


## Research Article

# Experimental Study of Evaporation Flux, Salt Precipitation, and Surface Temperature on Homogeneous and Heterogeneous Porous Media

Xinhu Li <sup>1,2,3</sup> and Min Guo<sup>1,2,3</sup>

<sup>1</sup>State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China

<sup>2</sup>Akesu National Station of Observation and Research for Oasis Agro-Ecosystem, Akesu 843017, Xinjiang, China

<sup>3</sup>University of Chinese Academy of Sciences, Beijing 100049, China

Correspondence should be addressed to Xinhu Li; [lixinhu@ms.xjb.ac.cn](mailto:lixinhu@ms.xjb.ac.cn)

Received 24 May 2022; Accepted 8 August 2022; Published 29 August 2022

Academic Editor: Zaher Mundher Yaseen

Copyright © 2022 Xinhu Li and Min Guo. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Salt precipitation in porous media is widespread, which has garnered great research attention. However, the mechanisms governing the salt precipitation, water flux, and surface temperature changes in homogeneous and heterogeneous porous media remain unclear. This study investigated the dynamics of salt precipitation, evaporative loss, and surface temperature in homogeneous fine sand (0.1–0.25 mm), coarse sand (1–2 mm), and a heterogeneous column with fine and coarse sand. All sand columns were initially saturated with NaCl solution. The experimental results showed that the salt was precipitated as efflorescence above the surface of the fine sand, whereas it was mainly precipitated as subflorescence below the surface of the coarse sand, causing the unconsolidated sand to form a strong stone-like mass. The evaporated loss was significantly higher in heterogeneous than in homogeneous sand, but this difference in evaporation was insignificant in the stage where vapor diffuses through the precipitated salt to the external air. The salt crust formed not only decreased the surface temperature due to increased albedo by salt precipitation, but also resulted in a more discrete temperature distribution in the porous media. Our research results can promote further understanding of salt precipitation and evaporation in porous media.

## 1. Introduction

A high concentration of dissolved salts usually causes salt precipitation in porous media [1, 2]. Salt precipitation in porous media is widespread and occurs in various systems, including soil, rocks, bricks, and ceramics, which could influence the water flux, matrix, temperature, dust emission, and rock weathering; such systems have previously received significant scholarly attention [3–6]. For drying porous media, evaporation is typically described in three stages (S1–S3): a high and relatively constant evaporation stage (S1); a significant falling evaporation rate stage (S2); and a low and stable evaporation stage (S3). Similarly, Nachshon et al. [7] defined three stages to describe the evaporation from porous media with saline solution: a reduction of

evaporation due to the change in osmotic potential (SS1); a great falling evaporation stage due to the salt crust formed (SS2); a final stable and low evaporation stage (SS3), where the vapor diffuses through the salt crust to the external air. Previous studies have shown that salt precipitation exhibits significant differences in various media textures, which further influences evaporation.

Previous studies have shown that salt precipitation exhibits significant differences in various media textures, which further influences evaporation. For homogeneous media, the precipitated salt was discrete, forming a thicker salt precipitation, and covered the surface as a “patch” if the medium was coarser (i.e., particle size  $>200\ \mu\text{m}$ ) [8–10]; further, if the salt was covered as a patch, evaporation was not inhibited [11]. This was mainly because water transport

bypassed the salt crust-covered section and flowed to the salt-free section (no precipitated salt on the surface) by the external air. However, most of the studies only focused on the salt precipitation by NaCl on the surface, but salt might be precipitated within the porous media below the surface if the evaporation front is within the porous medium [8], which is called subflorescence [12, 13]. Theoretically, if the salt precipitated in pores of porous media and the porosity or pore size was decreased, the water transport should have also been inhibited, because the reduction of pore size or porosity of porous media would increase the resistance of the fluid transport and vapor diffusion [7, 12, 14]. We could deduce that the coarse sand surface dries faster than fine sand, which leads to less salt precipitated on the coarse sand surface, but more salt may be precipitated within the porous, probably inhibiting the evaporation. Therefore, the relationship between salt precipitation, evaporation, and texture of the matrix was still unclear.

For heterogeneous porous media, Nachshon et al. [7] investigated the process of saline evaporation from heterogeneous media based on a theory by Lehmann and Or [15], who found that capillary forces induced pore water or solution from the coarse sand flow to the finer pores, leading to most of the precipitated salt being accumulated on fine sand due to more water loss occurring in the fine section, while few salts were precipitated in the coarse sand section. However, another study reported that salt precipitation first appeared in coarser sections [16]. Existing studies agreed that heterogeneous media enhanced evaporation not only in SS1 and SS2, but also in SS3. However, these studies only considered salt that precipitated as efflorescence above the surface, and salt precipitation as subflorescence below the surface was neglected. Therefore, it was still unclear whether the evaporation was decreased in SS3 if salt was precipitated as subflorescence. Additionally, the dynamic surface flux is reflected by the variation in surface temperature [17, 18], and the surface temperature is also influenced by salt precipitation [19, 20]. The objective of this study was to investigate the effects of salt precipitation, evaporation flux, and surface temperature on homogeneous and heterogeneous porous media.

## 2. Materials and Methods

Sand was sieved to obtain 0.1–0.25 mm (fine sand) and 1.0–2.0 mm (coarse sand) (Figure 1(a)) samples. The obtained sand was repacked into a polyvinyl chloride column which is 10 cm high and has an inner diameter of 5 cm. The experiment consisted of three treatments: (1) homogeneous fine sand, (2) homogeneous coarse sand, and (3) a heterogeneous column with equal amounts of fine and coarse sand (Figure 1(b)). The bulk density was  $1.59 \text{ g}\cdot\text{cm}^{-3}$  and  $1.65 \text{ g}\cdot\text{cm}^{-3}$ , and the saturated water content was 39.2% and 35.2% for fine sand and coarse sand, respectively. The capillary rise was 55.4 and 11.1 cm for fine sand and coarse sand, respectively. Each treatment included three replications, and a total of 9 columns were used in this experiment. The heterogeneous

sand column (Figure 1(c)) was similar to that reported by Nachshon et al. [7]. The homogeneous columns (fine and coarse sand) used for determining salt precipitation patterns (discrete or subflorescent salt precipitation) as evaporation progresses were formed with increased grain size. The heterogeneous columns were used to verify whether the heterogeneous composition could enhance evaporation, particularly in SS3. They were also used to clarify the controversy about which salt precipitation pattern is preferred on fine or coarse sand sections.

