

## Research Article

# Experimental Study on Influence of Vaporous Water on Salt Expansion of Sulfate Saline Soil

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The harm of salt expansion of saline soil in arid areas has always been a major problem to be solved urgently. According to the conversion rule between sodium sulfate and sodium sulfate decahydrate, sodium sulfate decahydrate crystals can be precipitated from sodium sulfate solution by cooling. Besides, when the relative humidity (RH) exceeds the critical relative humidity (CRH), sodium sulfate decahydrate can be formed by the combination of sodium sulfate and vaporous water, resulting in the salt volume expansion. However, at present, in the salt expansion mechanism of sulfate saline soil, only the influence of liquid water is considered while vaporous water is not involved. To study the effects of temperature, salinity, and ARH on salt expansion, the salt expansion test of dry sulfate saline soil under the action of vaporous water was conducted, and its composition was analyzed by X-ray diffraction (XRD) technology. Experimental results showed that sodium sulfate decahydrate crystals were produced in the sulfate saline soil if the relative humidity (RH) of pore gas exceeded the critical one so that salt expansion occurred. Salt expansion and salt expansion rate of sulfate saline soil increased with the increase of RH and salinity but decreased with the increase of temperature. Therefore, the new salt expansion mechanism of sulfate saline soil under vaporous water is verified. The experimental results further perfected the original salt expansion mechanism of sulfate saline soil under the action of liquid water and guided the study of new treatment methods of sulfate saline soil.

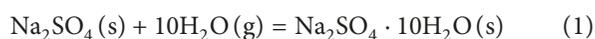
## 1. Introduction

Saline soils are widely distributed in the world; in China, sulfate saline soil is mainly distributed in northwest drought districts [1, 2]. With the decrease of precipitation from east to west in China, the drought measure increases continuously, and the soil salinization also increases [3]. Due to heavy rainfall and seasonal variations in semihumid areas in North and Northeast China, soil desalinization and salt accumulation occur alternately throughout the year. Although the surface salinity is high, the salt content in the core and subsoil is not high [4]. In the semiarid plain areas of Ningxia and Inner Mongolia [5], the annual precipitation is less, the annual salt content is greater than that of desalting, the surface soil salt content is high, and the salt content in the core and subsoil is also high, often

accompanied by salt crystallization to form salt crusts. As well, in the inland arid areas of Xinjiang and He-xi Corridor, the weak precipitation is not enough to soak the salt on the surface of salt accumulation, the relative humidity (RH) is high, the soil salt accumulation reaches the end of the year, and the thick salt shell appears on the surface of many places [6]. Sodium sulfate is one of the important salts in sulfate saline soil, which is named as sulfate saline soil. Sulfate saline soil has an obvious characteristic of salt expansion, resulting in damage to foundation and engineering facilities [5]. Lu [7] and Blaser and Scherer [8] proposed the salt expansion mechanism of sulfate saline soil based on the solubility law of sodium sulfate. In the process of cooling, sodium sulfate decahydrate crystals are precipitated from the sodium sulfate solution. The crystal volume of sodium sulfate decahydrate crystals is larger than

that of sodium sulfate crystals, which leads to the expansion of salt. On this basis, the salt expansion law of sulfate saline soil has been studied by many scholars. Bing and Ma [9], Zhang et al. [10] and Lai et al. [11] studied the salt expansion law of sulfate saline soil under the action of salinity, water content, temperature, dry density, and overlying load. Wu et al. [12] and Wan et al. [13] investigated the salt expansion characteristics of sulfate saline soil under variable water content. Wan et al. [14, 15] studied the precipitation law of sodium sulfate decahydrate crystals in sulfate saline soil during the cooling process and established the relationship between varying water content and temperature reduction. Chen et al. [16] and Lv et al. [17] experimentally studied the reduction law of salt expansion of sulfate saline soil under the action of insulating layer and soilbag. Niu and Gao [18] established an analytical calculation method for frost heaving of sulfate saline soil. All the above studies follow the salt expansion mechanism proposed by Lu [7] and Blaser and Scherer [8]. Although the research objects of salt expansion are mostly unsaturated sulfate saline soil containing liquid water and vaporous water, the salt expansion is affected by liquid water and vaporous water. The influence of liquid water was only analyzed in the salt expansion mechanism proposed by Lu [7] and Blaser and Scherer [8], but the effect of vaporous water was not considered. As a result, the salt expansion experiment based on this mechanism does not distinguish the influence of liquid water and vaporous water on the salt expansion of sulfate saline soil, and the calculated value is quite different from the measured value. This indicates that the influence of vaporous water on the salt expansion of sulfate saline soil cannot be ignored.

Flatt [19] and Wang et al. [20] concluded that sodium sulfate crystals, sodium decahydrate crystals, and sodium sulfate solution coexist at 32.4°C and RH of 82.5%, as shown in Figure 1 [19, 21]. When the temperature is greater than 32.4°C and the RH is less than the critical one, sodium sulfate decahydrate crystals lose water and become sodium sulfate crystals; vice versa, it absorbs water and becomes sodium sulfate solution. When the temperature is less than 32.4°C, the RH is greater than the critical relative humidity (CRH) and is less than the ultimate relative humidity (URH); the sodium sulfate crystals can form sodium sulfate decahydrate crystals with the combination of vaporous water, as shown in equation (1). When less than the CRH, sodium sulfates crystals are formed after the water loss of the sodium sulfate decahydrate crystals. It is inferred that when the temperature is less than 32.4°C and the RH of air exceeds the CRH, sodium sulfate decahydrate crystals are formed after the moisture absorption, resulting in salt expansion of sulfate saline soil:



where  $g$  represents the vaporous state and  $s$  represents the solid state.

