improving the key equipment and critical components for compression molding [6] and the other was optimizing the parameters of compression molding process [7-9]. Both of them intended to improve the quality of briquette fuel and reduce the energy consumption by optimizing external production conditions.

In recent years, some studies have shown that the quality of briquette fuel could be evidently improved by changing its internal material properties through baking and heating the materials [10,



11]. Taking into account the practical production of briquette fuel, wet storage is also a simple and operability pretreatment method. By storing the raw materials of biomass with consistent moisture, it is possible to change its physical and chemical characteristics by anaerobic fermentation theoretically, thus having a positive impact on the molding properties. However, there are no reports on the compression molding properties of sawdust based on wet storage. Our research group have analysed the effects of wet storage treatment on characteristics of compression molded wheat straw in the early stage [12]. Based on previous work, this study will further explore the effects of wet storage on the compression ratio energy consumption, briquette fuel quality and combustion performance of sawdust, and analyse the mechanism of action combining with the physicochemical properties.

2. Material and methods

2.1. Experimental material

The sawdust used in this study was obtained from a biofuel factory (Langfang City, Hebei Province), of which particle size range from 5 mm to 10 mm. The main source of sawdust material is discarded wood boards of the furniture factory. The collected sawdust was further pulverized to less than 2 mm by a cutter mill (Cutting Mill SM300, Lex, Germany).

2.2. Wet storage treatment

The pulverized sawdust of 200 g was put in a polyethylene bag and vacuum-sealed by packaging machine, totally 14 sample bags were treated and stored at room temperature. The sample bags were then opened after storing for 1 day, 3 days, 5 days, 7 days, 9 days, 11 days and 13 days respectively. Two parallel experiments were set for each treatment. The treated sawdust was subjected to compression molding experiment and characteristic measurement.

2.3. Compression molding test

The compression molding test was performed on a universal material meter (Instron 3367, Instron, USA) using a self-made mold with an inner diameter of 10 mm. Molding specific operation: the straw (1.0 g) was accurately weighed out using an electronic balance, then transferred to a mold. Following this, the plunger of the test apparatus compressed the sample at a rate of 50 mm/min to the point at which a pressure of 180 MPa was obtained. The resulting force displacement data was recorded. This pressure was maintained for 30 s, after which the molded sample was removed from the apparatus [13]. The figure below (Figure 1) shows a simplified mold.

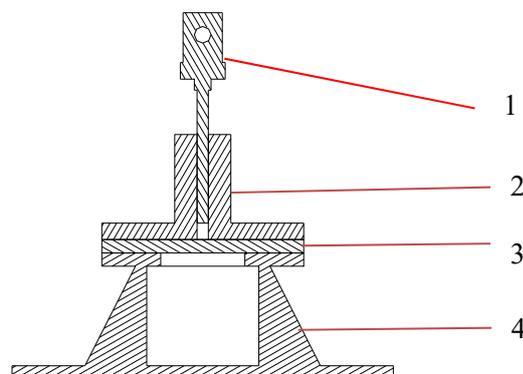


Figure 1. Densification die diagram. (1. Pressure bar 2. Sleeve 3. Baffle 4. Base)

2.4. Analysis of physicochemical properties and combustion characteristics

After the wet storage, the material and combustion characteristics were determined based on standard methods. These analyses determined the levels of moisture content (GB/T 1931-1991), cellulose and hemicellulose (NREL/TP-510-42618), lignin (ASTM E1721-2001(2009)) and ash (ASTM E1755-2001(2007)) as well as lower heat value (GB/T 30727-2014).

The surface microstructures of the pretreated sawdust specimens were observed using scanning electron microscopy (SEM)(SU3500, Hitachi, Japan) at 5kV. Prior to analysis, the samples were mounted on a stub and sputter coated with gold [14].