The evaporation was derived by the lamp; the lamp heated only the upper surface of the sample to induce evaporation (Figure 1(c)). The relative humidity was  $26 \pm 7\%$ , and the room temperature was  $22 \pm 1.2^\circ\text{C}$  during the experiment. The sand column was weighed to record water loss over time. All sand columns were initially saturated with saline water (NaCl, 17.5%). A digital camera was used to take pictures from the surface of the sand to determine the cover fraction of precipitated salt. A thermal camera (FLIR T540, FLIR Systems, Inc.) was employed to capture the thermal infrared images of the surface of the sand soil columns, and the FLIR Tools software was used to compute the surface temperature.

## 3. Results

**3.1. Salt Precipitation.** The salt precipitation distribution showed great differences for different treatments (Figures 2 and 3). For homogeneous sand columns, the cover fraction of salt precipitation reached over 80.0% on the second day for fine sand columns (Figure 2(a)) but only 2.4% for coarse sand columns (Figure 2(b)). Salt precipitation was relatively uniform over the surface of the fine sand. However, the precipitated salt was very discrete for coarse sand, and the salt precipitation was concentrated in several individual locations (Figures 2(a) and 2(b)). Salt precipitation continued to grow after several days, but the precipitation showed very minor changes for coarse sand after the second day. The fine sand surface was completely covered by the precipitation after the fifth day, but only several discrete locations were covered by precipitated salt of coarse sand until the experiment ended. Excluding the later progression of salt precipitation, the upward growth of salt precipitation was clearly observed, forming some salt domes on the fine sand surface (Figure 2(a)). This did not occur in the coarse sand sample (Figure 2(b)).

For the heterogeneous sand columns, a significant difference in the salt precipitation distribution between the fine and coarse sand columns was clearly observed. Salt precipitation was first observed at the interface between the fine and coarse sand, and also coarse sand sections (Figure 3). The fraction of salt precipitation was 26.1% on the first day for heterogeneous sand. Although salt precipitation was first found on the surface of the coarse sand section, more salt was precipitated on the surface of the fine sand section, and the salt precipitation continuously increased and showed upward growth.

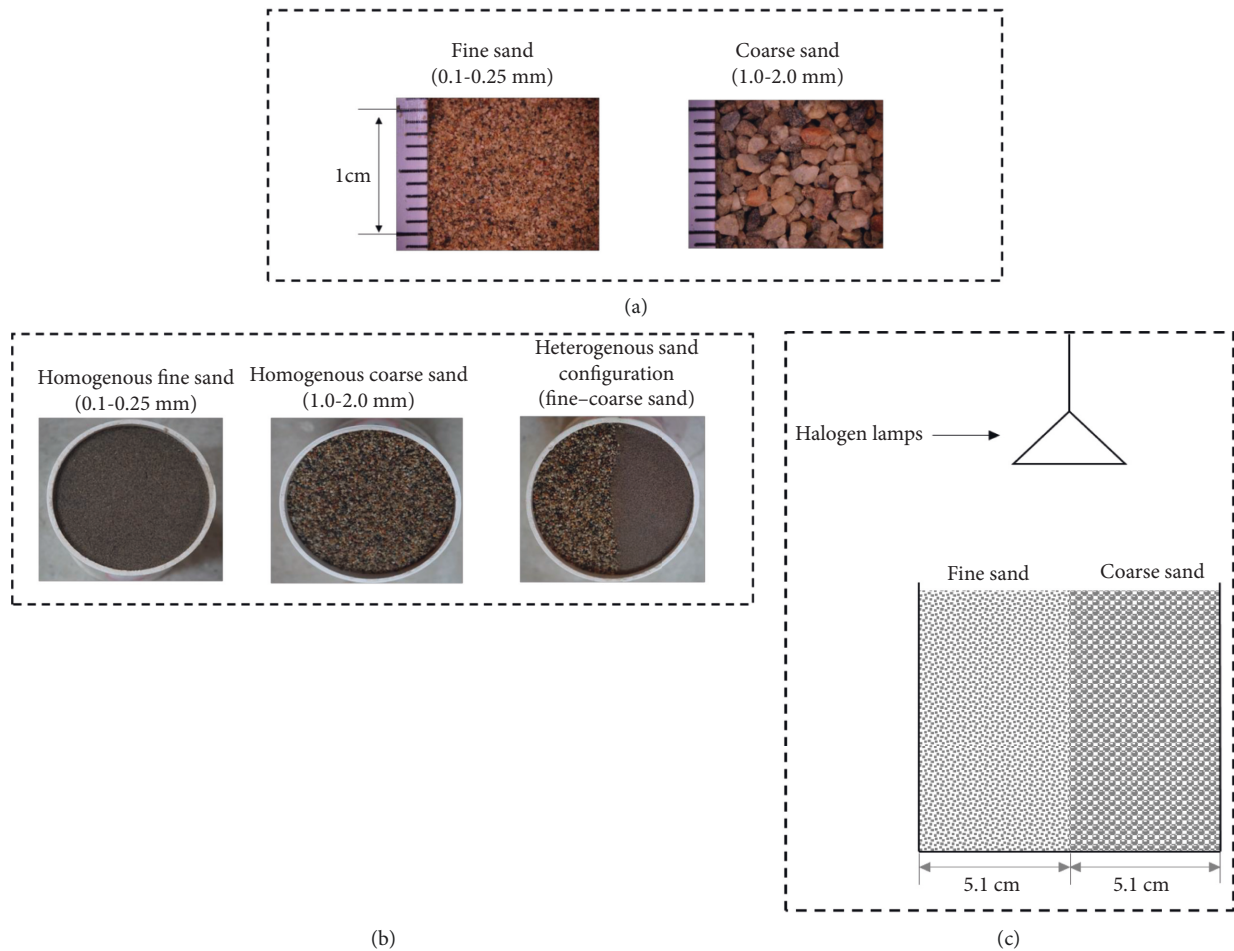


FIGURE 1: Experimental setup: (a) sand grade under microscope; (b) experimental treatment; (c) configuration of heterogeneous sand column.

**3.2. Evaporation Flux.** The dynamic variation of evaporated loss and accumulated evaporated loss is shown in Figures 4(a) and 4(b). For the homogeneous sand columns, the coarse sand showed a faster decrease in evaporation (Figure 4(a)). SS1 remained for only one day for homogeneous sand columns. A sharp decrease in the evaporation rate was observed on the second day for all homogeneous sand columns (SS2), and the water loss decreased by over 59%, which was different from the typical evaporation stage of pure water in S2. However, water loss was mainly inhibited by salt precipitation in SS2, particularly in fine sand. The whole media surface is usually considered to be covered by a salt layer in SS2; thus, the water loss was inhibited by precipitated salt instead of water content [19, 21]. A gradual decrease was observed after the third day and became stable after the 10<sup>th</sup> day (SS3). Typically, water loss dominated by vapor diffusion (SS3) shows a stable and low evaporation for saline water evaporation in porous media. The evaporated loss was 4.6 g and 2.0 g for fine sand and coarse sand on the last days, respectively (Figure 4(a)).