To further reveal the salt expansion mechanism, an experimental device under the vaporous action was designed to study the influence of salinity and vaporous water on salt expansion law of sulfate saline soil under constant

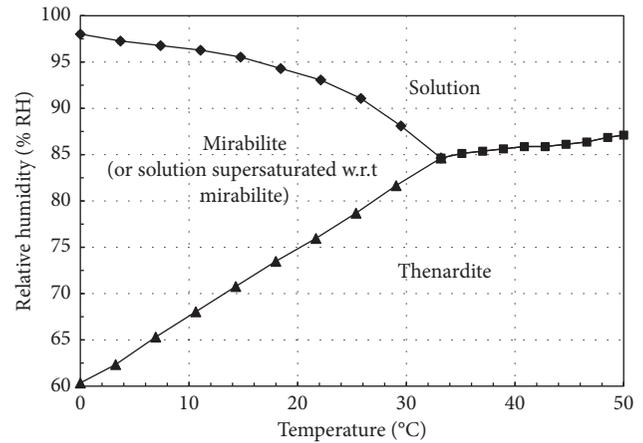


FIGURE 1: Phase diagrams for sodium sulfate [21].

temperature conditions. It is of great significance to enrich the treatment methods of sulfate saline soil.

## 2. Preparation of Dry Sulfate Saline Soil

Dry sulfate saline soil is prepared by standard sand and anhydrous sodium sulfate of pure grade. The standard sand is selected for it had a wide particle size range, uniform gradation, conformity of various indexes to standards, and representativeness of test results. The standard sand was produced by ISO, Xiamen, China. The particle size is 0.08–2.00 mm, the non-uniform coefficient is 6.25, and the curvature coefficient is 1.5625. According to ASTM D2487-17 and D-18 [22, 23], the standard sand was a well-graded soil. The particle grading curve is shown in Figure 2. Anhydrous sodium sulfate was produced by China National Pharmaceutical Group Corporation. It is anhydrous and transparent with the purity of 99.0%, and the particle size is about 0.15 mm.

Firstly, the standard sand and anhydrous sodium sulfate were baked in an electric thermostatic drying oven at the constant temperature of 121°C for 48 hours, and the dried samples were cooled to room temperature. Then, they were immediately sealed and preserved in a sealed polymer bag to ensure the drying state. Secondly, dried standard sand and anhydrous sodium sulfate were weighed by electronic scales according to Table 1 and packed into containers and stirred for 5 minutes at 150 r/s speed by a small mixer so that the salt was evenly distributed. Dried sulfate saline soil containing 2%, 3%, and 5% salt was prepared.

## 3. Experimental Setup

Considering the action of vaporous water, a test device for studying the salt expansion of sulfate saline soil was developed and shown in Figure 3. The device consisted of a constant temperature and humidity test chamber (CTHTC), a test cylinder, an air accelerator, and a data acquisition system, as shown in Figure 3(a). The test chamber provided a controlled test environment at a size of 1000 mm × 1000 mm × 800 mm, a temperature range of –20°C–150°C with 0.5°C accuracies, and an RH range of

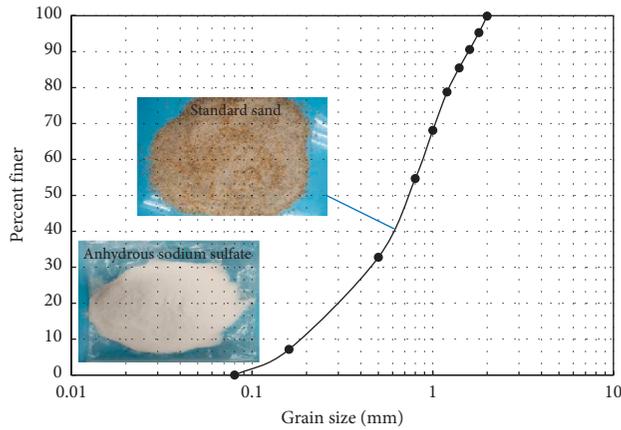


FIGURE 2: Grain size distribution for standard test sand.

TABLE 1: Ratio of sulfate saline soil.

Sample	Standard sand (g) (mass ratio (%))	Anhydrous sodium sulfate (g) (mass ratio (%))
2% salty saline soil	3121.86 (98)	63.71 (2)
3% salty saline soil	3090.00 (97)	95.57 (3)
5% salty saline soil	3026.30 (95)	159.28 (5)

20~98% with an accuracy of 2.5%. The test chamber was produced by Taiwan Hongyu Instrument Technology Co., Ltd with no. HYC-TH-800CH.

