Experimental Study of the Volume Drying Shrinkage Characteristics of Lignite under Low Temperatures

Wu Xian, Dong Ziwen,* Sun Lifeng, and Jia Tinggui

ABSTRACT: Low-temperature and humid drying experiments [temperatures of 20−30 °C; relative humidity (RH) of 40−60%] were conducted to investigate the drying shrinkage of lignite at low temperatures. The moisture content and volume variations of lignite during low-temperature drying were measured to analyze the change in the water content and volume drying shrinkage rate under low-temperature drying conditions. The results show that in the first 48 h of drying, the water evaporated rapidly. The amount of external water evaporated and lost accounted for 70−90% of the total water lost during the entire low-temperature drying period, and the average water content is reduced to about 12.8%. When the rapid loss of external water decreased to less than 12.8%, the water adsorbed on the external surfaces, the movable water between large particles was completely lost, and saturated lignite underwent heterogeneous volume shrinkage. The drying shrinkage was slow during the first 48 h, accounting for 20.8% of the total drying shrinkage in the entire low-temperature drying process. The volume shrinkage occurred in four stages as the water content decreased with time. With increasing drying time, the decrease in the water content occurred in four stages: the thermal expansion stage, rapid shrinkage stage, slow shrinkage stage, and stable shrinkage stage. The dry shrinkage rate has a significant positive correlation with the water evaporation quality and significant negative correlations with the water content and evaporation rate. The lower the evaporation rate, the greater the dry shrinkage rate when the saturated lignite is dried under low-temperature and humid conditions (temperature of <30 °C; RH of <60%). There is a time lag between volume shrinkage and water loss, and there is also a difference in their quantities. The volume shrinkage is lower than the water loss, and the difference is largest about 48 h into the initial stage of low-temperature drying. As the low-temperature drying time increases, the shrinkage due to drying becomes stable, and the moisture content remains unchanged. The larger the ratio of RH to temperature, the larger the stable shrinkage.

1. INTRODUCTION

With the consumption of coal resources, the mining, processing, utilization, storage, and transportation of lignite are increasing, and the problem of the spontaneous combustion of lignite is also becoming of increasing concern. Lignite has a large pore structure (mainly macropores and mesopores), a large surface area, rich functional groups, and a large electrostatic potential, which leads to its high water content and reactivity. After water loss, lignite is prone to spontaneous combustion or burning. It is not suitable for long-term stacking and long-distance transportation and has serious safety risks. The existence of water leads to coal softening. Under exposed conditions, the volume shrinkage of saturated coal is significant, and continuous drying can lead to cracking and serious crushing as the lignite shrinks. Low-rank coal has a high porosity and connectivity and a low pore structure curvature, which causes its strong drying shrinkage. When lignite is dried in the air, the water in the >120 nm pores is easily evaporated, the pores are emptied, and its porosity increases significantly. However, the volume shrinkage of the lignite is limited. When further drying and evaporation occur, the multilayer water is removed and the open gel structure collapses, resulting in significant volume shrinkage and an increase in porosity to 50%. In summary, owing to its characteristics, lignite undergoes significant drying shrinkage and cracking during low-temperature drying, its pore structure changes, its porosity increases significantly, and its pore connectivity increases. After contact with oxygen, its oxidation and spontaneous combustion processes change, and the risk of spontaneous combustion increases. At present, previous studies on this topic have generally focused on the drying shrinkage phenomenon and
experiments under special conditions such as negative pressure, an inert gas environment, high temperature and high pressure, underground gasification, modification, and utilization. There are few reports on drying in low-temperature air and the changes in the drying shrinkage, cracking, breakage, and spontaneous combustion caused by drying. Therefore, low-temperature drying experiments were conducted on saturated lignite in this study. During the experiments, the mass and volume of saturated lignite were measured, and the changes in the water content, evaporation rate, and volume drying shrinkage rate with increasing drying time were calculated to analyze the change in the volume drying shrinkage rate of saturated lignite at low temperatures.

2. ANALYSIS AND DISCUSSION OF EXPERIMENTAL RESULTS

2.1. Variation in Water Content with Time. Coal generally contains two types of water: (1) weakly associated water, which can be dissipated via evaporation at low temperatures and (2) strongly associated water. Generally, water can be released from the system when the temperature increases to 60 °C or above, and the two types of water can be turned into external and internal water. During evaporation, the water in coal mainly diffuses from the surface to the outside environment in the form of water vapor, and diffusion is the key form of water evaporation. Only when water vapor forms in a porous system can it evaporate and diffuse to the outside world. There is desorption and adsorption of water vapor in the porous system, and there is hysteresis between the desorption and adsorption during evaporation at low temperatures. The desorption of water vapor is faster than the adsorption of water vapor, and the apparent performance is water evaporation.

