

Article

Experimental Investigation of the Effects of Wetting–Drying Alternation on the Erodibility of Sodium Sulfate Salt Crusts

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Abstract

Salt dust storms are a distinct and highly hazardous type of dust storm in arid and semi-arid regions. Salt crusts commonly develop on the surfaces of desiccated lake beds, and variations in their structure and properties directly influence dust release. To investigate how wetting–drying alternation affects the erodibility of sodium sulfate salt crusts with varying salt contents, four crust types with 0%, 1%, 3%, and 5% sodium sulfate were prepared under controlled laboratory conditions. A combination of wind-tunnel tests, direct shear tests, and surface morphology observations was employed to evaluate changes in mechanical properties and wind-erosion responses before and after wetting–drying treatment. The results showed that wetting–drying alternation induced pronounced cracking, salt crystallization, and the formation of a loose surface layer in salt-bearing crusts, with structural damage severity increasing with salt content. In contrast, the physical crust without added salt exhibited minimal surface deterioration. Direct shear tests revealed that after wetting–drying, the internal friction angle of salt-bearing crusts first decreased and then increased with salt content, while cohesion declined markedly; the 5% salt crust showed a 32.4% reduction in cohesion, indicating substantial structural degradation. Wind-tunnel tests further demonstrated that wind-erosion intensity increased significantly after wetting–drying treatment across all salt contents, with the largest relative increase observed in the 1% salt crust. Wind-erosion intensity also scaled approximately as a power function of salt content. These findings demonstrate that wetting–drying alternation is a critical trigger for the degradation of sodium sulfate salt crusts and for enhancing their erodibility. Post wetting–drying, salt crusts may evolve into highly erodible surfaces, becoming major potential sources of salt dust storms. This study provides a theoretical foundation for understanding salt dust release from desiccated lake beds and for improving early warning of ecological hazards in arid regions.

Keywords: salt dust release; wind-erosion intensity; shear strength; cohesion; salt crystallization



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1. Introduction

Salt dust storms, a specialized type of dust storm, typically originate from desiccated lake beds in arid and semi-arid regions and pose greater hazards than ordinary dust storms [1]. Salt-rich dust particles transported during such events are corrosive and toxic,

threatening regional and global ecosystems and human health [2,3]. Many lakes in arid regions have progressively dried under the combined influence of climate change and human activities, forming extensive barren saline playa surfaces rich in salt sediments [4–6]. Strong winds can entrain particles from salt-rich surface sediments into the atmosphere through fluid entrainment, saltation, and aggregate breakdown, contributing to frequent salt dust storms [7–9]. Salt dust storms, a specialized type of dust storm, typically originate from desiccated lake beds and saline playas in arid and semi-arid regions, such as Ebinur Lake in Xinjiang, China, Owens Lake and the Salton Sea in California, USA, and saline playas in western Central Asia. Compared with ordinary dust storms, salt dust storms may pose greater environmental and health risks because salt-rich dust particles can contain soluble salts and other chemically active components.

Salt crusts, formed by cementation of soil particles by salt crystals, are widespread on desiccated lake-bed surfaces [10,11]. Salt crystal precipitation alters soil particle properties by promoting aggregation and cementation, where sodium sulfate facilitates the binding of fine particles into larger, more angular aggregates with increased surface roughness. This process reduces bulk porosity and modifies aggregate density. Although such morphological changes would typically increase the threshold friction velocity required for aeolian entrainment, the stabilizing effect is counteracted in salt-affected soils by structural weakening induced through repeated crystallization–dissolution cycles and wetting–drying-driven crack propagation, ultimately leading to enhanced overall erodibility. Salt cementation substantially increases the threshold friction velocity of surface particles, thereby suppressing dust emission [12,13]. However, dust release is influenced not only by surface properties and wind regimes but also by seasonal climatic variability [14–16]. Wetting–drying alternation driven by environmental fluctuations can alter the physicochemical properties of salt crusts, modifying their susceptibility to wind erosion [17,18]. Surface renewal processes also play a crucial role in periodic dust emissions from desiccated lake beds [19]. The high spatiotemporal variability of salt crusts implies that seasonal climate can lead to crust deterioration and enhanced erodibility, transforming these crusts into important dust sources [16,20,21].

In saline soils exposed to repeated wetting and drying, soluble salts dissolve, migrate, and recrystallize, altering the soil structure and mechanical properties of the crust [22,23]. Xu et al. reported that wetting–drying cycling of undisturbed sodium sulfate loess reduced both internal friction angle and cohesion, with values declining linearly with increasing salt content [24]. Li et al. found that wetting–drying cycles had a more pronounced effect on the physical properties of compacted loess than freeze–thaw cycles, reducing unconfined compressive strength, elastic modulus, and cohesion as the number of cycles increased [25]. Microscopic investigations using CT scanning and SEM revealed that wetting–drying cycles generate more medium and large pores, loosened particle skeletons, and reduced stability compared with freeze–thaw or coupled cycles [26,27].

These structural changes inevitably affect erosion resistance. The interaction of salinity and wetting–drying cycles promotes salt-crust cracking and modifies soil erodibility [28,29]. Field studies confirm that crusts with hydrated/anhydrous salts and distinct mineral habits become loose and fractured after wetting–drying, enhancing susceptibility to wind erosion [30–33].