Combustion characteristics were analyzed using a synchronous thermal analyzer (TA SDTQ600, Waters, USA). The flammability index, C ($\%/(\text{°C}^2 \cdot \text{min})$), was adopted as an important means of evaluating combustion behavior of the specimens, with a higher index value indicating better thermal performance. This factor was calculated using the Eq.(1):

$$C = \frac{(dm/dt)_{\max}}{T_1^2} \quad (1)$$

where $(dm/dt)_{\max}$ ($\%/min$) represents the maximum combustion weight loss rate, T_1 (°C) is the ignition temperatures, as determined by extrapolation of thermogravimetric (TG) and differential TG (DTG) data.

The comprehensive combustibility index, S_N ($\%^2/(\text{°C}^3 \cdot \text{min}^2)$), was employed as an indication of variations in the combustion characteristics of the sawdust following pretreatment [15]. A higher S_N value is associated with more rapid ignition and burn-out, meaning improved overall combustion of the fuel. The S_N value was calculated according to the Eq.(2):

$$S_N = \frac{(dm/dt)_{\max}(dm/dt)_{\text{mean}}}{T_1^2 T_2} \quad (2)$$

where T_2 (°C) is the burn-out temperatures, same as the determination method of T_1 . In this work, T_2 was defined as the temperature at which 99% of the original material had been burned, and $(dm/dt)_{\max}$ and $(dm/dt)_{\text{mean}}$ ($\%/min$) represent the maximum and mean weight loss rates, respectively, as obtained from DTG curves.

The combustion stability determination index R_w is used to determine the performance of the fuel for stable combustion, and the larger the R_w value, the better the combustion stability of the corresponding fuel. The R_w is defined based on the test parameters of pure carbon using the Eq. (3):

$$R_w = \frac{655}{T_1} \times \frac{763}{T_{\max}} \times \frac{(dm/dt)_{\max}}{8.73} \quad (3)$$

where T_{\max} (°C) is the temperature corresponding to the maximum combustion rate.

2.5. Determination of molding fuel quality and compression ratio energy consumption

The molding fuel quality in this study mainly measures the water resistance [16], bulk density [17], drop resistance (ASTM D440-86) and axial compressive strength [16].

The smaller the value of the water resistance measurement, the greater the value of the bulk density, drop resistance and axial compressive strength, the better of the molding fuel quality.

Molding energy consumption refers to the energy consumed by producing a unit mass of the product and was calculated using the Eq. (4):

$$E_e = \frac{\int Fds}{m} \times 10^{-3} \quad (4)$$

where E_e (MJ/t) is the molding energy consumption, F (N) is the compression load, s (mm) is the distance moved by the piston and m (g) is the mass of the pellet.

2.6. Data processing and analysis

One-Way ANOVA analysis of variance was performed using SPSS (V20.0, SPSS, USA) on the sawdust forming characteristics and material properties of different wet storage times.

3. Results and discussion

3.1. Moisture content of sawdust during wet storage period

Figure 2 shows the results of moisture content of sawdust during 13 days' wet storage. It can be seen from the figure that the overall trend of moisture content was relatively stable, ranging from 8.82% to 9.41%. There was no significant difference in the moisture content of sawdust between different storage times ($p>0.05$). It was obvious that the moisture content of the sawdust during storage was substantially stable without loss.

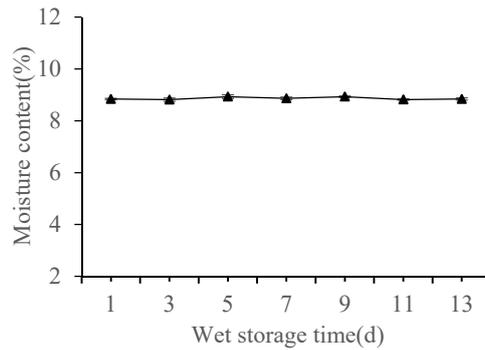


Figure 2. Moisture content of sawdust during wet storage.