Figure 1 shows the variations in the moisture contents over time of three groups of 18 samples during the low-temperature drying experiments. The results show that the moisture contents of lignite samples 4−1, 4−2, 4−3, 7−1, 7−2, and 7−3, which had original moisture contents of 25%, decreased to 15.5, 16.5, 16.3, 14.1, 14.7% and 15.2%, respectively, after 48 h of low-temperature drying evaporation.

Figure 1. Variations in water content with time. (a) Sample group nos. 4 and 7, (b) sample group nos. 5 and 2, and (c) sample group nos. 3 and 6.
decreased to 7.3, 13, 11.7, 9.6, 12, and 13.7%, respectively. The moisture contents of samples 3−1, 3−2, 3−3, 6−1, 6−2, and 6−3 decreased to 11.9, 12.7, 13.5, 6, 11.1, and 14.7%, respectively. During this period, the lignite samples did not exhibit significant volume shrinkage. As Pradeep et al. reported, when the drying shrinkage is not significant or does not lead to full drying and fragmentation of lignite, the mass transfer rate is not affected, so the loss of water through evaporation is not affected. Therefore, the rapid water loss stage begins 48 h after the beginning of the drying process, and the proportion of evaporation water mass in the total evaporation water mass of the whole low-temperature drying process is about 70–90%.

Figure 2. Volume shrinkage varies with time. (a) Sample group no. 4, (b) sample group no. 7, (c) sample group no. 5, (d) sample group no. 2, (e) sample group no. 3, and (f) sample group no. 6.
Figure 3. Plots of volume shrinkage versus water content. (a) Sample group no. 4, (b) sample group no. 7, (c) sample group no. 5, (d) sample group no. 2, (e) Sample group no. 3, and (f) sample group no. 6.
and the evaporation rate is not affected by shrinkage and cracking during drying.

### 2.2. Variation in Shrinkage Rate with Time

The definition of the volume dry shrinkage rate \( V_{sr} \) of lignite is shown in eq 1. Figure 2 shows the variations in \( V_{sr} \) with drying time. The negative volume shrinkage values in the figure indicate that the volume expansion of saturated lignite is caused by heat absorption in the initial drying stage, that is, the thermal expansion stage. Figure 2a shows that the overall volume shrinkage initially rapidly increases and then becomes stable with increasing drying time. The relationship between the volume shrinkage and time is the following logistic function

\[
V_{sr} = \frac{V_0 - V}{V_0} \quad (1)
\]

where \( V_{sr} \) is the volume drying shrinkage rate (100%); \( V_0 \) is the volume of the sample before drying (cm\(^3\)); and \( V \) is the volume of the sample during the drying stage (cm\(^3\)).

\[
V_{sr} = \frac{V_{sr_{\min}} - V_{sr_{\max}}}{(1 + t/x_0)^p} + V_{sr_{\max}} \quad (2)
\]

where \( V_{sr_{\min}} \) is the minimum volume drying shrinkage (maximum thermal expansion) (100%); \( V_{sr_{\max}} \) is the maximum volume drying shrinkage (100%); \( t \) is the drying time (h); and \( x_0 \) is the time correction parameter. The relationship between \( p \) and \( x_0 \) is

\[
\left( \frac{t_{sr_{\min}}}{x_0} \right)^p = \frac{p - 1}{p + 1} \quad (3)
\]

where \( t_{sr_{\min}} = 0 \) is the time when \( V_{sr} = 0 \).

In Figure 2, the curve of the positive volume shrinkage is the data as the sample enters the drying shrinkage stage after thermal expansion. As the drying continues, the volume increase caused by the thermal expansion gradually recovers and exhibits a volume shrinkage. The relationship between the volume shrinkage and time shows that the volume shrinkage initially rapidly increases, then slows down, and finally stabilizes at a relatively large value. In other words, after the beginning of the evaporation drying, saturated lignite experienced four processes with increasing drying time: initial thermal expansion, rapid drying shrinkage, slow drying shrinkage, and stable drying shrinkage (Figure 2b).