Surface cracks in crusted soils play a critical role in wind erosion by disrupting surface continuity, concentrating aerodynamic stress, and promoting the detachment of soil aggregates, thereby generating erodible fine particles. In salt-bearing soils, crack development is further enhanced by wetting–drying cycles, where sodium sulfate crystallization induces volumetric expansion and contraction that progressively weakens interparticle bonding and accelerates structural fragmentation. As crack networks develop, they significantly

reduce crust stability and lower the threshold for particle entrainment under wind action. Based on these mechanisms, it is hypothesized that wetting–drying alternation promotes crack formation in sodium sulfate salt crusts, that crack development intensifies with increasing salt content due to stronger crystallization pressure, and that enhanced cracking ultimately leads to higher wind-erosion intensity by facilitating particle detachment. Based on previous studies, we hypothesize the following: (1) wetting–drying cycles promote crack development in sodium sulfate crusts, (2) crack propagation enhances wind erosion by increasing surface roughness and reducing crust integrity, and (3) higher salt content intensifies cracking due to crystallization pressure, thereby increasing erodibility.

This study focuses on laboratory-prepared sodium sulfate salt crusts with varying salt contents. Wind-tunnel experiments, direct shear tests, and surface morphology analyses were conducted to systematically investigate how wetting–drying alternation influences salt-crust degradation and erodibility. The findings aim to elucidate mechanisms of salt dust release under coupled wetting–drying and wind action, providing insights into salt-dust-storm formation, risk assessment, and ecological protection strategies for desiccated lake beds.

2. Materials and Methods

2.1. Experimental Materials

Soil was collected from farmland in Yuzhong County, Lanzhou, China, at a depth of 0–10 cm. According to the USDA soil texture classification, the soil was classified as silt loam. The bulk density of the soil was 1.365 g/cm^3 . To remove roots, residual soluble salts, and gravel fragments, the original soil was first passed through a 2 mm sieve, washed with deionized water, and then oven-dried at 105°C to remove moisture. Particle-size distribution was determined using a Mastersizer 2000 laser particle-size analyzer (Malvern Instruments Ltd., Malvern, UK). The soil contained 2.83% clay particles ($\leq 4 \mu\text{m}$), 76.87% silt particles ($>4 \mu\text{m}$ and $\leq 63 \mu\text{m}$), and 20.30% sand particles ($>63 \mu\text{m}$ and $<2000 \mu\text{m}$), indicating that the soil was dominated by silt-sized particles. Anhydrous sodium sulfate (Na_2SO_4 ; purity $\geq 99\%$) was purchased from Sinopharm Chemical Reagent Co., Ltd. It was used as the soluble salt source for preparing the sodium sulfate salt-crust samples. The reagent was stored in a sealed container before use to minimize moisture absorption, and no additional purification or pretreatment was performed.

2.2. Preparation of Sodium Sulfate Salt Crusts

The salt content of a salt crust was defined as the mass ratio of sodium sulfate to dry soil, rather than the concentration of sodium sulfate in the added water. During preparation, the dry soil mass of each sample was fixed at 500 g. Four salt-content treatments were designed in this study: 0%, 1%, 3%, and 5%, corresponding to sodium sulfate masses of 0, 5, 15, and 25 g, respectively. The 0% treatment was used as the salt-free control. To minimize differences among samples, the bulk density of each soil sample was strictly controlled. For each treatment, the required amount of sodium sulfate was dissolved in 100 mL of deionized water. The deionized water was used only as a carrier solution to uniformly distribute the designed amount of sodium sulfate onto the soil surface. The solution was then uniformly sprayed onto the soil surface using a small sprayer to form crusts with the designed salt contents. Based on preliminary trials, 100 mL of deionized water was sufficient to fully dissolve the required amount of sodium sulfate under all salt-content treatments.

The preparation procedure was as follows:

1. Weighed 500 g of soil using a precision electronic balance and placed it in a Petri dish 150 mm in diameter and 25 mm high.

2. Weighed the required mass of sodium sulfate and prepared solutions of different concentrations using beakers, glass rods, and droppers.
3. Uniformly sprayed the sodium sulfate solution onto the soil surface, immediately sealed the Petri dish with plastic wrap, and stored it in a shaded indoor environment for 24 h to allow the solution to infiltrate uniformly into the soil.
4. Placed the equilibrated soil sample in a constant-temperature oven at 70 °C until all water had evaporated. The temperature of 70 °C was used during the initial crust formation stage to ensure complete evaporation of pore water and to accelerate sodium sulfate crystallization, consistent with established laboratory protocols in salt-crust and loess studies.

2.3. Wetting–Drying Alternation Treatment

The prepared salt-crust samples were subjected to wetting–drying treatment. One wetting–drying cycle was defined as a complete wet-to-dry process. Each 500 g dry soil sample was placed in a Petri dish with an inner diameter of 150 mm and a height of 25 mm. The soil was filled to a uniform thickness of approximately 25 mm in all treatments to ensure comparable wetting, drying, salt migration, and upward evaporation conditions among samples. Water addition was used to simulate rainfall-induced surface wetting. Specifically, the crust samples were wetted using a sprayer, and the post-wetting water content was controlled at 20%. After wetting, samples were sealed with plastic wrap, placed in insulated boxes, and stored in a shaded indoor environment for 24 h to allow moisture to infiltrate evenly into the crust. They were then dried in an oven at 25 °C until the mass difference between the dried sample and the pre-wetting sample was within 0.1%. The 25 °C condition was selected to simulate natural ambient temperatures in arid and semi-arid regions and to conduct wetting–drying cycles under realistic environmental conditions commonly adopted in previous soil structural evolution experiments. This constituted one wetting–drying cycle. Considering the actual water content of soils in arid and semi-arid regions and following Khatei et al. (2024) [34], a water content of 20% was selected for the wetting stage. Two treatments were established: no wetting–drying treatment, and one wetting–drying cycle. Samples assigned to the no-cycle treatment were sealed after crust formation, placed in insulated boxes, and stored in a shaded indoor environment.