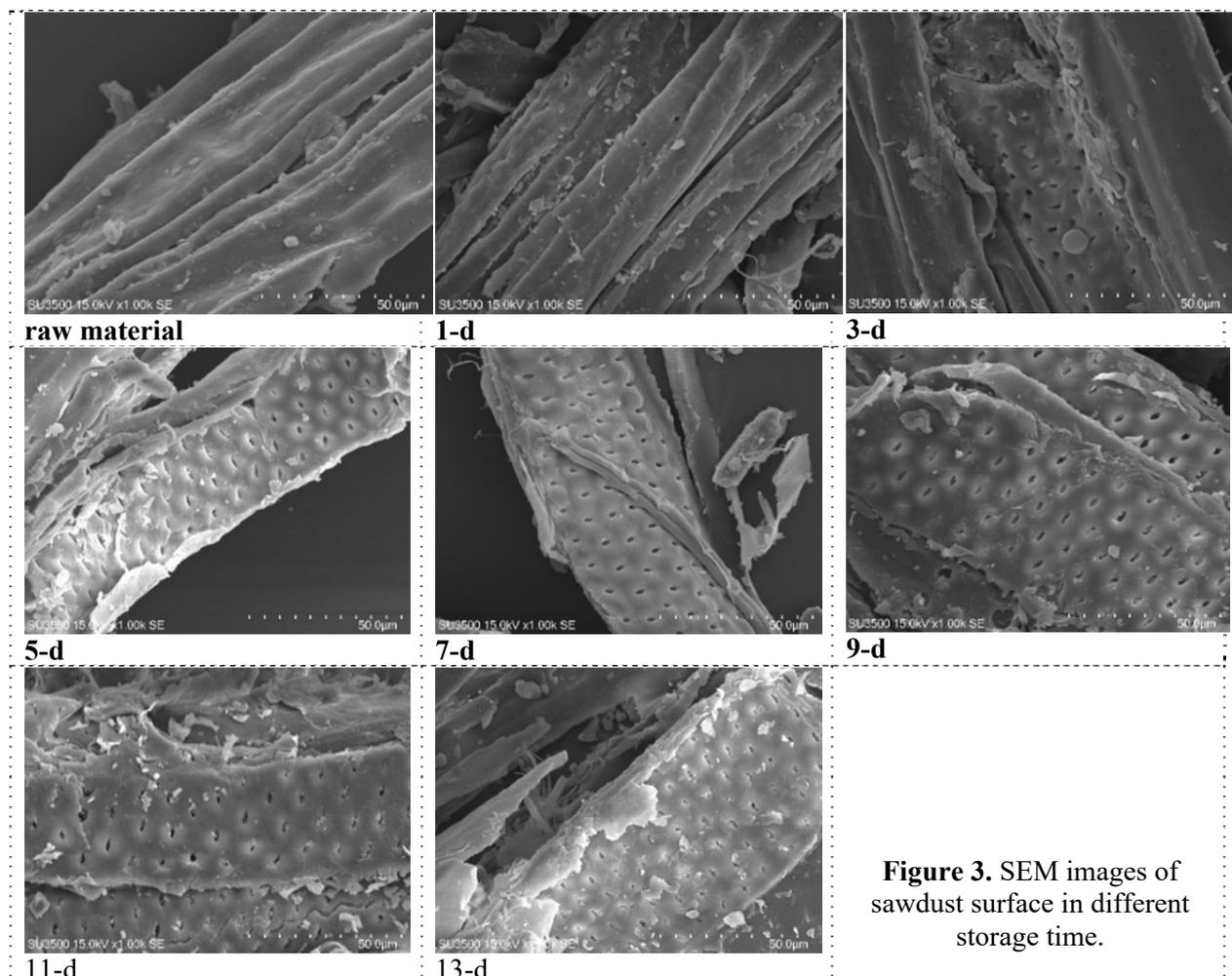


Figure 3. SEM images of sawdust surface in different storage time.

3.2. Analysis of physicochemical properties of stored sawdust

3.2.1. *Surface microstructure analysis.* Figure 3 shows the results of scanning electron microscopy of treated sawdust during 13 days' wet storage.