Compared with homogeneous sand columns, the heterogeneous sand column showed a higher evaporation rate (Figure 4(b)). The water loss was 66.3 g for heterogeneous sand columns on the first day and was higher for all

homogeneous sand columns (Figures 4(a) and 4(b)). The water loss was 46.9 g for heterogeneous sand columns on the second day; it was only decreased by 29.3%, which was significantly less ( $p < 0.01$ ) than that of all homogeneous sand columns (Figures 4(a) and 4(b)), indicating that the heterogeneous sand column enhanced the evaporation (Figure 4(b)). The evaporation became low and stable after 11 days, and the water loss was 4.0 g in the last days for the heterogeneous sand columns. There was no significant difference in the homogeneous fine sand in the evaporation stage in which water loss by vapor diffusion indicated that the heterogeneous column enhanced evaporation in SS1 and particularly in SS2, but not in SS3.

**3.3. Surface Temperature and IRT Image.** The initial surface temperature was mostly consistent before the experiment for all sand columns, but the surface temperature exhibited changes when the experiment began (Figures 2, 3, and 5). Although all columns were exposed to the same radiation, a significant difference was observed in the heterogeneous column between the fine and coarse sand sections (Figure 3). For the homogeneous sand column, the temperature increased rapidly on the first day and was 36.5°C and 40.5°C for

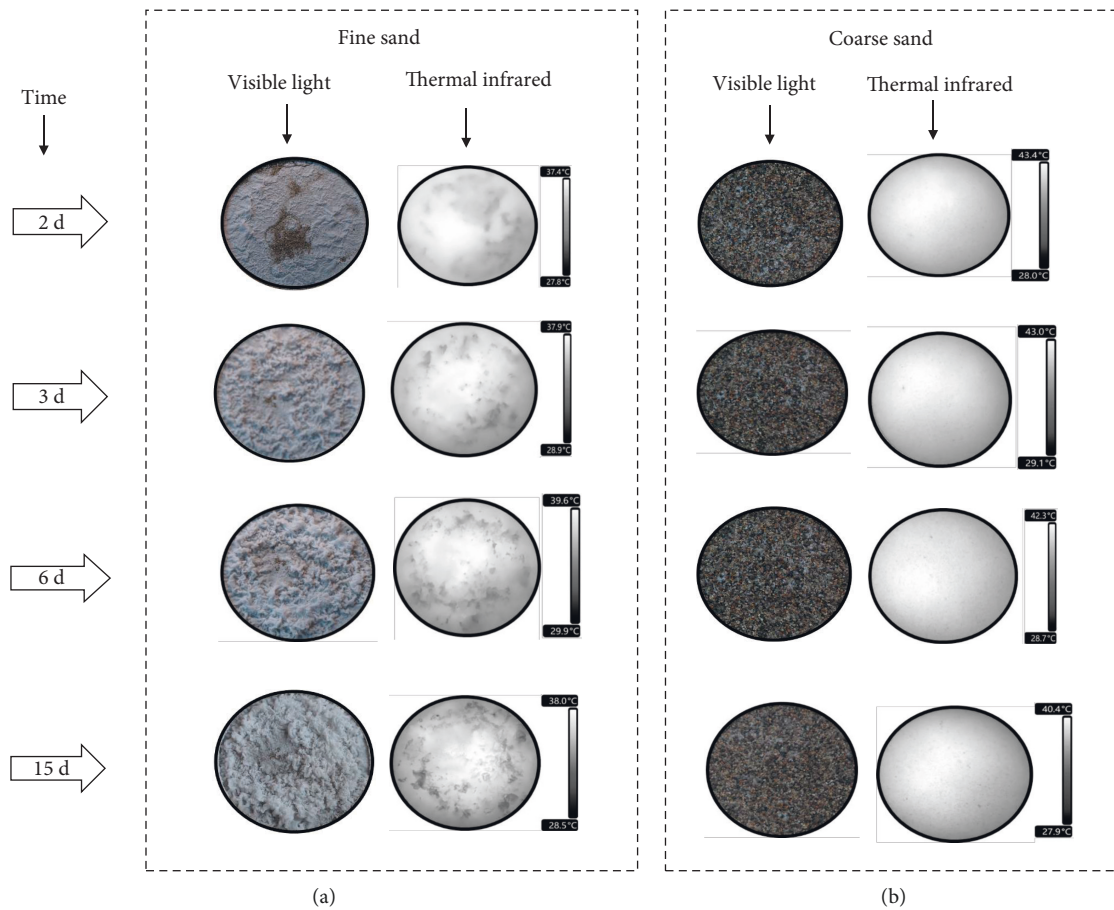


FIGURE 2: Dynamic variation in salt precipitation (visible light images) and thermal infrared images for homogeneous sand columns: (a) fine sand; (b) coarse sand.

fine and coarse sand columns, respectively. Then, the temperature was relatively stable with some fluctuations. However, the temperature fluctuation was smaller in fine sand than in coarse sand.

For example, the coefficient of variation of temperature was 1.37% and 1.96% after the first day for fine and coarse sand columns, respectively. The temperature ranged from 35.6 to 37.3°C (mean: 36.3°C) for the homogeneous fine sand column and from 39.6 to 42.6°C (mean: 40.3°C) for coarse sand during the experiment. For heterogeneous sand, the temperature increased rapidly on the first day, and similar to homogeneous sand, it was 37.2°C but then fluctuated. The heterogeneous sand sample ranged from 36.6 to 38.9°C, with a mean value of 37.7°C. The order of surface temperature from high to low was as follows: homogeneous coarse sand > heterogeneous sand > homogeneous fine sand. These findings are consistent with those of the salt precipitation cover area, indicating that the surface temperature was decreased by salt crust formation.

For homogeneous sand, the IRT image clearly showed some cold spots on the surface of the salt crust, and these cold spots became more discrete as salt precipitation continued (Figure 2). However, the cold spots were not observed in the coarse sand, and the temperature showed a relatively

uniform distribution, indicating that the salt crust not only decreased the temperature but also made the surface temperature distribution more discrete in porous media. For heterogeneous sand, a significant temperature difference was observed between the fine and coarse sand (Figure 3). A lower temperature was observed in the fine section than in the coarse section in the first 12 h, indicating that the coarse sand was fast dried. The temperature showed a relatively uniform distribution in the fine section (first 12 h), because the salt crust was not formed in the fine section at that time. The temperature was still lower in the fine section than in the coarse section when the salt crust was formed. Some cold spots were also found in the fine section when the salt crust formed; conversely, these cold spots were not observed in the coarse section, and the temperature distribution was relatively uniform. This further indicates that the salt crust formation resulted in increasing discretization of the temperature distribution. These cold spots in the salt crust for both homogeneous and heterogeneous sand changed during the growth of salt precipitation, and some cold spots were located in salt domes, indicating that the temperature distribution on the surface of the porous media was influenced by salt crust growth.