The one-cycle treatment was designed to examine whether wetting–drying alternation itself can trigger the degradation of sodium sulfate salt crusts. This treatment represents the initial response of the crust to a discrete wetting event followed by evaporation, such as may occur after rainfall, snowmelt, shallow ponding, or groundwater fluctuation on playa surfaces. It was used to isolate the effect of a single wetting–drying disturbance on crust morphology, mechanical properties, and wind erodibility under controlled laboratory conditions.

2.4. Direct Shear Test

A ZJ strain-controlled direct shear apparatus was used to determine the shear strength parameters of the crust samples, namely internal friction angle (φ) and cohesion (c), under different normal stresses. Vertical stresses of 100, 200, 300, and 400 kPa were applied, and the shear rate was 0.8 mm/min. Each treatment was repeated six times. According to the Coulomb failure criterion, $\tau = \sigma \cdot \tan \varphi + c$, the relationship between shear stress and normal stress was plotted and linearly fitted. The tangent of the internal friction angle was obtained from the slope of the fitted line, and cohesion was obtained from the intercept.

2.5. Wind-Tunnel Test

Wind-tunnel experiments were conducted in a wind-blown sand environmental wind-tunnel laboratory. The wind tunnel was a direct-current blow-down system with contin-

uously adjustable wind speeds from 4 to 35 m/s. The test section was 16 m long with a cross-section of 1.2 m × 1.2 m. Spires and roughness elements were arranged upstream of the test section to simulate an atmospheric boundary layer and promote turbulent boundary layer development. Each Petri dish containing a sample was placed in a circular recess along the central axis of the test section, 6 m downwind from the roughness elements, with the sample surface flush with the wind-tunnel floor to ensure accurate measurements.

Because field wind-erosion events are commonly associated with strong winds, the experimental wind speed was set to 16 m/s. This value was close to the 15 m/s used by Liu et al. (2025) for soil salt crusts and falls within the 9–27 m/s range used by Zhang et al. (2023) [13,35] for crusted playa surfaces. Therefore, 16 m/s was considered suitable for evaluating the relative erodibility of sodium sulfate salt crusts under a controlled strong-wind condition. Each erosion run lasted 10 min. Erosion loss was determined gravimetrically. Three replicate samples were prepared for each sodium sulfate crust treatment, and the average mass loss from the three runs was used to calculate wind-erosion intensity as follows:

$$E_R = m / At \quad (1)$$

where E_R is the wind-erosion intensity of the salt crust ($\text{g m}^{-2} \text{min}^{-1}$), m is the mean mass loss from three measurements (g), A is the surface area of the eroded sample (m^2), and t is the erosion duration (min).

3. Results

3.1. Effects of Wetting–Drying Alternation on Salt-Crust Surface Morphology

After one wetting–drying cycle, the salt-free crust showed only slight local undulation and limited exposure of fine particles, while no obvious cracking, surface peeling, or structural disintegration was observed. In contrast, the sodium-sulfate-bearing crusts underwent more pronounced morphological changes. The surface of the 1% salt crust became grayish white, accompanied by the appearance of loose salt–soil particles on the surface. For the 3% and 5% salt crusts, an uplifted and loose salt–soil layer developed, together with evident cracking and partial disintegration. These visible changes indicate that the presence of sodium sulfate made the crust structure more sensitive to wetting–drying disturbance. Similar salt-induced cracking, surface loosening, and structural degradation have been reported in saline soils and salt-crusts surfaces subjected to wetting–drying processes, where salt dissolution, migration, and recrystallization were identified as important causes of morphological change [12,27,28,30]. After one wetting–drying cycle, the salt-free crust showed only slight local undulation and limited exposure of fine particles, while no obvious cracking, surface peeling, or structural disintegration was observed.

The observed morphological evolution can be further interpreted based on the crystallization behavior of sodium sulfate reported in previous studies. During wetting–drying processes, soluble salts may dissolve during wetting, migrate with the pore solution, and recrystallize during subsequent drying [24–27]. For sodium sulfate, this process is more complex because it can involve hydration and dehydration between anhydrous sodium sulfate and mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$). Previous studies have shown that this phase transition is accompanied by substantial volume change and can generate crystallization or hydration pressure within confined pore spaces. During drying, sodium sulfate crystals may precipitate within pores as the evaporation front and salt solution redistribute through the soil matrix. During wetting, anhydrous sodium sulfate may absorb water and transform into mirabilite, further disturbing the particle arrangement. As salt content increases, a larger amount of sodium sulfate can participate in dissolution, migration, recrystallization, and hydration–dehydration processes. This provides a reasonable explanation for why the

higher salt crusts in this study showed more severe surface heave, cracking, peeling, and structural loosening after wetting–drying treatment, as shown in Figure 1.