The test cylinder was the container for the main reaction of test samples. In this test, the test cylinder was a plexiglass cylinder with an inner diameter of 130 mm, a thickness of 5 mm, and a height of 370 mm, and its bottom and top were sealed by using a fixed circular plexiglass plate using plexiglass adhesive and a screwed circular rubber cap, respectively, as shown in Figure 3(b). The screwed circular rubber cap had a venting hole and a test hole that tightened the LVDT displacement meter to the test cylinder using silica gel and glues (Figure 3(b)). The test cylinder was divided into a top chamber and a bottom chamber by using a fixed circular perforated plexiglass plate tightly bonded with its inner side wall. The top chamber was a container for the sulfate saline soil sample and had three holes on the test cylinder side wall to fix temperature and RH sensors. On top of the sulfate saline soil sample, a movable circular perforated plexiglass plate was arranged to transfer the salt expansion of sulfate saline soil sample to the LVDT displacement sensor. The bottom chamber was connected to an air accelerator with an air flow meter by rubber hose through the intake hole on its side wall, and thus, the air with vaporous water could be continuously and stably infiltrated from the CTHTC to the bottom chamber. The fixed and movable circular perforated plexiglass plates could make the air with vaporous water infiltrated from the bottom chamber into the CTHTC through sulfate saline soil sample and the venting hole in the screwed rubber cap (Figure 3(b)).

The data collector consisted of sensors, a reader, and a desktop computer (Figure 3(b)). The TH20R-EX temperature

and RH sensor with range and accuracy of  $-40^{\circ}\text{C}$ – $85^{\circ}\text{C}$  and 0–100% RH and  $\pm 0.2^{\circ}\text{C}$ ,  $\pm 2\%$  RH, respectively, and A Miran LVDT displacement sensor (0–50 mm and 0.001 mm) was used to monitor the temperature, RH, and salt expansion of sulfate saline soil sample, respectively.

#### 4. Experimental Processes

The test on the salt expansion of sulfate saline soil under the action of RH was designed as follows. There were 15 humidification procedures. In each procedure, the RH of air was set to 30%–60%–80%–90%. Sulfate saline soil salinity and temperature were constant, as shown in Table 2. The temperature was constant in the test cylinder, avoiding the influence of temperature change on the thermal expansion and deformation of the plexiglass test cylinder during the test process.

Before the test, Vaseline was uniformly coated on the inner wall of the test cylinder to reduce the friction between the inner wall of the cylinder and the sample. Double-layer medical gauze was placed on a fixed circular perforated plexiglass plate to prevent the standard sand from leaking from the diaphragm hole into the bottom chamber. Referring to the ASTM-D1557 standard [24], the sulfate saline soil in Table 1 was divided into three uniform parts and filled into three layers. After each filling, it was compacted by using 2.5 kg hammers from 0.305 m height to the sample. The compacting is performed for 25 times with the single-acting work of 7.5 J. After filling, the densities of soil samples with the salinity of 2%, 3%, and 5% were  $1.93\text{ g/cm}^3$ ,  $1.91\text{ g/cm}^3$ , and  $1.88\text{ g/cm}^3$ , respectively. To facilitate the measurement of salt expansion and gas permeation in the sample, organic glass plates of 5 mm in thickness and 120 mm in diameter were laid on the top of the sample with a pore diameter of 1 mm and a spacing of 8 mm. During the process of layered filling, temperature and RH sensors were installed in the middle part of the sample. The top was equipped with LVDT displacement sensor to connect the temperature and RH data acquisition system.

After the sample was filled, the test cylinder was carefully moved into CTHTC and placed smoothly. Then, the air accelerator was connected, the air accelerator was opened, and the gas flow rate was adjusted to  $20\text{ m}^3/\text{h}$  and kept constant. Moreover, considering the influence of liquefaction of vaporous water in a high RH environment, the consistency of inlet and outlet gas was detected by using a flow meter and sensor, and the moisture content changed before and after the test was detected. The results demonstrate that the moisture content before and after the test remains basically the same.

Then the test was carried out. The RH and temperature sensors were setup. The data collector was activated to monitor the temperature and RH inside the sample and in CTHTC. To reduce the influence of initial temperature and RH on test results, before the beginning of each humidification, salt expansion data were collected when CTHTC runs at a constant temperature for 8 hours and the difference between temperature and RH within the sample and the test