It can be seen that the surface structure of the raw material was dense and smooth, a small number of fine holes began to appear on the sawdust surface after 1-day storage. Then, as the storage time increased, the number of fine holes increased evidently, a large number of fine holes arranged neatly could be observed after 5-days' wet storage. After 11-days' storage, fine cracks were observed around the holes.

3.2.2. *Analysis of cellulose, hemicellulose and lignin.* Table 1 shows the results of cellulose, hemicellulose, and lignin content of sawdust during 13-days' wet storage.

Hemicellulose content showed a continuous downward trend during the 13-days' storage period, and the hemicellulose content after wet storage was significantly lower than that of the raw material ($p < 0.05$). There was no significant change in the cellulose and lignin content of sawdust during tested wet storage period.

Table 1. The content of cellulose, hemicellulose and lignin during storage.

Storage time	Cellulose (%)	Hemicellulose (%)	Lignin (%)
0	41.91±1.07	9.64±0.18	27.44±0.02
1	41.63±2.11	9.61±0.03	27.14±0.03
3	40.99±0.09	9.38±0.05	27.24±0.30
5	41.64±0.02	9.25±0.19	27.47±0.14
7	42.21±0.07	9.2±0.14	27.34±0.17
9	41.58±0.32	9.02±0.05	27.64±0.06
11	41.74±0.46	8.93±0.26	27.20±0.18
13	41.67±0.14	8.93±0.32	27.71±0.42

3.2.3. *Analysis of calorific value and ash content.* Figure 4 shows the results of lower heat value and ash content of treated sawdust samples.

No significant change was detected for the lower heat value and ash content of sawdust during storage for 13 days ($p > 0.05$), which indicated that wet storage treatment had no effect on combustion calorific value and ash.

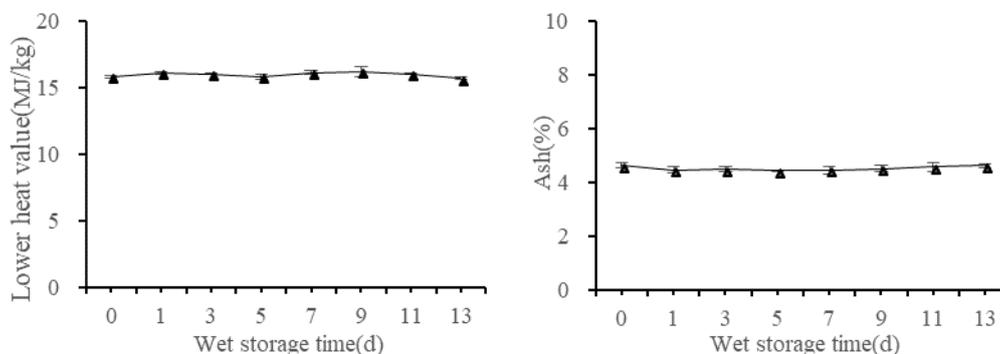


Figure 4. Lower heat value and ash in different storage time.

3.3. Analysis of compression ratio energy consumption of stored sawdust

Figure 5 shows the results of the compression ratio energy consumption of treated sawdust. During the wet storage period, the compression ratio energy consumption decreased firstly, and reached the lowest level when stored for 5 days which was 19.82% lower than that of raw materials. After that the compression ratio energy consumption showed a slight increase trend, and the value of stored sample for 7 days was significantly higher than that of stored for 5 days ($p < 0.05$). No significant difference was found for the compression ratio energy consumption of sawdust stored for 11 days and 13 days ($p > 0.05$). The high pressure applied to the sawdust to overcome the fiber resilience during the molding process was the main cause of high molding energy consumption [18]. The above analysis showed that the content of hemicellulose decreased significantly after wet storage ($p < 0.05$), and a large number of fine holes appeared on the surface of sawdust after 5 days' storage. This indicated that the structure of lignocellulosic fiber was destroyed, and the elastic deformation property of the fiber was weakened, which then led to the decrease of pressure required for molding.