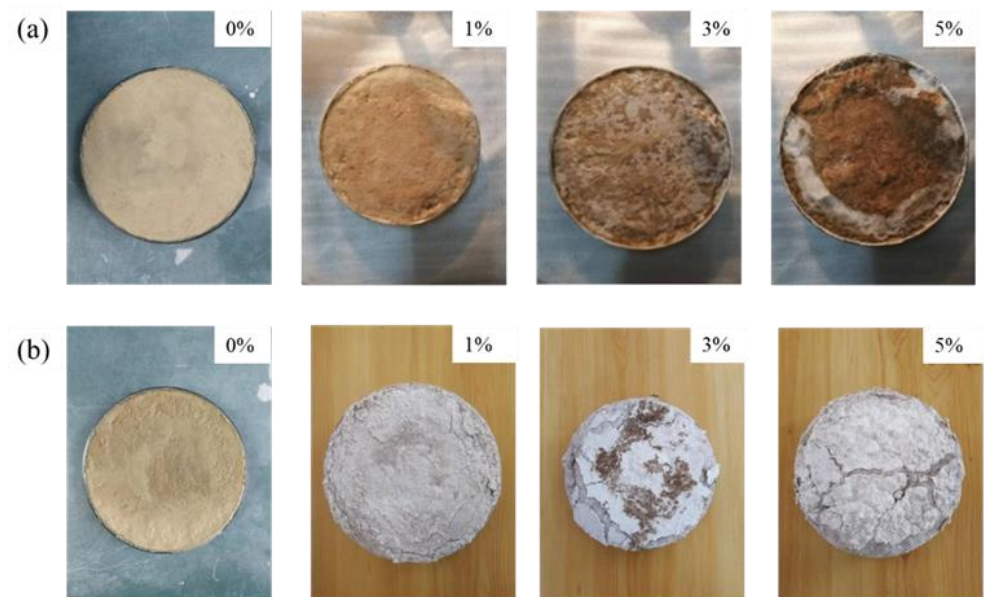


Figure 1. Morphological changes in sodium sulfate salt-crust samples before and after wetting–drying alternation. (a) Without wetting–drying alternation; from left to right, the salt contents are 0%, 1%, 3%, and 5%. (b) After one wetting–drying cycle; from left to right, the salt contents are 0%, 1%, 3%, and 5%.

3.2. Effects of Wetting–Drying Alternation on Salt-Crust Shear Strength

3.2.1. Changes in Internal Friction Angle

The internal friction angle is a key parameter characterizing the shear strength behavior of salt crusts. It reflects the frictional resistance and interlocking among soil particles within the salt-crust layer. A higher internal friction angle generally indicates stronger particle interlocking and greater resistance to shear deformation [22–27]. Based on the direct shear tests, the relationships between internal friction angle and salt content before and after wetting–drying alternation were obtained, as shown in Figure 2 ($p < 0.05$).

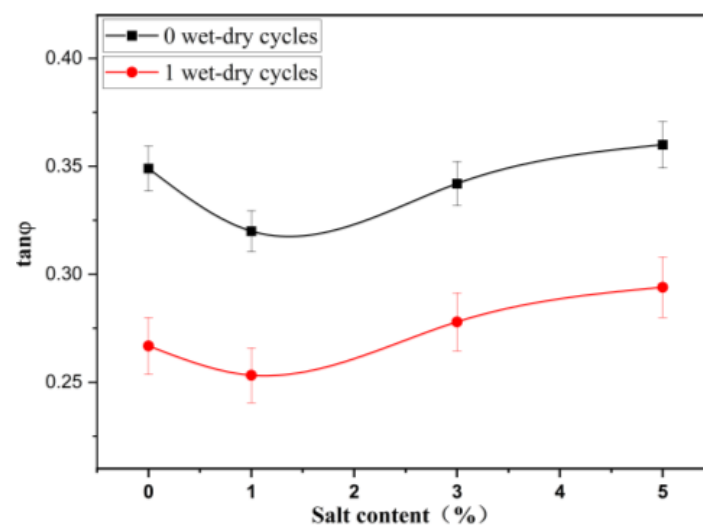


Figure 2. Relationship between internal friction angle and salt content.

Regardless of wetting–drying treatment, the internal friction angle first decreased and then increased with increasing salt content, reaching its minimum at a salt content of 1%. After one wetting–drying cycle, the internal friction angle increased for all salt contents. The increases were 1.9% and 6.3% at salt contents of 0% and 1%, respectively. From 0% to 1% salt content, the difference in internal friction angle between the treated and untreated crusts increased with increasing salt content. At salt contents of 3% and 5%, the internal friction angle increased by 6.2% and 4.3%, respectively, after wetting–drying treatment. Between 1% and 5% salt content, both the magnitude of increase and the difference between the treated and untreated crusts decreased gradually with increasing salt content and tended to stabilize. In addition, the decrease in internal friction angle from 0% to 1% salt content was more pronounced in the untreated sodium sulfate crust than in the crust subjected to one wetting–drying cycle, whereas the increasing trends from 1% to 5% salt content were similar under the two treatment conditions.

The variation in internal friction angle can be attributed to changes in particle arrangement, pore structure, and salt crystal distribution induced by sodium sulfate crystallization and phase transformation during wetting–drying alternation, which leads to progressive evolution of soil fabric and interparticle contacts. Similar mechanisms have been widely reported in saline and structured soils, where wetting–drying cycles and salt crystallization significantly alter microstructure and shear strength behavior [24,27]. At low salt contents, particularly from 0% to 1%, anhydrous sodium sulfate crystallized within soil pores during evaporation and crust formation in the untreated samples. The crystallization pressure displaced soil particles, enlarged local pore spaces, and modified particle spacing and contact patterns. These changes weakened interparticle friction and mechanical interlocking, thereby reducing the internal friction angle. In the samples subjected to wetting–drying treatment, sodium sulfate underwent repeated hydration, dissolution, migration, and recrystallization. During wetting, anhydrous sodium sulfate readily absorbed water and transformed into mirabilite before further dissolving into the pore solution. The formation of mirabilite was accompanied by a volume expansion of approximately three to four times, generating crystallization and hydration pressures that compressed pore walls and disturbed the particle framework. Together with the swelling of wetted soil particles, this process weakened the original crust skeleton and altered the mechanical behavior of the salt–soil cemented layer.

As salt content further increased, newly precipitated sodium sulfate crystals progressively filled pore spaces and adhered to particle surfaces. This crystal filling and surface coating increased particle-surface roughness and enhanced interparticle frictional resistance. Consequently, the internal friction angle increased at higher salt contents. Therefore, the non-monotonic variation in internal friction angle with salt content reflects the combined effects of pore expansion, particle rearrangement, salt crystal filling, and wetting–drying-induced restructuring of the salt-crust layer.

