Experimental study on salt deterioration of salt contaminated earthen materials under dry-wet cycles

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Abstract

On the Silk Road in the northwest of China, there is a large number of precious ancient relics, such as the Great Wall with beacon towers and castles, the Jiaohe Ruins etc. Most of these ancient relics are earthen architecture sites, which is different from many monuments that are usually made of rocks or metal materials. Specifically, these ancient relics have suffered different levels of deterioration due to long term dry-wet cycles in this typical arid and semi-arid region. The damage patterns have been studied by field investigations, and the dynamics of salt precipitation have been confirmed to be crucial for understanding the deterioration mechanism in these earthen relics. However, the influence of the nature of the salt and its content on the mechanical properties and erosion responses of relic soils under dry-wet cycles are not well understood. In the present research, the deterioration of the saline ancient relics soil under dry-wet cycles was investigated in comparison to the mechanical properties (i.e., direct shear test, unconfined compression test and tensile test) and the effect of erosion response to artificial sandstorms. The specimens studied were remoulded samples from the Jiaohe Ruins loaded with different concentrations of NaCl, Na_2SO_4 and a mixture of these two salts. Meanwhile, the deterioration process was monitored by an ultrasonic test. It is found that the P-wave velocity decreases with increasing number of dry-wet cycles and the salts added to the samples accelerate the deterioration process. The degree of deterioration is reflected by the decrease of shear strength, compression strength and tensile strength of the relic soils. We also conducted wind erosion tests to investigate the erosion characteristics of remoulded samples by considering different salt distributions. The results indicate that most serious deterioration is on the surface of the samples due to salt crystallisation. Na_2SO_4 contributed most of the surface weathering of the soils while NaCl played little role in the weathering.

Keywords: Jiaohe Ruins, dry-wet cycles, mechanical properties, wind erosion, salt crystallisation

1 Introduction

The Silk Road has been the main passage for commerce and cultural exchange between Central Asia and Europe for thousands of years. Hence, a large number of precious ancient relics, such as the Jiaohe Ruins, the Great Wall with beacon towers and castles etc. remain along this road. In contrast to many foreign monuments that are usually made of rocks or metal materials, most of these ancient sites are composed of soil. Due to continuous deterioration under adverse environmental conditions, only a small proportion of the ancient relics survived to the present day. Therefore, to provide effective treatments to preserve them, learning the fundamental deterioration mechanisms of this material is necessary.

Recently, based on the field investigations of many earthen relics, the damage patterns and the cause of damage have been described in detail [1]. The dynamics of salt precipitation under long term dry-wet cycles have been confirmed to be crucial for understanding the deterioration mechanism in these earthen relics. Salt crystallisation is widely recognized as a cause of damage in porous materials. A century and a half ago, Lavalle [2] provided the evidence that growing crystals can exert pressure and the research in salt deterioration has begun. The mechanism of salt damage including thermodynamic aspects was studied in detail [3-7]. Although these mechanisms are applied universally in porous materials, the applicability for earthen relics is unknown due to the lack of relevant research.

In this study, the influence of salt content and type of salts on the deterioration of contaminated earthen material under dry-wet cycles was examined experimentally by using a non-destructive ultrasonic wave velocity instrument. In addition, according to the results of the mechanical performance tests, the degree of deterioration was estimated. Finally, a wind tunnel erosion test was carried out with the salt contaminated specimens after dry-wet cycles.

2 Study area (Jiaohe Ruins)

The Jiaohe Ruins are located in the Xinjiang Uygur Autonomous Region, an arid and semi-arid area in the northwest of China. The main climate characteristic of this area is low rainfall in combination with high evaporation. Details are summarized in Table 1.

Table 1: The climate characteristics of Jiaohe Ruins

Climate factor	Characteristics	Data
Evaporation	High evaporation	Annual average 2787.1 mm
Precipitation	Arid and semi-arid	Annual 2.9-48.4 mm; Annual average 16.2 mm
Temperature	High temperature difference	High 47.4 ℃ Low -28 ℃; Difference 21.9 ℃ (daily)
Wind	Wind with sand	Max speed >40 m/s; Strong wind 36.2 days/year; Sandstorm 11.2 days/year