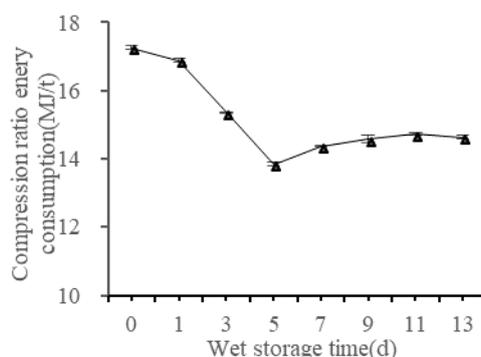


Figure 5. Compression ratio energy consumption in different storage time.

3.4. Analysis of molding characteristics of stored sawdust

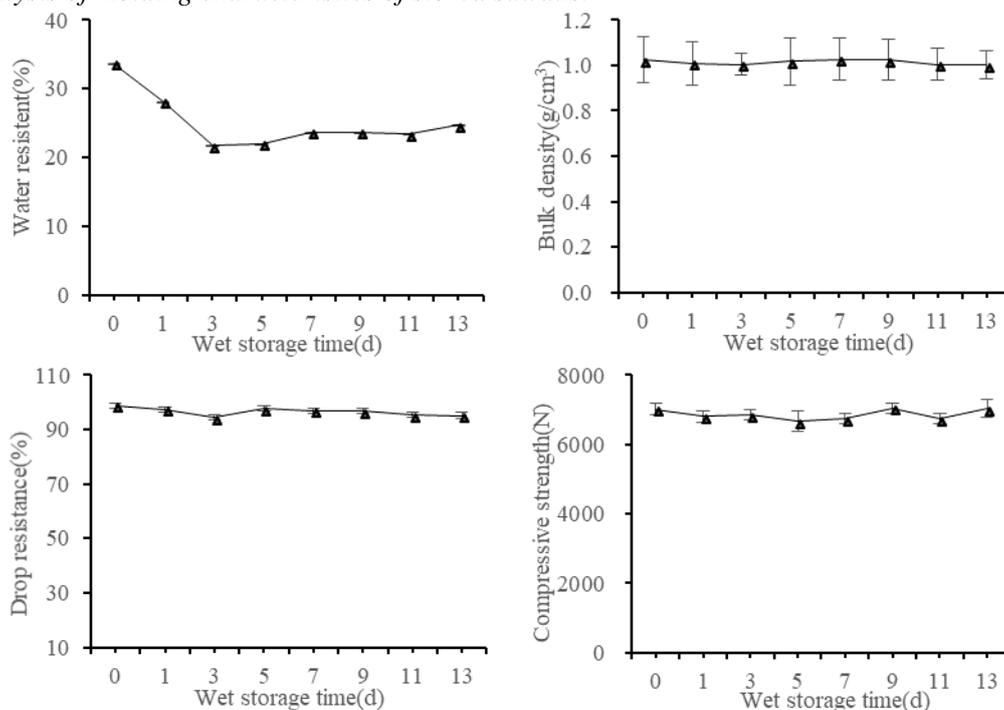


Figure 6. Molding characteristics results of sawdust pellets in different storage time.

Figure 6 shows the results of molding characteristics of sawdust during 13-days' wet storage. The water resistance of sawdust molded pellets decreased substantially firstly and tended to be stable after 3 days' storage. The water resistance of the biofuel pellet was significantly lower than that of the raw material ($p < 0.05$) even after 1-day's storage. And the water resistance of the sawdust stored for 3 days was the best. As mentioned before, the surface porosity and specific surface area of sawdust sample increased greatly after wet storage, which could then improve the dispersibility of water in sawdust and provided a better environment for the uniform contact of water and lignin. These microstructure changes contributed finally to the improvement of water resistance [19]. There was no obvious change for the bulk density, drop resistance and axial compressive strength at different storage time.