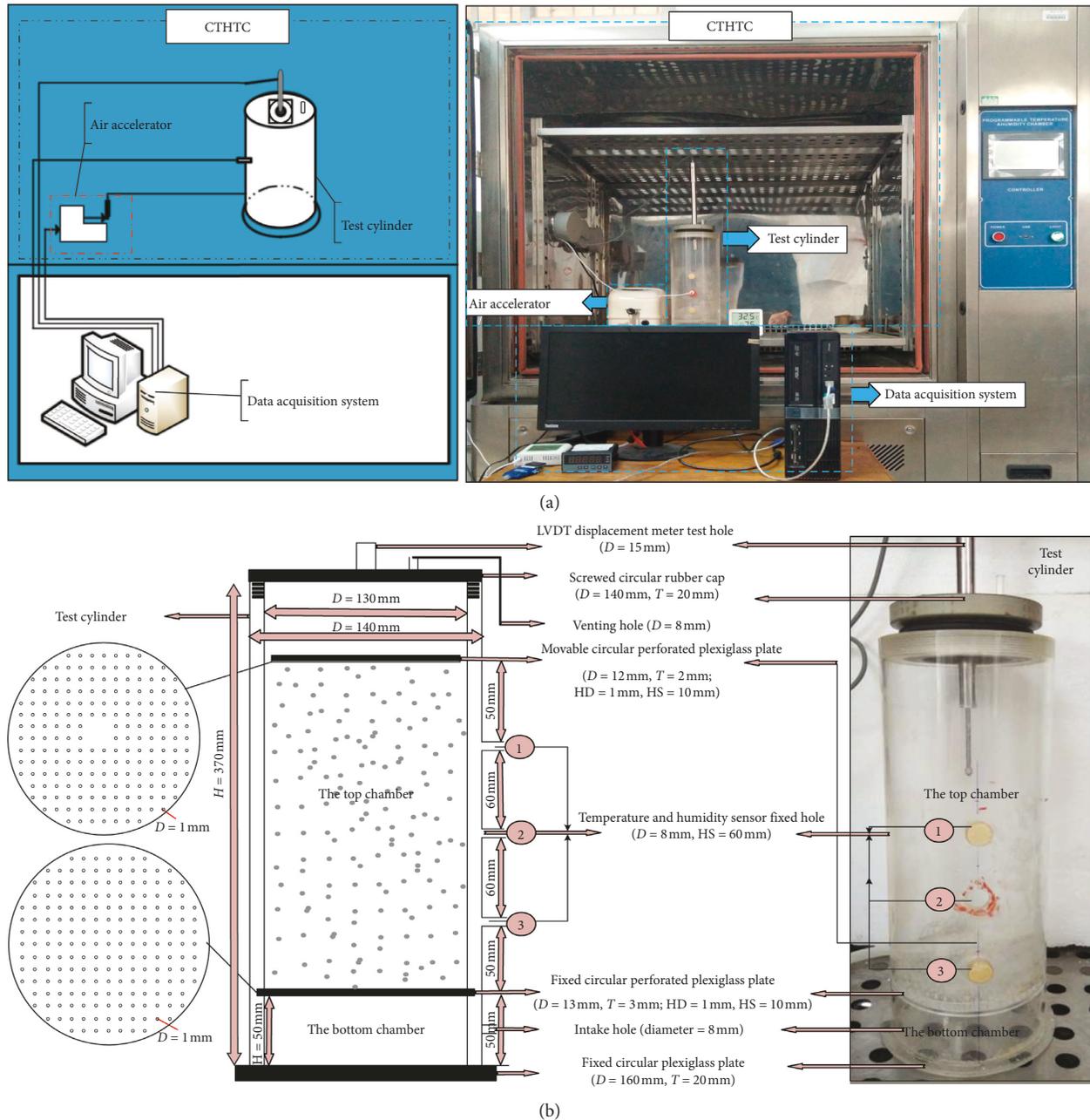


FIGURE 3: Sulfate saline soil displacement projection model device ( $D$ =diameter;  $H$ =height;  $T$ =thick;  $HD$ =hole diameter;  $HS$ =hole space). (a) Device design and physical drawing. (b) Sodium sulfate saline soil test cylinder [19, 21].

chamber was less than 3%. During the data collection, the temperature of CTHTC was kept to be stable. The RH action lasted for 8 hours, which can ensure that the difference of RH between CTHTC and the sample was less than 5%, and the change of salt expansion was less than 1% in the same condition. Each humidification process lasted for 32 hours.

After the test, the tested sulfate saline soil of 5 g was used to conduct the XRD analysis by X-ray diffractometer. The X-ray diffractometer had a scan start angle of  $5^\circ$ , a stop angle of  $80^\circ$ , and a scan speed of  $0.020^\circ/\text{s}$ . The image was recorded by using a goniometer that rotated  $1^\circ$  per minute.

## 5. Results and Discussion

**5.1. XRD Test Results.** The XRD diffraction test is carried out on the tested samples, and diffraction data are extracted and compared. A quantitative analysis of the components in samples is carried out. The results of the XRD diffraction test are shown in Figure 4. According to the cards of international standard samples (00-011-0647 Mirabilite; 98-000-0433 Thenardite; 03-065-0466 Quartz), it can be concluded that silicon dioxide, sodium sulfate decahydrate, and sodium sulfate all exist in tested samples with a good crystallinity of salt expansion products by the comparison

TABLE 2: Test parameters for salt expansion of sulfate saline soil under temperature and RH.

Test no.	Sodium sulfate content (%)	Temperature (°C)
1	2.0	10
2	2.0	15
3	2.0	20
4	2.0	25
5	2.0	30
6	3.0	10
7	3.0	15
8	3.0	20
9	3.0	25
10	3.0	30
11	5.0	10
12	5.0	15
13	5.0	20
14	5.0	25
15	5.0	30

and peak width analysis. Therefore, it is inferred that sodium sulfate decahydrate crystals are produced in the test process.