Figure 2 shows that the volume shrinkage rate continuously increases with increasing drying time and is largely stable after drying for a long time, that is, without a significant increase, indicating that the volume shrinkage caused by the drying of lignite will not always occur and has a certain limit. Figure 2 shows that the volume drying shrinkage rates of the three samples in each figure exhibit the same trend of increasing at any given time, but there are some differences in the shrinkage rates due to the different evaporation rates caused by the different wax seals used. Compared with the samples treated with the same wax seal under the same drying conditions, there are also some differences in the volume shrinkage rate, which are mainly due to the differences in the pore structures of the different samples, which are determined by the complexity of the natural pore structure of the coal and the multiple samples used.

Owing to the differences in the individual samples, the effect of the wax seals with different surface numbers on the volume of drying shrinkage was different in the different stages. In the first stage of coal drying shrinkage, the drying shrinkage rate increased rapidly with increasing drying time, but the effect of the different wax covers on the coal volume drying shrinkage rate was not significant under the same drying conditions. In stages 2–4 of the volume shrinkage, the dry shrinkage of the coal samples was significantly influenced by the different wax seals used under the same drying conditions. Because the structure and the surface of the coal are influenced by the environment, the evaporation rates were somewhat different. The differences in the evaporation rates lead to differences over time in the volume shrinkage rates and the change in the evaporation rate in the different stages of development, so the influence of the evaporation rate on the volume shrinkage rate was different.

### 2.3. Variation in Shrinkage Rate with Water Content

Figure 3 shows the variations in the drying shrinkage rate with moisture content after the samples enter the drying shrinkage stage without considering the initial thermal expansion process. After entering the drying shrinkage stage, as the moisture content decreases, the volume of the lignite still needs to undergo three processes: slow drying shrinkage, fast drying shrinkage, and stable drying shrinkage. By comparing Figures 2 and 3, it can be seen that there are some differences in the order of the drying shrinkage cycle in the different samples, which are determined by the complexity of the pore structures of the different stages. In phase 2 of the drying shrinkage cycle, the average volume shrinkage values in phase 2 for experimental groups 4, 7, 5, 2, 3, and 6 were 35.2, 23.5, 5, 3.7, 2.1, and 1.9%, respectively. The average stable (maximum) volume shrinkage values in phase 4 were 14.8, 14.2, 23.2, 17.9, 8.6, and 10.4%, respectively; and the proportions of volume shrinkage of the saturated lignite compared to the total shrinkage in phase 2 were 23.7, 16.4, 21.5, 20.8, 24.2, and 17.9%, respectively. In

---

**Table 1. Cubic Fitting Results for the Change in the Dry Shrinkage Rate with Water Content**

| sample numbers | \( b_0 \) | \( b_1 \) | \( b_2 \) | \( b_3 \) | \( R^2 \) |
|----------------|---------|---------|---------|---------|---------|
| 4–1:1–7 | 2.02 | −32.27 | 176.75 | −324.45 | 0.9784 |
| 4–2:7–2 | 0.47 | −3.33 | 4.58 | −3.73 | 0.9795 |
| 4–3:7–3 | −0.04 | 5.21 | −39.51 | 73.63 | 0.9900 |
| 5–1:2–1 | 0.28 | −3.34 | 16.73 | −37.40 | 0.9948 |
| 5–2:2–2 | 0.37 | −4.26 | 21.29 | −45.44 | 0.9890 |
| 5–3:2–3 | 0.33 | −2.62 | 7.56 | −10.99 | 0.9853 |
| 3–1:6–1 | 0.17 | −2.68 | 18.48 | −45.32 | 0.9937 |
| 3–2:6–3 | 0.23 | −3.07 | 22.46 | −60.03 | 0.9886 |
| 3–3:6–3 | 0.33 | −5.08 | 33.92 | −79.96 | 0.9779 |