3.5. Analysis of combustion characteristics of stored sawdust

From the analysis of Figures 7, the combustion process of sawdust can be divided into four stages: water precipitation stage, volatilization analysis and combustion stage, fixed carbon combustion stage and burnout stage. The rate of weightlessness of treated sawdust was obviously higher than that of raw material, and the combustion rate increased obviously. This indicated that wet storage could accelerate the combustion of sawdust and make the combustion reaction more intense, which meant the easily degradable components in sawdust structure were decomposed preferentially. This was consistent with the decrease of hemicellulose content and the result of surface microstructure analysis. The produced fine holes on the surface effectively increased the contact area between material and oxygen and made the reaction more intense.

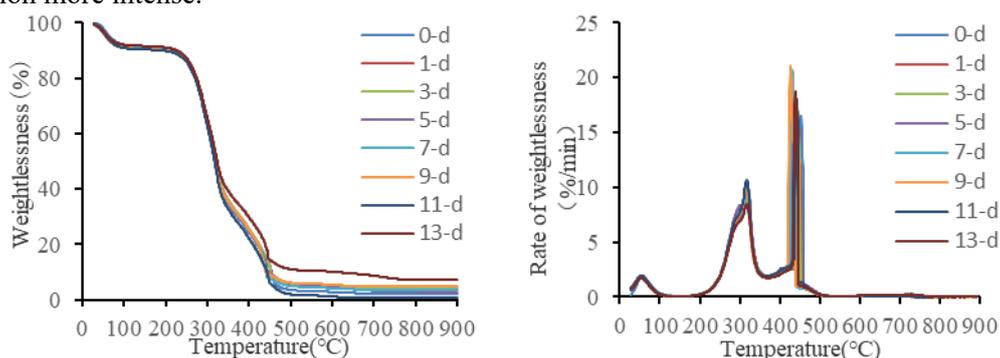


Figure 7. TG, DTG curve of sawdust in different storage time.

Table 2. Combustion characteristics parameters of sawdust in different storage time.

Storage time	T_1^a (°C)	T_2^b (°C)	C^c ($10^{-6} \cdot ^\circ\text{C}^{-2} \cdot \text{min}^{-1}$)	S_n^d ($10^{-11} \cdot ^\circ\text{C}^{-3} \cdot \text{min}^{-2}$)	R_w^e ($\% \cdot \text{min}^{-1} \cdot ^\circ\text{C}^{-2}$)
0	269.71	461.99	2.31	6.37	7.89
1	268.28	458.69	2.12	5.72	7.28
3	263.25	453.85	2.43	6.62	8.24
5	262.27	446.66	2.54	7.24	8.72
7	263.94	447.71	2.98	8.94	10.43
9	266.44	443.45	2.97	8.98	10.62
11	268.35	452.93	2.51	7.19	8.73
13	264.83	451.35	2.68	7.35	9.28

^a T_1 is the ignition temperature.

^b T_2 is the burnout temperature.

^c C is the flammability index.

^d S_n is the comprehensive combustibility index.

^e R_w is the combustion stability determination index.

Table 2 shows the results of the combustion characteristic parameters. It was proved that the ignition temperature and burnout temperature of treated sawdust was reduced by wet storage. The sawdust stored for 5 days had the lowest ignition temperature, and the sawdust stored for 9 days had the lowest burnout temperature. Compared with raw materials, the flammability index, comprehensive combustion characteristic index and combustion stability discriminant index of stored samples showed an overall increase. The flammability index of the samples stored for 7 days reached the highest point, increasing by 22.37% compared with the raw materials, and the comprehensive combustion characteristic index and combustion stability discrimination index of the samples stored for 9 days increased most by 41.63% and 34.6% respectively. Above all, good ignition performance, stable combustion and better combustion characteristics was found for the sawdust stored for 5~9 days.

4. Conclusions

The compression ratio energy consumption, molding fuel quality and combustion characteristics of sawdust during 13-days' wet storage were discussed. Wet storage treatment could significantly reduce the compression ratio energy consumption of sawdust, improve the water resistance and the combustion characteristics of the biofuel pellets. Mechanism analysis showed that the fibre structure and constitution of the sawdust was changed by wet storage, which contributed mostly to the improvement of the quality of sawdust pellets. The best wet storage time for sawdust was proved to be 5 days.

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