**5.2. Relative Humidity Effect on the Salt Expansion of Sulfate Saline Soil.** The RH effects on the salt expansion of sulfate saline soil are shown in Figure 5. Furthermore, as can be seen from Figure 5(a), under the condition of a constant salinity of 2% and a constant temperature of 10°C when the RH in the sample exceeds over 60% stage, the salt expansion of the sulfate saline soil happens. And the increasing of RH increases salt expansion. According to the phase transformation rule of sodium sulfate [19], when the ARH in the sample exceeds the CRH of 68% (10°C) at 1 atmosphere and 10°C, sodium sulfate decahydrate crystals are formed by the combination of vaporous water in the pores and the sodium sulfate which is located in the pores of the sample and in the contact area of particles, and the volume is expanded by 3.4 times. Sodium sulfate decahydrate crystal, produced by sodium sulfate in the pores, first fills the sample pore. When the crystal size is larger than the pore size, it has a pushing effect on sand particles and results in sample expansion. Sodium sulfate decahydrate crystal, produced by sodium sulfate in the particle contact area, has a pushing effect on sand particles and results in the sample expansion. While under the restraining of the test cylinder and lubricating of Vaseline on the cylinder wall, salt expansion is generated along the upper direction. However, the initial RH of salt expansion is smaller than the theoretical value with 68%. On the one hand, the reason for the difference may be that the gas accelerating device accelerates the movement of vaporous water, resulting in the CRH of this test being lower than the theoretical value. On the other hand, it is caused by the error of the test equipment, only 0.01~0.02 mm displacement is generated in the figure, which is within the range of equipment error.

Figures 5(b) and 5(c) show that the salt expansion trend of sulfate saline soil with the salinity of 3% and 5% is the same as that of 2% salinity. As the RH exceeds over the CRH, the salt expansion of sulfate saline soil whose salinity is 3%

and 5% also can occur at the test constant temperatures of 10°C, 15°C, 20°C, 25°C, and 30°C. And with the increase of RH, the salt expansion of sulfate saline soil increases.

**5.3. Temperature and Salinity Effects on the Salt Expansion of Sulfate Saline Soil.** Figure 6 is the influence curve of salinity and temperature on the maximum salt expansion of sulfate saline soil under the constant RH. As shown in Figure 6, when the RH is 90%, salt expansion can occur in the range of 283.15 K–303.15 K (10°C–30°C), and the salt expansion of sulfate saline soil with salinity of 2%, 3%, and 5% decrease with the increase of temperature. It can be seen from reference [19] that, under one atmosphere and the CRH, the enthalpy change  $\Delta H_r^0$  is  $-522.28$  KJ/mol in equation (1), and Gibbs free energy,  $\Delta G_r^0 = -522.28 + 1.446699(T + 273.15)$ . When the temperature is 10°C,  $\Delta G_r^0 = -112.56$  KJ/mol. When the temperature is 30°C,  $\Delta G_r^0 = -83.62$  KJ/mol. Therefore, in the range of 283.15 K–303.15 K, Gibbs free energy is less than zero. Equation (1) can spontaneously react to form sodium sulfate decahydrate crystals in sulfate saline soil, and then salt expansion occurs. Considering that enthalpy change is less than zero in equation (1), equation (1) can be considered as an exothermic reaction. Reducing temperature is beneficial to the positive reaction of equation (1) and promotes the formation of sodium sulfate decahydrate crystal by sodium sulfate. On the contrary, the increasing temperature is beneficial to the inverse reaction of equation (1) and promotes the formation of sodium sulfate decahydrate by sodium sulfate, leading to the reduction of salt expansion. Meanwhile, Figure 6 shows that, when the RH is 90% and the temperature is constant between 10°C and 30°C (with an interval of 5°C), the salt expansion of sulfate saline soil increases with the increase of salinity. When the salinity increased, the absolute amount of sodium sulfate increased. Therefore, under constant RH and temperature conditions, the more the sodium sulfate decahydrate crystals are produced, the larger the salt expansion displacement.

**5.4. Relative Humidity Effect on the Salt Expansion Rate of Sulfate Saline Soil.** Figure 7 shows the influence curve of RH in pores on the salt expansion rate of sulfate saline soil. The salt expansion rate of sulfate saline soil increases with the increase of RH when the salinity is 2% and the constant temperature is 10°C (Figure 7(a)). Theoretically, with the increase of RH, the absolute amount of water vapor increases in the sample pore, the vapor pressure increases correspondingly, the diffusion rate of water vapor to sodium sulfate particles increases, the reaction rate of sodium sulfate hygroscopicity converting to sodium decahydrate crystal increases, and the salt expansion rate also increase. Meanwhile, Figures 7(b) and 7(c) show that when the salinity is 3% and 5%, the salt expansion rate of sulfate saline soil increases with the increase of RH at a constant temperature of 15°C, 20°C, 25°C, and 30°C, respectively.

**5.5. Temperature and Salinity Effects on the Salt Expansion Rate of Sulfate Saline Soil.** Figure 8 shows that the salt

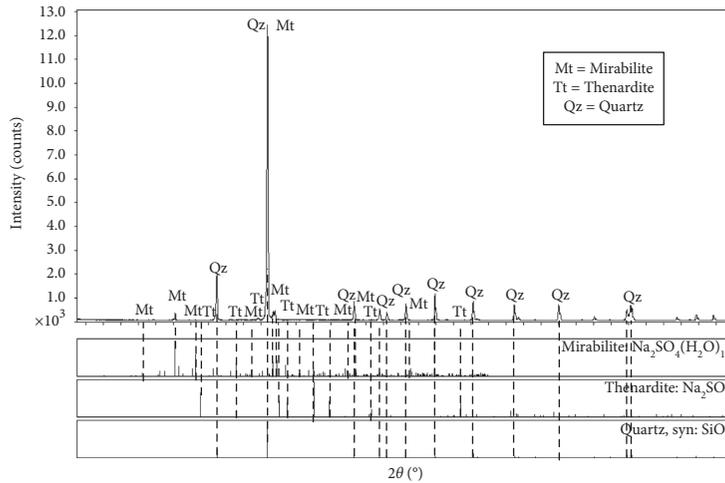


FIGURE 4: XRD results.