**Table 2. Data Normalization Processing Results**

| \( s_i/s_0 \) | \( (RH_i) \) | \( (T_i) \) | \( (b_0)_i \) | \( (b_1)_i \) | \( (b_2)_i \) | \( (b_3)_i \) |
|--------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 0.32 | 0.41 | 0.41 | 0.92 | −0.90 | 0.88 | −0.86 |
| 0.06 | 0.41 | 0.41 | 0.00 | 0.08 | −0.15 | 0.20 |
| −0.27 | 0.41 | 0.41 | −0.29 | 0.37 | −0.41 | 0.43 |
| 0.47 | 0.00 | −0.41 | −0.11 | 0.08 | −0.07 | 0.07 |
| −0.21 | 0.00 | −0.41 | −0.05 | 0.05 | −0.05 | 0.04 |
| −0.40 | 0.00 | −0.41 | −0.08 | 0.11 | −0.13 | 0.15 |
| 0.46 | −0.41 | 0.00 | −0.17 | 0.10 | −0.06 | 0.04 |
| −0.01 | −0.41 | 0.00 | −0.13 | 0.09 | −0.04 | 0.01 |
| −0.42 | −0.41 | 0.00 | −0.08 | 0.02 | 0.03 | −0.07 |
other words, the volume shrinkage in the slow shrinkage stage accounted for 20.8% of the drying shrinkage in the entire low-temperature drying process. This stage corresponds to the first 48 h of the rapid decrease in the moisture content of lignite under low-temperature drying conditions, which indicates that as the moisture content decreases, significant drying shrinkage can only occur after a large amount of moisture is lost during the low-temperature drying of lignite, while a small amount of shrinkage and insignificant shrinkage occur during the rapid moisture loss stage and the slow shrinkage stage, respectively.

According to the changes in the evaporation rate and moisture content during the drying of saturated lignite, the evaporation rate and moisture content of lignite decrease rapidly in the first 48 h of drying, and the water dispersion loss accounts for 70−90% of the total water dispersion loss. The rapid water loss stage corresponds to the first and second stages of lignite volume drying shrinkage with time—that is, the thermal expansion and slow shrinkage stages—and the shrinkage is not significant. This indicates that the volume shrinkage of lignite causes a lag in the water loss under low-temperature drying conditions. This is because when most of the movable external water between the large particles has evaporated, the large pores between the particles empty and enter the stage in which the water between the small particles (small pore water) evaporates, and the lignite undergoes significant volume drying shrinkage.

The accelerated shrinkage stage corresponds to the slow evaporation stage, which is characterized by a low evaporation rate and slow water loss. The main water lost in this stage is the water between the small particles (micropore water). Because of the extremely low water content between these pores, the narrow discharge channel of the water between the small particles, and the great difficulty of evaporation, the evaporation is slow, but the evaporation of this part of the water easily produces a great difference between the internal and external capillary pressure. When the shrinkage stress is greater than the tensile strength of lignite, significant dry cracking occurs and many dry cracks form, which is the
First, it is necessary to understand that lignite drying shrinkage at low temperatures and marks the beginning of the rapid evaporation stage.

Based on the relationship between the different stages of drying shrinkage and the decrease in the moisture content as well as the proportion of water loss, it is concluded that when a large amount of external water evaporates and the drying shrinkage of saturated lignite is not significant, the original space occupied by movable external water in the porous structure system of lignite is replaced by air owing to loss of the external water, the drying shrinkage is in the initial stage, and the shrinkage is not significant. The pore structure of lignite has not been significantly damaged, and significant macropore collapse cannot occur, which jointly determines that lignite with a high water content is in the initial stage of evaporation and drying. In addition, its spontaneous combustion risk increases. This phenomenon is basically consistent with the problem of the high spontaneous combustion risk of lignite after decreases of 12–9% in water content proposed by some scholars. When evaporation drying enters the slow evaporation stage, which is dominated by the evaporation of the water in the small pores, the drying shrinkage stress increases, and many spaces and macropores are formed after the loss of the movable external water in the early stage, and collapse occurs under the action of the shrinkage pressure stress. The drying shrinkage accelerates, the proportion of small pores and micropores increases significantly, and the porosity decreases, which may lead to a gradual increase in the difficulty of spontaneous combustion of lignite in the rapid shrinkage stage, that is, the risk of spontaneous combustion is reduced.

Cubic curve fitting was performed using the average water content as the dependent variable and the average volume shrinkage as the independent variable. The cubic curve fitting formula is shown in eq 4, and the fitting results are presented in Table 1.

\[ V_a = b_0 + b_1W_c + b_2W_c^2 + b_3W_c^3 \] (4)

To clarify the relationship between the volume shrinkage and moisture content under the different drying conditions and for different samples, according to stepwise regression theory, the data for the cubic fitting results \((b_0, b_1, b_2, \text{ and } b_3)\), the ratio of the initial surface area to the initial volume \((s_0/v_0)\), the RH, and the temperature \((T)\) in Table 2 were normalized using eq 5 so that the data were in the range of \([-1, 1]\). The results of the data normalization are presented in Table 2.