3.2.2. Changes in Cohesion

Cohesion is mainly derived from cementing materials and molecular attraction associated with bound-water films. It is therefore another important parameter characterizing the shear strength of sodium sulfate salt crusts, as it quantifies the attractive forces among soil particles within the salt-crust layer [6–8]. The relationship between cohesion and salt content before and after wetting–drying treatment is shown in Figure 3.

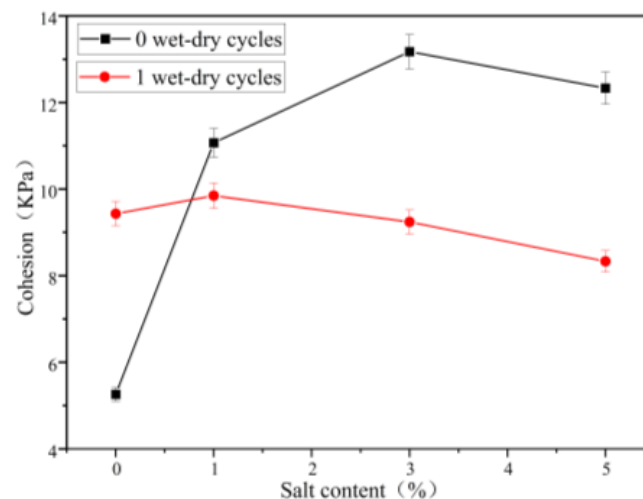


Figure 3. Relationship between cohesion and salt content.

As shown in Figure 3, cohesion generally first increased and then decreased with increasing salt content under both treatment conditions, although the detailed trends differed between untreated and wetting–drying–treated samples. For sodium sulfate salt crusts without wetting–drying treatment, cohesion increased as salt content rose from 0% to 3%, and then decreased when salt content increased from 3% to 5%. The most pronounced increase occurred between 0% and 1% salt content, with cohesion increasing by 110.5%. In contrast, the increase in cohesion from 1% to 3% was much smaller, and cohesion gradually declined as salt content further increased. For crusts subjected to one wetting–drying cycle, cohesion increased slightly from 0% to 1% salt content but decreased continuously from 1% to 5%. The increase from 0% to 1% was only 4.5%, which was substantially lower than that observed in the untreated samples ($p < 0.05$).

In the untreated samples, cohesion under all salt-bearing conditions was higher than that of the salt-free crust, indicating that sodium sulfate crystallization initially enhanced interparticle bonding. However, after one wetting–drying cycle, the maximum cohesion occurred at 1% salt content and then decreased with further salt addition. At salt contents of 3% and 5%, cohesion was even lower than that of the salt-free crust. Notably, wetting–drying treatment markedly increased the cohesion of the salt-free crust, whereas it reduced the cohesion of sodium-sulfate-bearing crusts.

The reduction in cohesion of salt-bearing crusts after wetting–drying treatment can be attributed to repeated hydration–dehydration and dissolution–recrystallization of sodium sulfate within the pore space. During wetting, anhydrous sodium sulfate absorbs water and transforms into mirabilite, whereas during drying, mirabilite dehydrates and sodium sulfate recrystallizes. These repeated phase transformations generate crystallization and hydration pressures that compress pore walls, disturb particle contacts, and progressively loosen the salt–soil skeleton. With increasing salt content, more crystals form and transform within the pore network, producing stronger salt-heave effects, enlarging pores, and weakening the cemented structure. Consequently, cohesion decreases markedly in high-salt crusts after wetting–drying alternation [23–27].

In contrast, the 0% salt crust is essentially a physical crust formed by the aggregation and rearrangement of soil particles. After wetting–drying treatment, particle packing may become denser and interparticle contacts may be strengthened, leading to a substantial increase in cohesion. These results demonstrate that wetting–drying alternation has opposite effects on salt-free and sodium-sulfate-bearing crusts: it can stabilize physical crusts, but it degrades salt crusts by disrupting the salt–soil cemented structure. The direct shear re-

sults therefore indicate that sodium sulfate salt crusts become mechanically weakened after wetting–drying alternation, which may increase their susceptibility to wind erosion [22–25].

3.3. Effects of Wetting–Drying Alternation on Salt-Crust Wind-Erosion Intensity

The intrinsic properties of crusts are important factors controlling wind erosion. Salt modifies the physical and mechanical properties of soil, and variations in salt content can alter soil structure to different degrees, thereby producing distinct wind-erosion responses. To clarify the influence of salt content on crust erodibility under wetting–drying alternation, wind-tunnel tests under clean airflow conditions were conducted on four types of sodium sulfate salt crusts, both before and after wetting–drying treatment. The eroded mass under wind action was measured, and the wind-erosion intensity was calculated. The relationships between wind-erosion intensity and salt content under the two treatment conditions are shown in Figure 4, and the corresponding values are listed in Table 1. These results demonstrate that wetting–drying alternation has opposite effects on salt-free and sodium-sulfate-bearing crusts: it can stabilize physical crusts, but it degrades salt crusts by disrupting the salt–soil cemented structure. The direct shear results therefore indicate that sodium sulfate salt crusts become mechanically weakened after wetting–drying alternation, which may increase their susceptibility to wind erosion. Consistent with previous studies, salt-induced structural changes significantly control crust erodibility and dust emission potential under wind action [12,13,18,21].