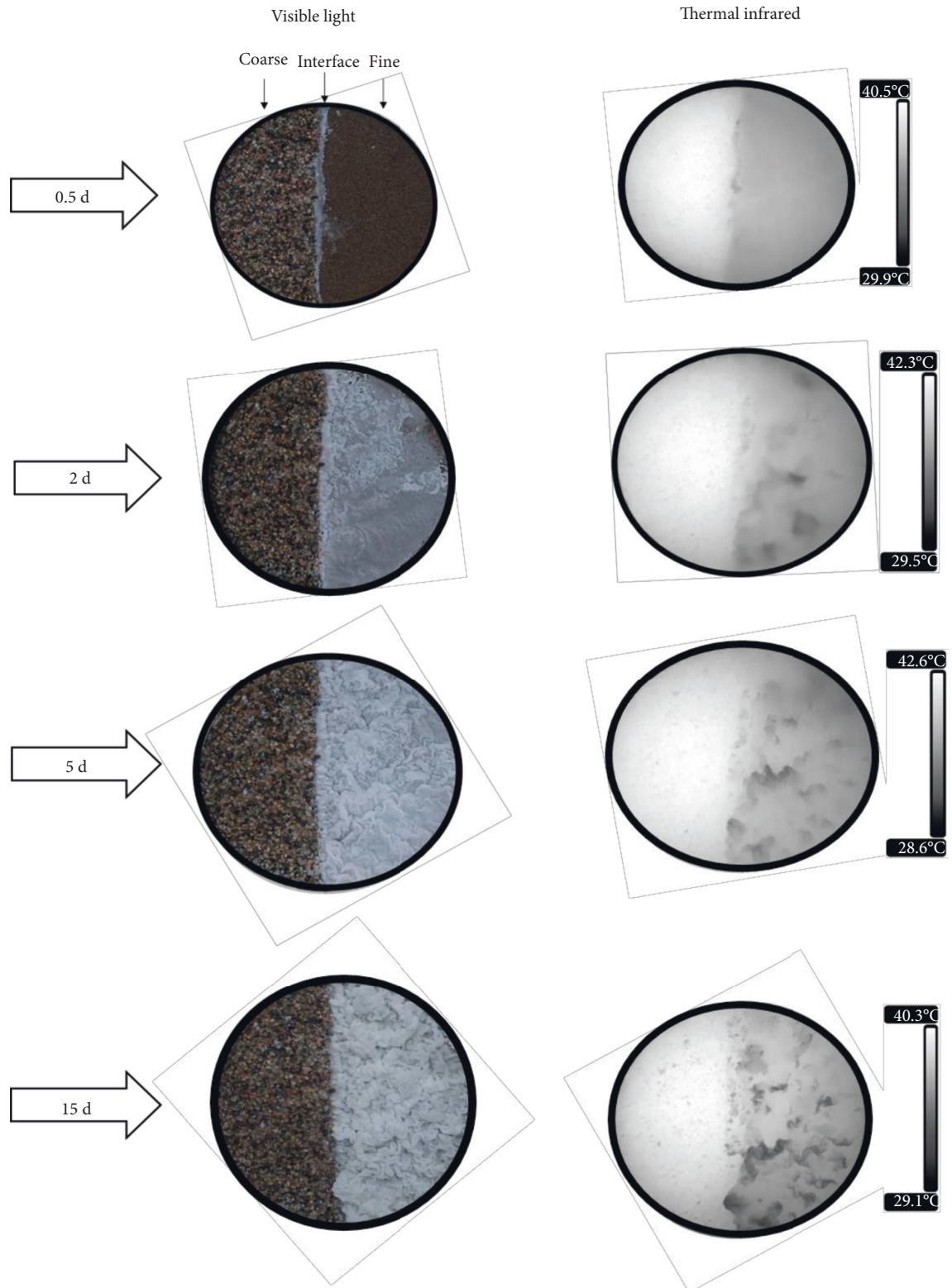


FIGURE 3: Dynamic variation in salt precipitation (visible light images) and thermal infrared images for heterogeneous sand columns.

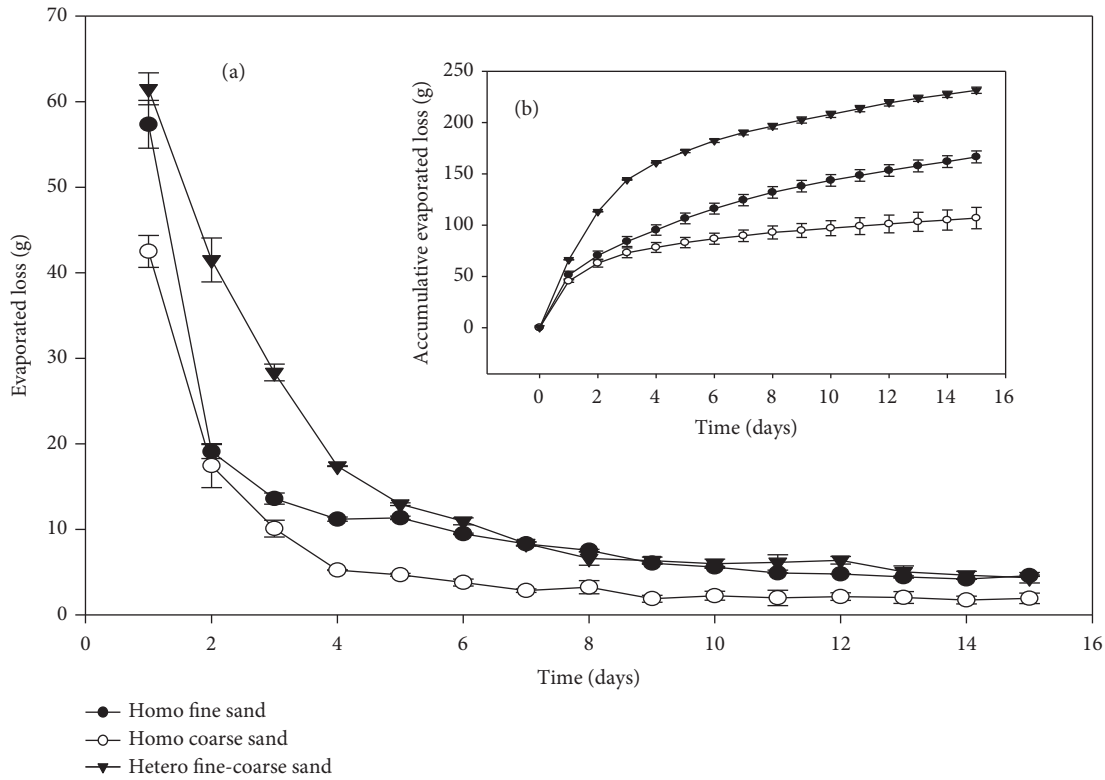


FIGURE 4: Dynamic variation of evaporation loss with time for three treatments: (a) evaporative loss with time; (b) accumulative evaporated loss.