\[
\begin{align*}
(s_0/v_0)' &= (s_0/v_0 - 1.22)/1.37 \\
(RH)' &= (RH - 50)/24.5 \\
(T)' &= (T - 25)/12.25 \\
(b_0)' &= (b_0 - 0.46)/1.70 \\
(b_1)' &= (b_1 + 5.72)/29.40 \\
(b_2)' &= (b_2 - 29.14)/167.23 \\
(b_3)' &= (b_3 + 58.47)/309.15
\end{align*}
\] (5)

The normalized data were fitted using linear regression, and the functions in eq 6 and the ratio of the initial surface area to

### Table 3. Results of the Correlation Analysis

| sample | \(E_{	ext{group}}\) | \(W_{	ext{free}}\) | \(M_i\) |
|--------|----------------|-----------------|-------|
| 4–1    | -0.85404**    | 0.85972**       | -0.87163** |
| 4–2    | -0.97057**    | 0.97287**       | -0.97926** |
| 4–3    | -0.97076**    | 0.98655**       | -0.98489** |
| 7–1    | -0.95584**    | 0.96418**       | -0.96965** |
| 7–2    | -0.97524**    | 0.97103**       | -0.97893** |
| 7–3    | -0.9678**     | 0.99344**       | -0.98931** |
| 5–1    | -0.78526**    | 0.94328**       | -0.96019** |
| 5–2    | -0.82642**    | 0.95765**       | -0.96865** |
| 5–3    | -0.75594**    | 0.93399**       | -0.95137** |
| 2–1    | -0.83903**    | 0.97044**       | -0.97963** |
| 2–2    | -0.81063**    | 0.97496**       | -0.98494** |
| 2–3    | -0.82388**    | 0.98368**       | -0.99072** |
| 3–1    | -0.94618**    | 0.97504**       | -0.98122** |
| 3–2    | -0.96707**    | 0.97431**       | -0.96738** |
| 3–3    | -0.97918**    | 0.98888**       | -0.98509** |
| 6–1    | -0.93465**    | 0.94136**       | -0.94101** |
| 6–2    | -0.96647**    | 0.97453**       | -0.96835** |
| 6–3    | -0.98499**    | 0.94363**       | -0.93818** |

Figure 5. Stable shrinkage rates of different experimental groups.
the initial volume \((s_0/v_0)\), the RH, and the temperature \((T)\) were obtained. The relationships between the relevant fitting functions \((h_1, b_1, b_2, b_3)\) and \((s_0/v_0)\), RH, and \(T\) were obtained by substituting the corresponding eqs 6 into 5. The volume drying shrinkages of saturated lignite samples with different initial shapes were obtained under different low-temperature drying conditions and different water contents.

\[
(b_1)' = 0.21 + 0.44(s_0/v_0)' + 0.17(RH)'
+ 0.72(s_0/v_0)'^2(RH)' - 63.16(s_0/v_0)'^3(T)'
- 11.65(s_0/v_0)'^3 - 9.90(T)'^3
\]
\[
(b_2)' = -0.22 - 0.46(s_0/v_0)' - 0.14(RH)'
- 0.511(s_0/v_0)'^2(RH)' - 67.53(s_0/v_0)'^2(T)'
+ 11.93(s_0/v_0)'^3 + 10.60(T)'^3
\]
\[
(b_3)' = 0.22 + 0.46(s_0/v_0)' + 0.10(RH)'
+ 1.64(s_0/v_0)'^2(RH)' - 69.87(s_0/v_0)'^2(T)'
- 11.89(s_0/v_0)'^3 - 10.76(T)'^3
\]
\[
(b_4)' = -0.23 - 0.45(s_0/v_0)' - 0.067(RH)'
- 3.35(s_0/v_0)'^2(RH)' - 71.32(s_0/v_0)'^2(T)'
+ 11.66(s_0/v_0)'^3 + 10.72(T)'^3
\]

(6)

The difference \((\Delta, \text{eq 7})\) between the mass of evaporated water and the change in the volume shrinkage with time is shown in Figure 4. The mass of water lost was greater than the volume shrinkage. As the drying time increased, first, the value increased rapidly to the maximum, and then it decreased to a stable value. This is shown for nine samples in experimental groups 4, 5, and 7 in Figure 4, and for \(\Delta\) for samples 4 and 9 in experimental group 3 (e.g., samples 2, 3, and 6). Although the difference between the mass of water evaporated and the amount of volume shrinkage obeys the above two relationships, 18 samples also exhibited similar relationships. The difference between the mass of water evaporated and the amount of volume shrinkage reaches the maximum at about 48 h of drying, that is, the volume shrinkage causes a lag in the water evaporation, and the most significant shrinkage occurs after 48 h of drying. The larger the difference between them, the larger the volume of the void spaces in the porous structure after the water vapor replacement and the more air can enter the pore structure and remain.

\[
\Delta = V_i - V_w \tag{7}
\]

where \(V_i\) is the amount of volume drying shrinkage (cm³) and \(V_w\) is the volume of water evaporated (cm³).