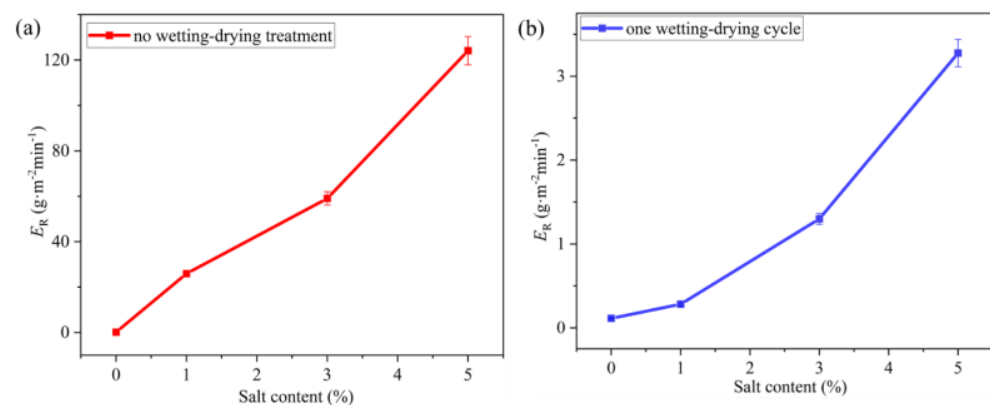


Figure 4. Relationship between wind-erosion intensity and salt content: (a) no wetting–drying treatment; (b) one wetting–drying cycle.

Table 1. Comparison of wind-erosion intensity with and without prior alternating dry and wet conditions.

Wind Speed (m/s)	Salt Content (%)	No Wetting– Drying ($\text{g m}^{-2} \text{min}^{-1}$)	Increase (%)	One Wetting– Drying Cycle ($\text{g m}^{-2} \text{min}^{-1}$)	Increase (%)
16	0	0.113	–	0.169	–
	1	0.282	149.6	25.932	15,244.4
	3	1.299	1049.6	59.077	34,856.8
	5	3.277	2800.1	124.124	73,346.2

As shown in Figure 4, wind-erosion intensity increased significantly with increasing salt content at the same wind speed, regardless of whether wetting–drying treatment was applied. The physical crust with 0% salt content consistently exhibited the lowest erosion intensity, with values close to zero, indicating that it was only weakly affected by wind erosion. This result suggests that the salt-free physical crust had the highest surface stability and the lowest erodibility. In contrast, the wind-erosion intensity of sodium-

sulfate-bearing crusts varied substantially between the two treatment conditions, and this variation was closely related to salt content. Under the same wind speed, higher salt content generally resulted in greater wind-erosion intensity, indicating that high-salt crusts were more susceptible to wind erosion than salt-free or low-salt crusts ($p < 0.05$).

Under both treatment conditions, the 5% sodium sulfate crust exhibited the highest wind-erosion intensity, whereas the salt-free crust showed the lowest. According to the mean wind-erosion intensity values listed in Table 1, without wetting–drying treatment, the wind-erosion intensity of the 5% salt crust was approximately 29.0 times that of the salt-free crust, 11.6 times that of the 1% salt crust, and 2.5 times that of the 3% salt crust. After one wetting–drying cycle, the corresponding values increased markedly: the wind-erosion intensity of the 5% salt crust was approximately 734.5 times that of the salt-free crust, 4.8 times that of the 1% salt crust, and 2.1 times that of the 3% salt crust. The results in Table 1 further indicate that one wetting–drying cycle substantially enhanced the wind-erosion intensity of crusts at all salt contents. Compared with the salt-free crust, salt-bearing crusts showed a much stronger increase in wind-erosion intensity after wetting–drying treatment, with even the smallest increase exceeding 101.8%. These results demonstrate that wetting–drying alternation modifies the influence of salt content on wind-erosion intensity and strongly promotes the degradation of sodium sulfate salt crusts. Consequently, salt-rich crusts become more erodible after wetting–drying alternation and may provide more readily entrainable material for wind erosion.

4. Discussion

4.1. Degradation Mechanism of Salt-Crust Structure Under Wetting–Drying Alternation

Similar structural degradation induced by repeated wetting–drying cycles in sulfate-bearing soils has been widely reported. Xu et al. [24] demonstrated that sodium sulfate significantly weakens the shear strength of loess after wetting–drying cycles through repeated dissolution and recrystallization. Likewise, Li et al. [25] found that cyclic wetting and drying generated more pronounced deterioration of soil strength than freeze–thaw cycles. CT and SEM observations further confirmed that wetting–drying cycles increase pore volume, reduce particle contacts, and gradually destroy the soil skeleton [26,27]. The present observations of surface cracking, particle loosening, and salt crystal accumulation are therefore consistent with previous microstructural studies.

This mechanism agrees well with the crystallization pressure theory proposed by Steiger and Asmussen [36], who demonstrated that sodium sulfate hydration and dehydration generate sufficient crystallization pressure to fracture porous geomaterials. Flatt [37] further suggested that repeated supersaturation and crystallization are the primary driving forces for salt-weathering damage in porous materials. Therefore, the structural deterioration observed in this study can be interpreted as a consequence of repeated crystallization pressure exceeding the bonding strength of the salt–soil matrix.

This study observed pronounced cracking, loosening, and salt crystallization on sodium sulfate salt crusts after wetting–drying alternation. These morphological changes are fundamentally associated with the distinctive crystallization and phase-transition behavior of sodium sulfate. Sodium sulfate can occur in different hydration states, among which anhydrous sodium sulfate and mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) are particularly important during wetting–drying processes. Under the experimental drying condition of 25 °C, one wetting and drying cycle promoted the transformation between anhydrous sodium sulfate and mirabilite, exerting a strong disruptive effect on the crust structure. Compared with the salt-free crust, salt-bearing crusts showed much higher wind-erosion intensity after one wetting–drying cycle.