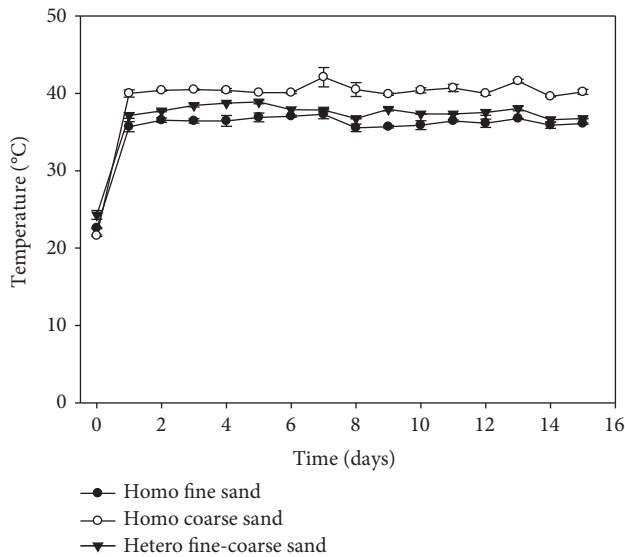


FIGURE 5: Dynamic variation in surface temperature with time.

## 4. Discussion

### 4.1. Salt Precipitation

**4.1.1. Salt Precipitation in Homogeneous Media.** In our research, the salt was relatively uniformly precipitated in fine sand but was very discrete in coarse sand, which has been

reported by several studies [8, 10, 11, 22]; our findings partly agree with those of the studies. Compared with coarse sand, the precipitated salt completely covered the surface of fine sand, but discrete salt precipitation covered only a small fraction of the surface area of coarse sand (Figure 2). However, significant upward growth of salt structures was not observed in coarse sand and was only found in fine sand. This difference likely occurred due to the rapid drying of coarse sand in our experiment, resulting in the evaporation front receding below the surface. Consequently, the hydraulic connection between the surface and the solution was disrupted, and the solution could not reach the surface to form salt precipitation. Figure 2 clearly shows that the salt precipitation exhibited very minor changes after the second day for coarse sand, and the IRT image showed a high and relatively uniform temperature distribution, indicating that this hydraulic connection was disrupted in the early stage and was limited to the growth of salt precipitation. Drying was faster than that in the above studies because of the different experimental conditions. The samples were placed in a chamber, and the temperature was controlled at approximately 30°C [11] and 35°C [10]. However, in our research, the evaporation was driven by a lamp, and the high surface temperature reached 41°C on the first day (Figure 5). Therefore, the upward growth of salt precipitation or thick salt crust was not observed in coarse sand.

However, upward salt growth was observed in fine sand, although this increase in salt growth did not simply increase the thickness but formed a salt dome (Figures 2 and 3). Salt

precipitation by NaCl tends to form salt domes over the matrix surface, resulting in a salt crust that was separated from the sand surface, which has been reported in several studies [23–27]. Figure 6(a) clearly shows that salt domes were formed on the surface of fine sand, and some salt crust was elevated and separated from the sand surface. These salt domes were observed in the first several days, and more salt domes were formed in the next several days. The height of the salt domes also increased with time in the fine sand. The upward growth of salt precipitation to form salt domes has been investigated in various media textures [23–28], but no studies have reported that it is related to particle size. Therefore, this study presents new insights into the relationship between the pattern of salt precipitation and texture of the matrix.

*4.1.2. Salt Precipitation in Heterogeneous Media.* Our experimental results indicate that salt precipitation was first found in coarser sections because the drying front first invaded, but the salt was not continuously precipitated due to the dry surface. The salt accumulated at the interface because of the important contribution of evaporation through the vertical fine–coarse interface. More salt was precipitated in the fine section because water flowed from the coarse to fine sand due to the difference in capillary pressure to provide more water loss in the fine section [7]. Our research results agree with those of Nachshon et al. [7], who also reported salt precipitation mainly located on the surface of the fine section.

*4.1.3. Salt Precipitation within the Matrix.* The salt crystal was found within the matrix of coarse sand in our experiment (Figure 6(b)). When the evaporation front is within the porous medium, salt crystals may precipitate inside the porous medium; this is called “subflorescence” [8]. The salt precipitated below the surface due to the fast drying of coarse sand, and the evaporation front receded below the surface. Figure 6(b) clearly shows that the salt was precipitated within the matrix and the cement sand particles formed a very strong massive texture like the stone. This strength was beyond the measuring range of a handheld penetrometer (Model FDN 32, Wagner Instruments, Greenwich, CT). A similar phenomenon was also observed in homogeneous coarse sand. The coarse sand section could be easily removed because the sand had formed a hard mass. Figure 6 clearly shows that the salt was precipitated at different locations in the fine and coarse sand. Salt precipitation tended to occur on the surface of fine sand and exhibited upward growth to form salt domes, but little salt was precipitated on the surface of coarse sand.

Salt is precipitated above or below the surface within the media pores, depending on the salt type and the location of the evaporation front, that is, whether the evaporation front is located on the surface or within the matrix [13]. Only NaCl solutions were used in our experiment; therefore, the salt was precipitated within the matrix profile mainly because the hydraulic conditions changed, and the evaporation front receded within the coarse sand profile, resulting in salt

precipitation occurring above the evaporation front. However, several studies [7, 12] reported that the salt was precipitated just below the surface in the order of a few millimeters and evaporation occurred at the matrix surface. However, in our study, a thick salt layer below the surface of coarse sand was found (Figure 6(b)), which has not been reported by previous studies.

## 4.2. Evaporation

*4.2.1. Evaporation Process for Homogeneous Media.* The evaporation rate was the lowest on the first day in coarse sand and then showed a sharp decrease on the second day. This was attributed to fast drying rather than salt precipitation, because only a small amount of salt precipitated on the surface. The fast drying caused the evaporation front to recede below the surface, resulting in a sharp decrease in evaporation. Typically, a coarse porous medium with larger pores has a short S1 [29]. The evaporation loss in fine sand was higher than that in coarse sand on the first day, followed by a decrease in evaporation, similar to coarse sand. However, this decrease was mainly attributed to the salt crusts formed.