The correlations between the volume shrinkage and the moisture content \((M_i)\), the mass of water lost through evaporation \((W_{i,\text{loss}})\), the evaporation rate of dry matter per unit mass \((E_{\text{lim}})\), and the initial volume, area, thickness, drying temperature, and humidity were analyzed. As shown in Table 3, at the 0.01 significance level, the volume shrinkage is significantly negatively correlated with the evaporation rate and water content and is significantly positively correlated with the quality of water evaporation. This indicates that the volume shrinkage increases as the water loss, water content, and evaporation rate decrease. For the same drying time, the higher the evaporation rate of the coal sample, the faster the water evaporates, the greater the decrease in the water content of the coal sample, the lower the residual water content, and the smaller the volume shrinkage, at low temperatures, if the water in the coal evaporates quickly, the volume drying shrinkage will not be significant. In contrast, slow evaporation will lead to significant drying shrinkage. Based on the negative correlation between the evaporation rate and the environment’s RH, it can be concluded that lignite with a high moisture content in an environment with a low RH undergoes more evaporation and less volume drying shrinkage. When the evaporation and volume shrinkage are stable, the volume shrinkage rate increases to the highest value.

The corresponding relationship determined via statistical analysis between the contraction rate \((V_i)\) and the ratio between the RH and temperature \((R/H/T)\) for 18 samples during the stable contraction stage is shown in Figure 5. The results show that the stable shrinkage rates of experimental groups 3 and 6 were the lowest, the stable shrinkage rates of experimental groups 2 and 6 were the highest, and the stable shrinkage rates of experimental groups 4 and 7 were in the middle. The corresponding stable shrinkage rate was analyzed using the RH/T value. The positive correlation between RH/T and stable shrinkage is significant; that is, the larger the RH/T ratio, the greater the stable shrinkage rate. According to the distribution of the RH/T value, the temperature change has less influence on the RH/T ratio than the RH value, and the range of the change in \(T\) is low under low-temperature conditions. Therefore, the RH has a more significant influence on the stable shrinkage rate. The larger the RH, the larger the RH/T, the lower the evaporation rate, the more significant the drying shrinkage and the greater the stable shrinkage rate.

3. DISCUSSION

As the evaporation and drying shrinkage continues, the shrinkage stress increases significantly due to evaporation of the water in the small pores and micropores. When the shrinkage tensile stress is greater than the compressive strength of lignite, many cracks are generated. The generation of these cracks provides many oxygen channels for the drying shrinkage and compaction of lignite. In addition, many unconnected small pores and areas can be connected by the cracks, and the difficulty of spontaneous combustion changes. The changes in the pore structure, connectivity, and spontaneous combustion characteristics of lignite under the influence of drying shrinkage cracks need to be studied further using nuclear magnetic resonance and oxidation experiments.

4. CONCLUSIONS

(1) The volume shrinkage of lignite is caused by the loss of water under low-temperature drying conditions. As the drying time increases, the volume changes or shrinks through four different processes: thermal expansion, rapid shrinkage, slow shrinkage, and contraction and stability. The dry shrinkage rate decreases with the moisture content, which involves four stages: (1) thermal expansion, (2) slow shrinkage, (3) rapid shrinkage, and (4) stable shrinkage.

(2) The dry shrinkage of lignite causes a lag in the water loss during evaporation and drying under low-temperature conditions, and the differences between them are the time lag and quantity. In the stage that includes rapid evaporation and loss of external water, slow shrinkage and heat expansion occur, and the dry shrinkage rate in the slow stage accounts for 24.2–16.4% of the total dry
shrinkage, with an average of 20.75%. The dry shrinkage in the slow stage accounts for 70–90% of the total water loss. When the moisture content is reduced to below 12–14%, shrinkage occurs, and the rapid drying stage begins.