From the perspective of crystallization thermodynamics, the phase transition of sodium sulfate can be described as follows. During wetting, anhydrous sodium sulfate (Na_2SO_4) absorbs water and transforms into mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$). This hydration reaction is exothermic and is accompanied by substantial volume expansion, which can reach approximately 314%. When mirabilite crystallizes within confined pore spaces, the resulting crystallization pressure may reach tens of megapascals, far exceeding the cementation strength among soil particles. During drying, mirabilite dehydrates and re-crystallizes as anhydrous sodium sulfate, accompanied by pronounced volume contraction and changes in crystal habit. The transformation from acicular or prismatic mirabilite to granular anhydrous sodium sulfate redistributes contact stresses between salt crystals and pore walls, thereby disturbing the original particle-contact structure.

Notably, crust degradation in this study occurred primarily within the subsurface layer rather than directly at the exposed surface. This behavior can be explained by the evaporation and crystallization dynamics of sodium sulfate. Unlike sodium chloride, sodium sulfate does not readily form a dense surface skin during the early stage of evaporation. Instead, as drying proceeds, the evaporation front migrates downward into the soil, and salt crystallization occurs mainly within internal pores. The crust formed in this study can therefore be regarded as a subsurface salt crust, in which salt–soil cementation was concentrated beneath the immediate surface.

During wetting–drying alternation, repeated dissolution, migration, crystallization, and expansion of sodium sulfate crystals within this subsurface layer continuously compressed the surrounding soil particles. When the accumulated crystallization and hydration stresses exceeded the interparticle cementation strength, salt bonds between particles were progressively fractured, resulting in loosening of the crust structure. As drying continued, the salt solution migrated upward through capillary action and evaporated near the surface. The newly precipitated acicular or prismatic mirabilite crystals gradually became exposed and mixed with detached soil particles, ultimately forming a loose salt–soil composite powder layer on the crust surface.

4.2. Mechanical Significance of Wetting–Drying Effects on Shear Strength Parameters

The shear strength results indicate that wetting–drying alternation exerted significant and complex effects on the mechanical properties of sodium-sulfate-bearing crusts. These changes can be interpreted from particle-scale mechanisms. The internal friction angle (φ) reflects frictional resistance and mechanical interlocking among particles. In this study, the internal friction angle of salt-bearing crusts generally increased after wetting–drying alternation. Although this trend may appear inconsistent with the observed structural degradation, it represents a change in the dominant frictional mechanism rather than an improvement in overall crust integrity.

Before wetting–drying treatment, the salt crusts were formed by drying at 70 °C, during which sodium sulfate mainly precipitated as anhydrous crystals. At low salt contents, particularly from 0% to 1%, the precipitated salt crystals were embedded at particle contacts and may have acted as small rigid inclusions, producing a rolling or spacing effect that reduced direct soil-particle contact and weakened frictional resistance. Consequently, the internal friction angle decreased. At higher salt contents, however, abundant salt crystals adhered to particle surfaces and filled pore spaces, increasing surface roughness and strengthening mechanical interlocking among particles. As a result, the internal friction angle increased with further salt addition.

Similar phenomena have also been reported in structured soils subjected to environmental cycling. Ma et al. [38] suggested that increases in internal friction angle do not necessarily indicate stronger soil structures because shear resistance is jointly controlled by

frictional resistance and interparticle bonding. In structured geomaterials, cohesion generally contributes more to structural integrity than friction angle. Therefore, although wetting–drying alternation slightly increased the internal friction angle, the significant reduction in cohesion indicates an overall deterioration of the salt-crust mechanical properties.

After wetting–drying alternation, sodium sulfate crystals underwent repeated dissolution, migration, and recrystallization, accompanied by changes in crystal morphology from granular anhydrous sodium sulfate to acicular or prismatic mirabilite. These acicular crystals could interlace among soil particles and form an anchoring-like structure, thereby increasing resistance to relative particle movement and leading to an increase in internal friction angle. However, this increase should not be interpreted as an enhancement of overall crust strength, because shear strength is controlled jointly by frictional resistance and cohesion. For wind erosion, cohesion often plays a more decisive role in maintaining crust stability and resisting particle entrainment.

Cohesion (*c*) reflects the cementation strength among particles and is a key indicator of crust structural stability. In this study, the cohesion of sodium-sulfate-bearing crusts decreased significantly after wetting–drying alternation, whereas that of the salt-free physical crust increased by 79.3%. This contrast highlights the different mechanical responses of physical crusts and salt crusts. In salt-bearing crusts, repeated expansion and contraction of salt crystals during wetting–drying produced fatigue damage at particle contacts and progressively weakened salt–soil cementation. Without wetting–drying treatment, cohesion increased by 110.5% when salt content increased from 0% to 1%, indicating that an appropriate amount of sodium sulfate crystallization can enhance interparticle bonding. However, once wetting–drying alternation occurred, even the 1% salt crust showed a decrease in cohesion from 11.07 kPa to 9.85 kPa, corresponding to a reduction of 11.0%. This result further demonstrates that wetting–drying alternation is a dominant factor responsible for the destruction of cementation between salt crystals and soil particles.

The substantial increase in cohesion of the salt-free physical crust after wetting–drying treatment further reveals the fundamental difference between physical crusts and salt crusts. In physical crusts, cohesion is mainly associated with clay-particle bonding, van der Waals attraction, and capillary or adsorbed-water-film effects. During wetting followed by drying, fine particles can rearrange and pack more densely, reducing interparticle spacing and increasing the number of effective contacts. This process strengthens interparticle attraction and produces a denser, more stable surface structure. This finding has important implications for wind-erosion resistance. In areas with very low salinity, natural wetting–drying cycles may enhance surface stability and reduce wind erodibility. In saline environments, however, the same climatic process can produce the opposite effect by disrupting salt-induced cementation and transforming salt-crust surfaces into potential sources of salt dust.