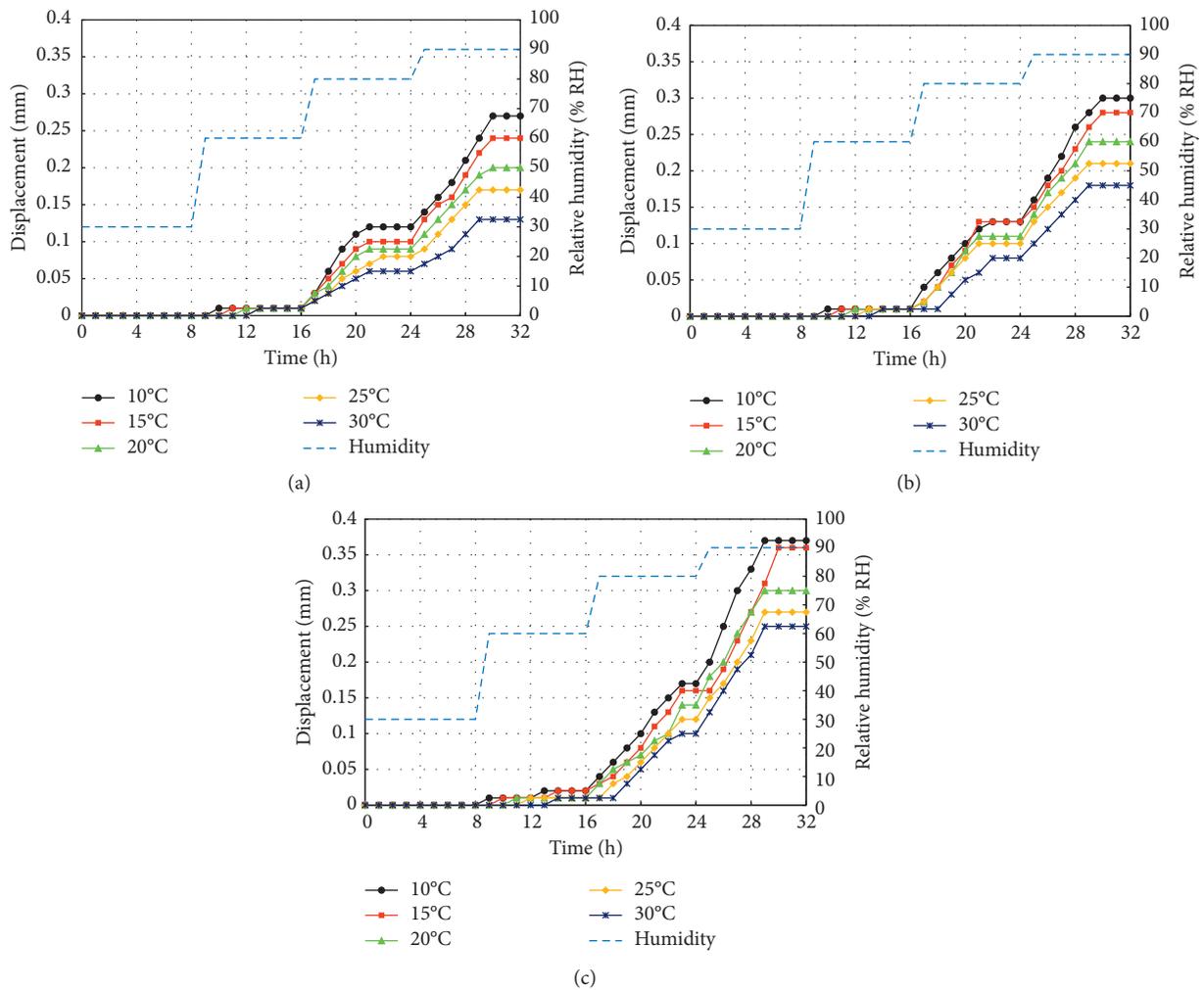


FIGURE 5: Displacement curve of different salinity of sodium sulfate saline soil under the RH. (a) 2% salinity; (b) 3% salinity; (c) 5% salinity.

expansion rate of sulfate saline soil decreases with the increase of temperature, under the condition that the RH of gas in the sample pore is 90% and the salinity remains

constant. As it is mentioned above, under one atmosphere and above the CRH, equation (1) reacts spontaneously and sodium sulfate absorbs moisture to form sodium sulfate

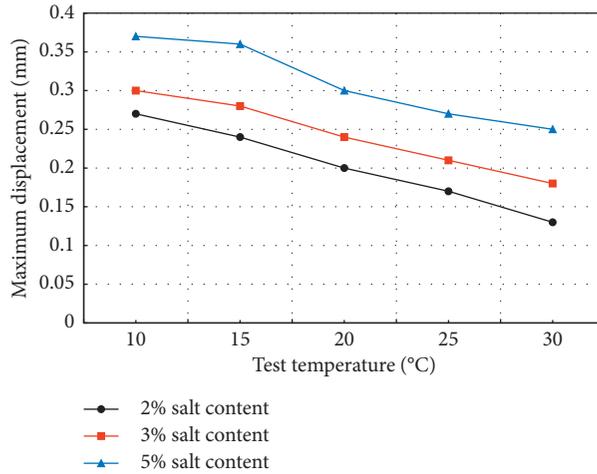


FIGURE 6: Maximum salt expansion displacement corresponding to temperature and salinity.