(3) The cubic equation for the drying shrinkage of saturated lignite under low-temperature conditions was established. The volume drying shrinkage is lower than the water dispersion loss. The difference between the volume drying shrinkage and the mass of water lost reaches its maximum value after about 48 h of drying. The slow evaporation rate is equivalent to the time lag between the water evaporation and the volume shrinkage, and the dry shrinkage is significantly enhanced. The volume drying shrinkage rate is positively correlated with the quality of the lost water at the 0.01 level and is significantly negatively correlated with the water content and evaporation rate. The larger the ratio of the RH (1) to the temperature (T, °C), the larger the final stable volume shrinkage rate.

5. SAMPLE SELECTION AND EXPERIMENTAL METHODS

5.1. Sample Selection and Characteristics. The samples of lignite used in the experiments were obtained from the Fengshuigou Coal Mine of the Pingzhuang Coal Company in Inner Mongolia, China. Old lignite from the coal seam no. 1 to no. 4 was used to cut the large pieces, and then an SJJ-YG-MD02 multi-function jade cutting and grinding machine was used to grind the edges and corners until all the sides were flush and the edges were straight. In this experiment, three temperature and humidity conditions were set, and six coal samples were used in each group, three of which were in one group (Table 5).

5.2. Experimental Methods and Processes. Before drying, the samples’ surfaces were numbered, and the measuring points were measured using an electron microscope and a high beat instrument. A constant temperature and humidity box TGP-1260 plant growth room was used for the drying, and the low-temperature experimental conditions are described in Table 5.

Table 4. Results of the Proximate Analysis of the Coal Samples

| proximate analysis test number | M(ad) (%) | A(ad) (%) | V(ad) (%) | FC(ad) (%) | n (1) |
|-------------------------------|----------|-----------|-----------|------------|-------|
| 1                             | 10.83    | 15.93     | 40.62     | 32.62      | 0.35  |
| 2                             | 10.40    | 40.62     | 45.81     | 3.17       | 0.38  |
| 3                             | 10.80    | 23.02     | 43.24     | 22.94      | 0.42  |
| 4                             | 10.19    | 22.52     | 42.51     | 24.78      | 0.45  |
| 5                             | 10.91    | 11.68     | 39.43     | 37.98      | 0.37  |
| average value (excluding sample 2) | 10.63    | 18.29     | 41.45     | 29.58      | 0.40  |

5.2.3. Drying Experiments. Before drying, the samples’ surfaces were numbered, and the measuring points were measured using an electron microscope and a high beat instrument. A constant temperature and humidity box TGP-1260 plant growth room was used for the drying, and the low-temperature experimental conditions are described in Table 5.

Table 5. Temperature and Humidity Conditions of the Low-Temperature Drying Experiments

| sample number | number of wax covers | temperature (°C) | sample serial number | number of wax covers | humidity (%) | temperature (°C) | sample serial number | number of wax covers | humidity (%) | temperature (°C) | sample serial number | number of wax covers | humidity (%) |
|---------------|----------------------|------------------|----------------------|----------------------|--------------|------------------|----------------------|----------------------|--------------|------------------|----------------------|----------------------|--------------|
| 4–1           | 0                    | 30               | 5–1                  | 0                    | 20           | 3–1              | 0                    | 25                   |
| 4–2           | 2                    | 5–2              | 2                    | 3–2                  | 4            | 6–1              | 0                    | 40                   |
| 4–3           | 4                    | 5–3              | 4                    | 3–3                  | 6–2          | 2                | 3                     |
| 7–1           | 0                    | 60               | 2–1                  | 0                    | 50           | 5–3              | 4                    | 6–3                  |
| 7–2           | 2                    | 2–2              | 2                    | 6–2                  | 2            | 6–3              | 4                    |
| 7–3           | 4                    | 2–3              | 4                    | 6–3                  | 4            | 6–3              | 4                    |

Complete contact information is available at: https://pubs.acs.org/doi/10.1021/acs.omega.1c05575

Funding
This research was funded by the National Natural Science Foundation of China (grant number 51804107), the Natural Science Foundation of Hunan Province (grant numbers 2020JJ4260 and 2019JJ50109), and the Key Projects of Hunan Education Department (grant numbers 20A142, 19A123, 19B138, and 18A420).
Notes
The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

The results of this study could not have been possible without the efforts of the staff on the research team, and at the same time, we sincerely thank the editors and reviewers for spending their valuable time reviewing and providing valuable comments. We thank LetPub (www.letpub.com) for its linguistic assistance during the preparation of this manuscript.

**REFERENCES**

(1) Fu, X. H.; Lu, L.; Ge, Y. Y.; Tian, J. J.; Luo, P. P. China Lignite Resources and Physical Features. Coal Sci. Technol. 2012, 40, 104–107.