4.3. Implications and Prospects for Salt-Dust-Storm Prevention and Control

The findings of this study have practical implications for the prevention and control of salt dust storms in arid and semi-arid regions. First, salt crusts should not be regarded as permanently stable wind-resistant surfaces. After rainfall–evaporation events or similar wetting–drying processes, their resistance to wind erosion may decline sharply. Therefore, assessments of dust emission potential from desiccated lake beds should incorporate seasonal climatic variability and wetting–drying history, rather than relying solely on surface conditions observed during dry periods.

Second, spring and autumn are periods during which wetting–drying alternation occurs frequently, and they often coincide with seasons of high salt-dust-storm activity [4]. The results of this study provide a mechanistic explanation for this seasonal pattern. Evap-

oration following spring snowmelt or autumn rainfall represents a critical stage during which sodium sulfate salt crusts undergo dissolution, migration, recrystallization, and structural degradation. These processes weaken the salt–soil cemented structure, increase surface looseness, and promote the release of salt-rich dust under wind action.

This finding is consistent with previous field investigations on saline playas. Gillette et al. [20] reported that the integrity of surface crusts is one of the primary factors controlling dust emission from dry lake beds. Nield et al. [21] further demonstrated that wetting–drying processes accelerate crust breakdown and substantially enhance wind erodibility under natural climatic conditions. These previous observations support the present experimental results showing that wetting–drying alternation transforms relatively stable sodium sulfate crusts into highly erodible surfaces.

For desiccated lake beds dominated by sodium sulfate salts, naturally formed salt crusts alone may be insufficient to suppress dust emission over the long term. Effective control strategies should therefore focus on limiting salt accumulation, stabilizing vulnerable surfaces, and identifying high-risk zones. Potential measures include maintaining an appropriate groundwater level to inhibit upward salt migration, applying artificial sand-fixation measures in key areas, such as straw checkerboards or environmentally compatible chemical stabilizers, and implementing zoning-based management for saline lake-bed surfaces. Particular attention should be given to high-salinity areas with high absolute erosion intensity and to salt content ranges that are highly sensitive to wetting–drying disturbance. Integrated implementation of these measures may help reduce both the frequency and intensity of salt dust storms.

From the perspective of aeolian transport theory, dust emission depends on the balance between aerodynamic driving forces and surface resistance. Kok et al. [39] emphasized that the breakdown of protective crusts markedly reduces threshold friction velocity and accelerates dust entrainment. Therefore, wetting–drying alternation should be regarded as a critical environmental trigger linking climatic variability with salt dust emission in arid environments.

This study also has several limitations. First, laboratory-prepared salt crusts may differ from natural salt crusts in structure, mineral composition, pore characteristics, and physicochemical properties. Second, the constant-temperature wetting–drying treatment used in this study cannot fully reproduce complex field conditions, where temperature, humidity, groundwater fluctuation, wind regime, and multiple coexisting salts vary simultaneously. Future research should therefore focus on field wind-tunnel experiments on natural salt crusts, the coupled effects of multiple salts such as sulfates, chlorides, and carbonates, predictive models of salt-crust wind erosion that incorporate wetting–drying processes, and long-term field monitoring to validate laboratory findings.

5. Conclusions

This study combined wind-tunnel tests, direct shear tests, and surface morphology analysis to systematically investigate the mechanisms by which wetting–drying alternation affects the erodibility of sodium sulfate salt crusts. The results show that wetting–drying alternation induced pronounced cracking, salt crystal precipitation, and the formation of loose surface layers in salt-bearing crusts. The severity of structural damage increased with salt content, whereas the salt-free physical crust showed no obvious surface deterioration. Wetting–drying alternation also produced contrasting effects on crust cohesion: cohesion decreased significantly in sodium-sulfate-bearing crusts but increased markedly in the salt-free physical crust. The degree of mechanical degradation increased with salt content, with the cohesion of the 5% salt crust decreasing by 32.4%, while that of the physical crust increased by 79.3%. Wind-tunnel tests further showed that wetting–drying alternation

substantially enhanced the wind-erosion intensity of salt-bearing crusts, with the largest relative increase observed in the 1% salt crust. Wind-erosion intensity increased approximately as a power function of salt content. These results indicate that wind speed provides the direct aerodynamic driving force for erosion, whereas salt content is an intrinsic factor controlling the erodibility of crusted surfaces.

This study identifies wetting–drying alternation as a key environmental trigger for the transformation of salt crusts in arid regions from relatively stable, wind-resistant surfaces into highly erodible dust sources. This transformation is closely related to the distinctive crystallization and phase-transition behavior of sodium sulfate. During wetting, anhydrous sodium sulfate absorbs water and transforms into mirabilite, accompanied by a volume expansion of approximately 314%. During drying, mirabilite dehydrates and recrystallizes as anhydrous sodium sulfate. Repeated hydration–dehydration and dissolution–recrystallization cycles generate crystallization pressure, disrupt interparticle cementation, and progressively degrade the crust structure. The salt-dust release pathway can therefore be summarized as follows: salt-crystal phase transition, volume expansion, cementation failure, structural loosening, and enhanced wind erosion. After wetting–drying alternation, sodium sulfate salt crusts may become important potential sources of salt dust storms. These findings provide theoretical and experimental support for understanding salt dust release from desiccated lake beds and for developing effective strategies to mitigate related ecological hazards.

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