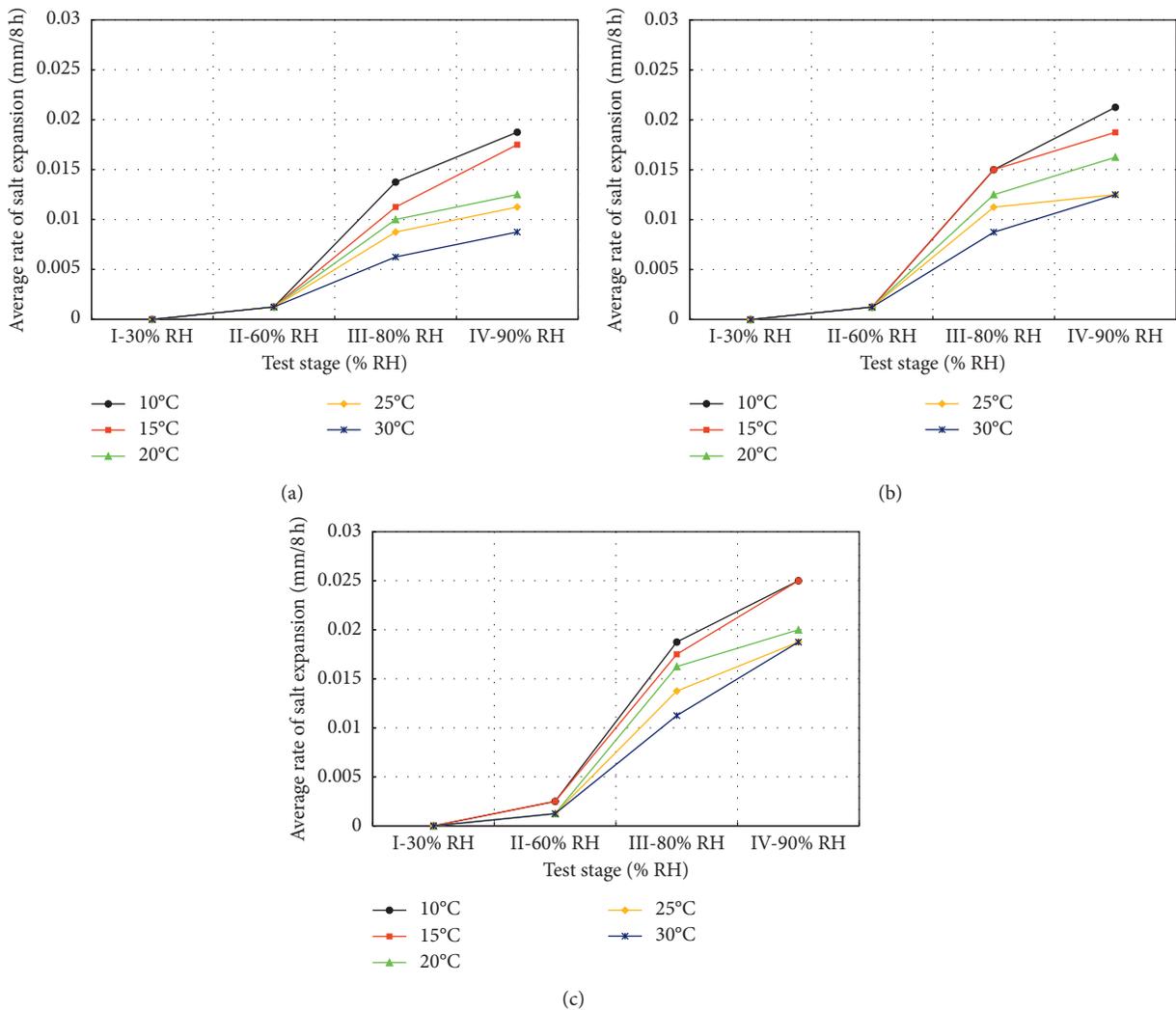


FIGURE 7: Salt expansion rate of sodium sulfate saline soil affected by RH. Salt content at (a) 2%, (b) 3%, and (c) 5%.

decahydrate crystal. According to the Arrhenius equation  $k = Ae^{-Ea/RT}$  [25], where  $k$  is the rate constant of chemical reaction,  $R$  is the constant of molar gas,  $T$  is the

thermodynamic temperature,  $Ea$  is the table activation energy, and  $A$  is a preexponential factor. With the increase of the temperature, the rate constant increases, the reaction rate

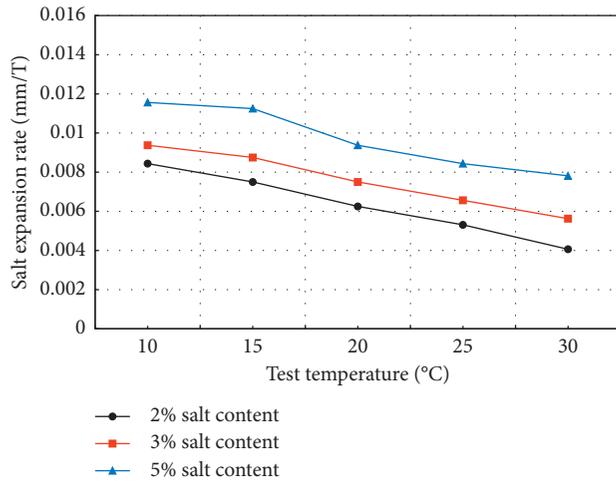


FIGURE 8: Salt expansion rate of sodium sulfate saline soil affected by temperature and salinity.