(2) Yin, L. Q. Lignite resources and utilization outlook in China. Coal Sci. Technol. 2004, 8, 12–14.

(3) Komatsu, Y.; Sciazko, A.; Zakrzewski, M.; Kimijima, S.; Hashimoto, A.; Kaneko, S.; Szmyd, J. S. An experimental investigation on the drying kinetics of a single coarse particle of Belchatow lignite in an atmospheric superheated steam condition. Fuel Process. Technol. 2015, 131, 356–369.

(4) Yang, W.; Li, Q. C.; Zhang, Z. G. Effect of different carbon structure with different metamorphic degree on pyrolysis product characteristics. Coal Sci. Technol. 2017, 45, 212–218.

(5) Xie, W.; Wang, P.; Qu, S. J. Regulation effect of blending coal on pore structure of coal-based activated carbon prepared by briquetting method. Coal Sci. Technol. 2017, 2, 13199.

(6) Ping, A.; Xia, W.; Peng, Y.; Xie, G. Comparative filtration and dewatering behavior of vitrinite and inertinite of bituminous coal: Experiment and simulation study. Int. J. Min. Sci. Technol. 2021, 31, 233–240.

(7) Wang, X.; Sutimin; Edy, S.; Thomas, G. Experimental study on the effect of micro-cracks on Brazilian tensile strength. Arch. Min. Sci. 2015, 60, 985–996.

(8) Li, D.; Wong, L. N. Y.; Liu, G.; Zhang, X. Influence of water content and anisotropy on the strength and deformability of low porosity meta-sedimentary rocks triaxial compression. Eng. Geol. 2012, 126, 46–66.

(9) Francis, C. B. Engineering geology of "D" power station YALLOURN AUSTRALLA. Q. J. Eng. Geol. Hydrogeol. 1975, 2, 103–117.

(10) Xin, F.; Xu, H.; Tang, D.; Cao, L. An improved method to determine accurate porosity of low-rank coals by nuclear magnetic resonance. Fuel Process. Technol. 2020, 205, 106435.

(11) Murray, J. B.; Evans, D. G. The brown-coal/water system: Part 3. Thermal dewatering of brown coal. Fuel 1972, 51, 290–296.

(12) Evans, D. The brown-coal/water system: Part 4. Shrinkage on drying. Fuel 1973, 52, 186–190.

(13) Ling, K. R.; Song, B.; Yin, W. Z. Drying behaviors of low-rank coal under negative pressure: Kinetics and model. Dry. Technol. 2016, 35, 173–181.

(14) Kelemen, S. R.; Kwiatek, L. M.; Siskin, M.; Lee, A. G. K. Structural Response of Coal to Drying and Pentane Sorption. Energy Fuels 2006, 20, 205–213.

(15) Mu, C.; Zhang, S.; Li, Y.; Li, H.; Wu, S.; Huang, X. Evolution of microstructure and combustion reactivity of lignite during high-temperature drying process. Dry. Technol. 2018, 36, 1170–1178.

(16) Zhao, H. Y.; Zheng, X.; Fu, X. M.; Jia, J. W.; Xu, G. H.; Lu, M. Y.; Zeng, M.; Shu, X. Q. Effect of hot pressing dewatering on the structure and pyrolysis characteristics of lignite. J. China Coal Soc. 2015, 5, 1165–1173.

(17) Joshua, T.; Derek, E. Thermal-hydrologic-mechanical-chemical processes in the evolution of engineered geothermal reservoirs. Int. J. Rock Mech. Min. Sci. 2009, 5, 855–864.

(18) Hongqiang, M.; Hongyu, C.; Hongguang, Z.; yangyang, S.; Yadong, N.; Qingjie, H.; Zetao, H. Study on the drying shrinkage of alkali-activated coal gangue-slag mortar and its mechanisms. Construct. Build. Mater. 2019, 225, 204–213.

(19) Allardice, D.; Evans, D. The brown-coal/water system: Part 1. The effect of temperature on the evolution of water from brown coal. Fuel 1971, 50, 201–210.

(20) Allardice, D. J.; Evans, D. G. The brown coal/water system. Part 2. Water sorption isotherms on bed-moist Yallourn brown coal. Fuel 1971, 50, 236–253.

(21) Pradeep, K. A.; William, E. G.; Yam, Y. L. Pseudo steady state receding core model for drying with shrinkage of low ranked coals. Chem. Eng. Commun. 1984, 27, 9–21.