*4.2.2. Evaporation Process for Heterogeneous Media.* A higher evaporation rate was found in the heterogeneous sand columns than in the homogeneous fine sand columns. This difference was mainly observed for SS1 and SS2. Several studies have reported the use of pure water and saline water [13, 15, 16]. The main reason was that the water flows could move from coarse to fine sand when the surface of coarse sand was drying. Consequently, it could sustain more evaporation in the fine section than in the homogeneous fine sand. Additionally, evaporation was also contributed by a vertical interface between the coarse and fine sand. Nachshon et al. [7] reported that the interface contributes to water loss of approximately 47% of the total. In our research, salt precipitation was clearly observed in the first 12 h, indicating that this interface contributed to evaporation in the early stage, hence the higher evaporation in heterogeneous sand than in homogeneous fine sand in SS1 and SS2.

Our experimental results indicate that the heterogeneous sand configuration enhanced evaporation in SS1 and SS2, but the difference between the heterogeneous and homogeneous sand was insignificant in SS3. Nachshon et al. [7] reported that the evaporation rate for the heterogeneous column was significantly higher than that for the homogeneous fine sand in SS3 because this relatively salt-uncovered area provided a bypass for vapor blocked by salt. Similar results were reported in a numerical simulation by Mejri et al. [16]. Our research results do not agree with the two studies, despite the salt distribution being almost consistent on the surface. One probable reason for this is that the salt crystal was found within the matrix of coarse sand in our experiment (Figure 6(b)). A similar phenomenon was also observed in homogeneous coarse sand. Salt precipitation occurred inside the media of coarse sand, which blocked the pores within the matrix and inhibited vapor diffusion



FIGURE 6: Heterogeneous column after the experiment. (a) The salt crust was elevated and formed salt domes. (b) The salt precipitated below the surface of coarse sand.

(Figure 7(b)); therefore, the difference was insignificant for evaporation between the heterogeneous and homogeneous sand in SS3. Our research results did not agree with those of Nachshon et al. [7] owing to a lower solution concentration being used in our experiments (5% NaCl was used in their experiment, while 17.5% NaCl was used in our work) and a numeric simulated study by Mejri et al. [16]; the higher solution concentration tended to form salt crystals.

**4.2.3. Vapor Transport through Precipitated Salt.** If the media surface was covered by precipitated salt, the evaporation was considered a result of vapor diffusion through the precipitated salt (Figure 7); the reduction of evaporation is attributed to the increase in vapor diffusion resistance [7, 30]. Usually, the effective diffusion coefficient can reflect the physical properties of the salt layer. It can be calculated according to Fick's Law:

$$J = -D_s \frac{\Delta \rho_s}{\Delta L_s}, \quad (1)$$

where  $J$  is vapor diffusion flux ( $\text{kg s}^{-1} \cdot \text{m}^2$ ),  $D_s$  is effective diffusion coefficient for water vapor through the salt layer ( $\text{m}^2 \text{ s}^{-1}$ ),  $\rho_s$  is vapor concentration ( $\text{kg m}^{-3}$ ), and  $L_s$  is the thickness of the precipitated salt layer ( $m$ ). Considering the ideal gas behavior of water vapor, a model to describe the vapor transport the salt crust [21] is as follows:

$$J = D_s \frac{M}{RT} \frac{(p_b - p_s)}{L_s(t)}, \quad (2)$$

where  $p_b - p_s$  is vapor pressure difference at the bottom and on the surface of the salt crust,  $R$  is the gas constant,  $M$  is the molar mass, and  $T$  is the temperature of the gas ( $k$ ).

Usually,  $D_s/D_a$  can be used to characterize the porous media structure " $D_s=0.04 D_a$ " which has been reported by [7] for a similar texture (grain size: 0.1–0.3 mm) of fine sand and evaporation environment when salt precipitation is efflorescent (Figure 7(a)).  $D_a$  is vapor diffusion in free air.

In our research, salt was precipitated in a subflorescent manner within the media pores of coarse sand (Figure 7(b)), and previous studies have not reported this. The thickness of the salt layer in coarse sand was easily measured because the cement sand particles formed a very strong massive texture like a stone (Figure 6(b)). During drying, advection and diffusion will compete, as predicted by the Peclet number

( $Pe$ ) [31]. For  $Pe < 1$ , diffusion dominates, and the ion profiles will be uniform. The  $Pe$  was  $< 0.3$  for coarse sand treatment on the last five days of the experiment. We assumed that the thickness of the precipitated salt layer did not change on those five days.  $D_a$  was calculated by the following equation:

$$D_a = 2.29 \times 10^{-5} (T/273)^{1.75}. \quad (3)$$

The mean thickness of the precipitated salt layer was 0.03 m. We obtained  $D_s \sim 0.03 D_a$ , similar to efflorescently precipitated salt. For vapor diffusion through porous media without salt precipitation,  $D_{eff}$  is commonly employed:

$$D_{eff} = D_a \epsilon_a^{4/3}, \quad (4)$$

where  $\epsilon_a$  is air-filled porosity, assuming the sand has a residual water content of 0.05 for S3 and  $D_{eff} = 0.23 D_a$  for coarse sand. Evidently, the precipitated salt in both efflorescent and subflorescent manners significantly reduced the diffusion coefficient of vapor by almost an order of magnitude relative to vapor diffusion through porous media without salt precipitation. It is important to note that evaporation was less in coarse sand than in fine sand. The total evaporation observed with coarse sand was 59% that of fine sand. Usually, the mass of the precipitated NaCl is proportional to the mass of evaporated water [19, 21]. Consequently, the salt mass for subflorescent precipitation in coarse sand should be 59% that of efflorescent precipitation in fine sand.

Evidently, the calculated results showed less subflorescently precipitated salt in coarse sand (just 59% that of efflorescent salt) but an almost similar vapor diffusion resistance compared to efflorescent precipitation in fine sand. Our calculated results illustrate that heterogeneous media with salt precipitation cannot enhance evaporation in SS3 because subflorescent precipitation also reduces vapor diffusion. Vapor diffusion was simultaneously inhibited by efflorescent and subflorescent precipitation in heterogeneous media, different from previous studies [7]. Therefore, our research results provide new knowledge. This research result can promote further understanding of salt precipitation and evaporation in porous media.