of sodium sulfate to form sodium sulfate decahydrate increases, and the rate of sodium sulfate decahydrate crystals increases. But equation (1) is the exothermic reaction. Increasing the temperature promotes the dehydration of sodium sulfate decahydrate crystals to form sodium sulfate. Thereby, it reduces the rate of sodium sulfate decahydrate formation, leading to the decrease of the sulfate expansion rate of sulfate saline soil. Figure 8 shows that the salt expansion rate of sulfate saline soil increases with the increase of salinity under the condition that the RH in the sample pore is 90% and the temperature is constant. According to the chemical reaction rate equation [25], increasing the salinity can be considered as increasing the concentration of reactants. The reaction rate and the formation rate of sodium sulfate decahydrate crystals increase so that the salt expansion rate is increased.

**5.6. Discussion on the Salt Expansion of Sulfate Saline Soil.** These test results show that the maximum salt expansion displacement of sulfate saline soil in this experiment is 0.27 mm under the condition of 2% salinity, 10°C constant temperature, and 90% RH, while Zhang [10] reported that the maximum salt expansion of sand sulfate saline soil with similar condition (2% salinity and 8% water content) is 0.88 mm. The maximum salt expansion of this test is about 30% that of Zhang et al. [10], indicating the vaporous water also plays an indispensable role in the salt expansion of sulfate saline soil. In addition, the salt expansion is obviously less affected by temperature and vaporous water. This may be because that sodium sulfates in the soil can form mirabilite crystals in different forms, depending on the degree of wetting and drying of the soil. In this experiment, the mirabilite crystals formed in the dry sulfate saline soil under the vaporous water circulation are often powdery, while the crystals formed in sulfate saline soil with certain water content under the same conditions are often in massive. The particle size of powdered mirabilite is smaller than that of massive mirabilite. And powdery crystals easily fill the pores of the soil, while massive crystals will directly squeeze the soil

due to their large volume, which may be one of the main reasons for the difference of salt expansion of between vaporous water and liquid water [10, 12]. Therefore, it is inferred that salt expansion of unsaturated sulfate saline soil is affected not only by liquid water in the soil but also by vaporous water; thus, salt expansion affected by vaporous water cannot be ignored.

As shown in Figures 5–8 of this article, the decrease of temperature is conducive to salt expansion and the increase of RH promotes the generation of salt expansion under the effect of temperature and vaporous water. This is consistent with the results under liquid water content [4, 10, 15], but the mechanism of salt expansion under vaporous water is different from that under liquid water content. The decrease of external environmental temperature will reduce the temperature of soil internal environment. In sodium sulfate saline soil with vaporous water, the low temperature and high RH make the thenardite in sulfate saline soil transfer into mirabilite according to phase diagrams for sodium sulfate (Figure 1) and equation (1), while in sulfate saline soil with liquid water, the low temperature and relative high water content are based on the curve of sodium sulfate solubility.

In addition, standard sand with uniform gradation distribution is used to prepare dry sulfate saline soil samples for the tests in this paper, while salt expansion of sulfate saline soil is also significantly affected by the particle size distribution, density, porosity, and overlying load of the soil sample [5, 10–14, 20, 26]. The effects of these factors on salt expansion are more complicated [10, 13, 14], which need to be verified by further research.

The test scale has a great influence on the test results. The scale chosen in this test is the space limitation of CTHTC and is fully considered in combination with the field conditions [4, 10]. What is more, in order to eliminate the significant influence of the test scale on the test results, this paper adopts the testing device with the same scale. Theoretically, the increase of the sample scale will increase the total salt expansion value, but the salt expansion rate will decrease accordingly. In this regard, further experimental research is needed to explore the influence law of scale effect.

## 6. Conclusions

In this paper, the salt expansion law of sulfate saline soil under the action of salinity, temperature, and vaporous water is studied experimentally, and the following conclusions are obtained:

- (1) At 10°C–30°C, when the RH of air in pores exceeds the CRH, the sodium sulfate in the sulfate saline soil absorbs moisture to form sodium sulfate decahydrate crystals and the volume expands to 3.4 times, causing salt expansion of sulfate saline soil.
- (2) The salt expansion of sulfate saline soil increases with the increase of RH and salinity but decreases with the increase of temperature. Salt expansion rate of sulfate saline soil increases with the increase of RH and

salinity while decreases with the increase of temperature.

- (3) Vaporous water can promote the salt expansion of sulfate saline soil. Controlling the content of vaporous water in sulfate saline soil area was conducive to reducing salt expansion. This research perfects the salt expansion mechanism of sulfate saline soil, guiding the study of new treatment methods of sulfate saline soil.

### Data Availability

The figure and table data used to support the findings of this study are included within the article. The test result data used to support the findings of this study are available from the corresponding author upon request.

### Conflicts of Interest

The authors declare that they have no conflicts of interest.

### Acknowledgments

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