Existing studies have focused more on salt precipitation above the surface of the matrix [4, 11, 20, 25, 32], but less attention has been paid to salt precipitation within the matrix profile. Our research results showed that salt



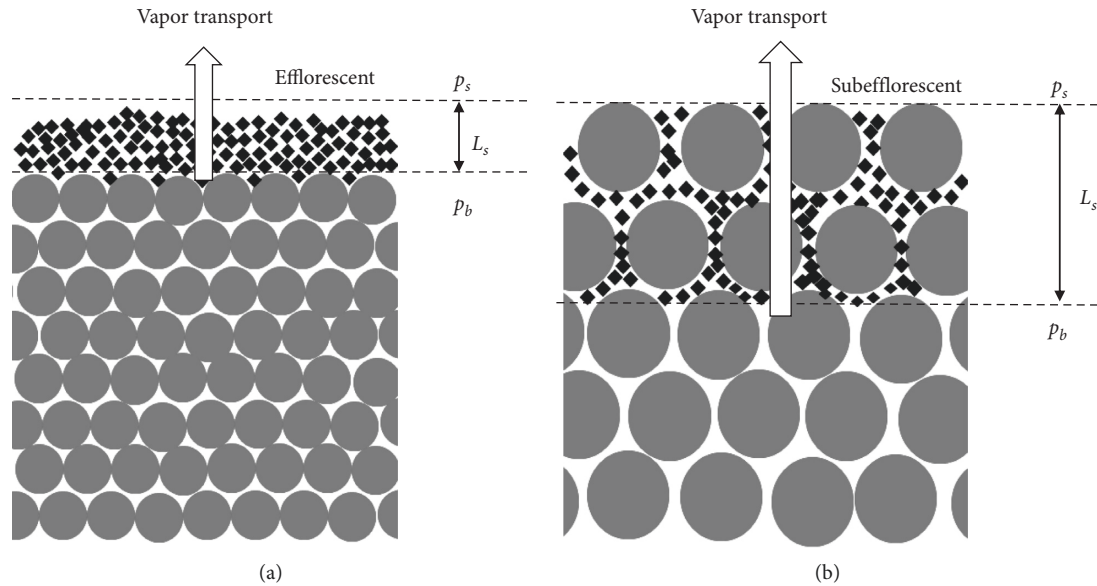


FIGURE 7: Scheme of vapor transport through efflorescently precipitated salt in fine sand (a) and (b) subefflorescently precipitated salt in coarse sand.

precipitation in coarse sand was limited by inhibited vapor diffusion and caused the sand to form a hardened stone-like mass, greatly changing the properties of porous media, and that although the subflorescently precipitated salt mass was less, a similar vapor transport resistance was observed compared to efflorescent precipitation. These findings may elucidate directions for future research.

**4.3. Temperature.** The experimental results showed that the surface temperature was higher in fine sand than in coarse sand, and this difference was also significant in the heterogeneous sand column (Figures 2, 3, and 5). This is probably because the soil albedo increased when the salt crust formed [33]. The IRT image showed that the temperature distribution was not uniform, with some cold spots on the salt crust, and these cold spots varied with the growth of salt precipitation (Figures 2 and 3). The cold spots on the salt crust have been reported by previous studies [20], because water vaporizes on the surface of the salt crust, indicating that the hydraulic connection between the precipitated salt and the solution remained. In our research, the area covered by the salt crust showed a lower temperature than that covered by salt on the first day (Figure 2(a)), indicating that the hydraulic connection between the precipitated salt and solutions remained on the first day. Then, this hydraulic connection was gradually disrupted, and the vapor diffusion was gradually dominated by water loss to the air, causing the area of cold spots to decrease. Fujimaki et al. [33] reported an expected tendency for albedo to correlate with the mass of precipitated salt; it is likely that the increase in the mass of salt precipitation caused the albedo to increase, which compensated for the decrease in cold areas; consequently, the temperature remained relatively stable. Additionally, cold spots were found at the top of the salt domes, indicating that the morphology of salt precipitation

may influence the temperature, which provides new insight to the surface temperature of saline soil. However, the correlation between surface temperature and changing salt crust was not perfectly explained by existing studies; thus, it should be considered in the future.

## 5. Conclusions and Recommendations

This study investigated the effect of salt precipitation, evaporative flux, and surface temperature on homogeneous and heterogeneous porous media. The laboratory experiment consisted of three treatments: (1) homogeneous fine sand, (2) homogeneous coarse sand, and (3) a heterogeneous column with fine and coarse sand. All soil columns were saturated with NaCl solution (17.5%). The main conclusions are summarized as follows:

- (1) For homogeneous sand, salt precipitation was uniformly distributed on the surface as efflorescence in fine sand and showed upward growth that formed some domes; however, salt precipitation was discrete on the surface of coarse sand, and more salt precipitated as subflorescence. The sand particle was cemented by such a subflorescent substance, which led to the former unconsolidated sand turning into a strong mass-like stone.
- (2) For heterogeneous sand configuration, although salt precipitation was first found on the surface of the coarse sand section, more salt was precipitated on the surface of the fine sand section, and the salt precipitation continuously increased and showed upward growth.
- (3) The evaporation was higher in the heterogeneous sand than in the homogeneous sand, but this evaporation difference was insignificant in the stage

where vapor diffuses through the precipitated salt to the external air. Although less salt was precipitated in a subflorescent manner, a similar vapor transport resistance was observed compared with efflorescent precipitation. Therefore, we suggest that subflorescence in porous media should be considered in the future.

- (4) The surface temperature was higher in the coarse sand than in the fine sand, and this difference was also significant between the fine and coarse sections in the heterogeneous sand column. The temperature distribution was relatively uniform for the area uncovered by salt but was more discrete for the areas covered by the salt crust. The cold spots were located in the salt dome, implying that the temperature might be influenced by the morphology of salt precipitation.

### Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

### Conflicts of Interest

The authors declare no conflicts of interest.

### Acknowledgments

This research was supported by the National Natural Science Foundation of China (Grant no. 41977013) and West Light Foundation of Chinese Academy of Sciences (Grant no. 2020-XBQNXX-012).

### References

- [1] X. Li and M. Guo, "The impact of Salinization and Wind Erosion on the texture of surface soils: an investigation of Paired samples from soils with and without salt crust," *Land*, vol. 11, no. 7, Article ID 11070999, 2022.
- [2] S. M. S. Shokri-Kuehni, M. Sahimi, and N. Shokri, "A personal perspective on prediction of saline water evaporation from porous media," *Drying Technology*, vol. 40, pp. 691–696, 2021.
- [3] L. Dong, Y. Xiong, Q. Huang, X. Xu, Z. Huo, and G. Huang, "Evaporation-induced salt crystallization and feedback on hydrological functions in porous media with different grain morphologies," *Journal Of Hydrology*, vol. 598, Article ID 126427, 2021.
- [4] S. M. S. Shokri-Kuehni, B. Raaijmakers, T. Kurz, D. Or, R. Helmig, and N. Shokri, "Water table Depth and soil Salinization: from pore-Scale processes to Field-Scale Responses," *Water Resources Research*, vol. 56, no. 2, Article ID e2019WR026707, 2020.
- [5] J. Piotrowski, J. A. Huisman, U. Nachshon, A. Pohlmeier, and H. Vereecken, "Gas Permeability of salt crusts formed by evaporation from porous media," *Geosciences*, vol. 10, no. 11, Article ID 10110423, 2020.
- [6] Y. W. Xiong, X. X. Long, G. H. Huang, and A. Furman, "Impact of pore structure and morphology on flow and transport characteristics in randomly repacked grains with different angularities," *Soils and Foundations*, vol. 59, no. 6, pp. 1992–2006, 2019.
- [7] U. Nachshon, N. Weisbrod, M. I. Dragila, and A. Grader, "Combined evaporation and salt precipitation in homogeneous and heterogeneous porous media," *Water Resources Research*, vol. 47, no. 3, Article ID W03513, 2011.
- [8] S. Veran-Tissoires, M. Marcoux, and M. Prat, "Discrete salt crystallization at the surface of a porous medium," *Physical Review Letters*, vol. 108, no. 5, Article ID 054502, 2012.
- [9] S. Veran-Tissoires, M. Marcoux, and M. Prat, "Salt crystallisation at the surface of a heterogeneous porous medium," *Europhysics Letters*, vol. 98, no. 3, Article ID 34005, 2012.
- [10] M. N. Rad, N. Shokri, A. Keshmiri, and P. J. Withers, "Effects of grain and pore size on salt precipitation during evaporation from porous media," *Transport in Porous Media*, vol. 110, no. 2, pp. 281–294, 2015.
- [11] H. Eloukabi, N. Sghaier, S. Ben Nasrallah, and M. Prat, "Experimental study of the effect of sodium chloride on drying of porous media: the crusty–patchy efflorescence transition," *International Journal of Heat and Mass Transfer*, vol. 56, no. 1–2, pp. 80–93, 2013.
- [12] E. Ruiz-Agudo, F. Mees, P. Jacobs, and C. Rodriguez-Navarro, "The role of saline solution properties on porous limestone salt weathering by magnesium and sodium sulfates," *Environmental Geology*, vol. 52, no. 2, pp. 269–281, 2007.
- [13] U. Nachshon and N. Weisbrod, "Beyond the salt crust: on combined evaporation and subflorescent salt precipitation in porous media," *Transport in Porous Media*, vol. 110, no. 2, pp. 295–310, 2015.
- [14] M. Gran, J. Carrera, S. Olivella, and M. W. Saaltink, "Modeling evaporation processes in a saline soil from saturation to oven dry conditions," *Hydrology and Earth System Sciences*, vol. 15, no. 7, pp. 2077–2089, 2011.
- [15] P. Lehmann and D. Or, "Evaporation and capillary coupling across vertical textural contrasts in porous media," *Physical Review E*, vol. 80, no. 4, Article ID 046318, 2009.
- [16] E. Mejri, R. Bouhlila, and R. Helmig, "Heterogeneity effects on evaporation-induced Halite and Gypsum Co-precipitation in porous media," *Transport in Porous Media*, vol. 118, no. 1, pp. 39–64, 2017.
- [17] E. Shahraeeni and D. Or, "Thermo-evaporative fluxes from heterogeneous porous surfaces resolved by infrared thermography," *Water Resources Research*, vol. 46, no. 9, Article ID W09511, 2010.
- [18] G. Y. Qiu and J. Ben-Asher, "Experimental Determination of soil evaporation stages with soil surface temperature," *Soil Science Society of America Journal*, vol. 74, no. 1, pp. 13–22, 2010.
- [19] U. Nachshon, E. Shahraeeni, D. Or, M. Dragila, and N. Weisbrod, "Infrared thermography of evaporative fluxes and dynamics of salt deposition on heterogeneous porous surfaces," *Water Resources Research*, vol. 47, no. 12, Article ID W12519, 2011.
- [20] S. M. S. Shokri-Kuehni, T. Vetter, C. Webb, and N. Shokri, "New insights into saline water evaporation from porous media: Complex interaction between evaporation rates, precipitation, and surface temperature," *Geophysical Research Letters*, vol. 44, no. 11, pp. 5504–5510, 2017.
- [21] J. Desarnaud, H. Derluyn, L. Molari, S. de Miranda, V. Cnudde, and N. Shahidzadeh, "Drying of salt contaminated porous media: effect of primary and secondary nucleation," *Journal of Applied Physics*, vol. 118, no. 11, Article ID 114901, 2015.
- [22] S. Veran-Tissoires and M. Prat, "Evaporation of a sodium chloride solution from a saturated porous medium with

- efflorescence formation,” *Journal of Fluid Mechanics*, vol. 749, pp. 701–749, 2014.
- [23] X. Li and F. Shi, “The effect of flooding on evaporation and the groundwater table for a salt-crust soil,” *Water*, vol. 11, no. 5, Article ID w11051003, 2019.
- [24] U. Nachshon, N. Weisbrod, R. Katzir, and A. Nasser, “NaCl crust architecture and its impact on evaporation: three-dimensional insights,” *Geophysical Research Letters*, vol. 45, pp. 6100–6108, 2018.
- [25] S. Dai, H. Shin, and J. C. Santamarina, “Formation and development of salt crusts on soil surfaces,” *Acta Geotechnica*, vol. 11, no. 5, pp. 1103–1109, 2016.
- [26] G. Licsandru, C. Noiriél, P. Duru, S. Geoffroy, A. Abou Chakra, and M. Prat, “Dissolution-precipitation-driven upward migration of a salt crust,” *Physical Review E - Statistical Physics, Plasmas, Fluids, and Related Interdisciplinary Topics*, vol. 100, no. 3, Article ID 032802, 2019.
- [27] X. Li and F. Shi, “Effects of evolving salt precipitation on the evaporation and temperature of sandy soil with a fixed groundwater table,” *Vadose Zone Journal*, vol. 20, no. 3, Article ID e20122, 2021.
- [28] X. H. Li and F. Z. Shi, “Salt precipitation and evaporative flux on sandy soil with saline groundwater under different evaporation demand conditions,” *Soil Research*, vol. 60, no. 2, pp. 187–196, 2021.
- [29] J. A. Kozak and L. R. Ahuja, “Scaling of Infiltration and Redistribution of water across soil textural Classes,” *Soil Science Society of America Journal*, vol. 69, no. 3, pp. 816–827, 2005.
- [30] H. Fujimaki, T. Shimano, M. Inoue, and K. Nakane, “Effect of a salt crust on evaporation from a bare saline soil,” *Vadose Zone Journal*, vol. 5, no. 4, pp. 1246–1256, 2006.
- [31] H. P. Huinink, L. Pel, and M. A. J. Michels, “How ions distribute in a drying porous medium: a simple model,” *Physics of Fluids*, vol. 14, no. 4, pp. 1389–1395, 2002.
- [32] C. Zhang, L. Li, and D. Lockington, “Numerical study of evaporation-induced salt accumulation and precipitation in bare saline soils: Mechanism and feedback,” *Water Resources Research*, vol. 50, no. 10, pp. 8084–8106, 2014.
- [33] H. Fujimaki, S. Shiozawa, and M. Inoue, “Effect of salty crust on soil albedo,” *Agricultural and Forest Meteorology*, vol. 118, no. 1-2, pp. 125–135, 2003.