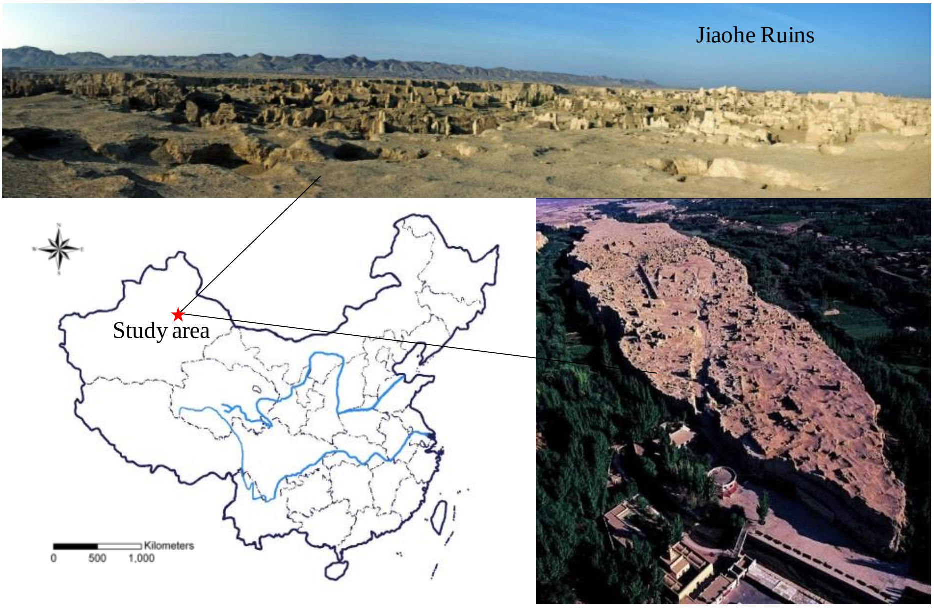

Figure 1: Jiaohe Ruins

The Jiaohe Ruins are the largest, oldest and best-preserved earthen relics over the world (Figure 1). The total area of the Jiaohe site is more than 350,000 m^2, including a 220,000 m^2 construction area. This large city was built during the Han dynasty (206 BC-AD 220), on a willow leaf-shaped loess plateau atop a cliff of over 30 meters. After the conversion and expansion of several dynasties, it achieved most prosperity in the Tang Dynasty and was abandoned during Yuan dynasty (AD 1271-1368). Most of the ancient earthen structures that have been preserved to the present were built in the 3rd to 6th century AD.

Most buildings of the city were dug from earth and the soils have been used for the manufacture of mud bricks, rammed earth and cob. Hence, the material of Jiaohe Ruins is soil, a soft material much more easily damaged than stone and brick. After thousands of years of exposure to the environment, these structures show significant damage such as erosion, cracks and even collapse. Specifically, the ancient relics that contain soluble salts have suffered severe deterioration due to long term dry-wet cycles.

3 Materials and methods

3.1 Sample preparation

Soil for the experiments was collected from blocks of a collapsed part of the cliff of the Jiaohe Ruins. This consists of undisturbed loess material, named raw soil. All the soil samples were desalinated using distilled water until the electrical conductivity of the filtered water was less than 300 μs/cm followed by drying at 105 °C [8]. Physical properties of the desalinated soil (Table 2) were determined according to the Chinese National Standards (CNS) GB/t50123-1999.

The salt content and the type of salt were determined on the basis of an analysis of the ion concentration of aqueous extracts from more than 100 samples collected from many different earthen ruins. The results indicate that Na_2SO_4 and NaCl are the most common salts in this material with contents up to 2% and 1%, respectively. Therefore, the two particular single salts and mixtures of them were used for the laboratory deterioration experiments. Details are listed in Table 3.

Table 2: Basic physical properties of the sample

Initial water content （%）	Specific gravity (g/cm^3)	Atterberg limits (%)		Particle size distribution (mm,%)		
		Liquid limit (%)	Plastic limit (%)	Clay (<0.002)	Silt (0.002-0.075)	Sand (0.075-2)
0.77	2.76	29.9	19.6	11.54	88.25	0.21

Cubic specimens, 7.07*7.07*7.07 cm^3 [9], were remoulded with the optimum moisture content (21.0%) and maximum dry density (1.71 g/cm^3), which was determined by the compaction test. Before being remoulded, the dried soil was thoroughly mixed with the brine, then placed in plastic bags and kept in a humidity-controlled room (100% relative humidity) for at least 48 hours to ensure water in the specimens in the state of equilibrium. All specimens were subjected to three cycles of wetting and drying (temperature: 25 °C; relative humidity: 95%-15%). The samples were kept at constant humidity for one month.

Table 3: The salts and salt contents used in the laboratory deterioration experiments

Remoulding water content	21.0%	Remoulding dry density	1.71 g/cm^3
Type of salts	Salt content *(wt %)	Type of salts	Salt content (wt %)
NaCl	0.2	Na_2SO_4	0.2
NaCl	0.4	Na_2SO_4	0.4
NaCl	0.6	Na_2SO_4	0.6
NaCl	0.8	Na_2SO_4	0.8
NaCl	1.0	Na_2SO_4	1.0
$NaCl+Na_2SO_4$	0.2+0.4	Na_2SO_4	1.2
$NaCl+Na_2SO_4$	0.4+0.8	Na_2SO_4	1.4
$NaCl+Na_2SO_4$	0.6+1.2	Na_2SO_4	1.6
$NaCl+Na_2SO_4$	0.8+1.6	Na_2SO_4	1.8
$NaCl+Na_2SO_4$	1.0+2.0	Na_2SO_4	2.0

*the salt content is related to the dry material.

3.2 Methods

3.2.1 Ultrasonic test

The basic principle of the ultrasonic test (US) is to analyse the change of the US wave velocity through the sample to estimate its internal structure. The primary wave (P-wave) is normally used in such tests due to its fast velocity and low interference. In order to monitor the influence of the salt content and the number of wet-dry cycles on the soil deterioration induced by salt, the P-wave velocities of all the specimens were determined after every cycle using the RSM-SY5 ultrasonic instrument manufactured by the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences. Transmitter and receiver were coupled to the surface of the specimens using vaseline. The instrument was calibrated with a standard material before every test. All the P-wave velocities of specimens were measured after complete drying at 15% RH, due to the high sensitivity of the US velocity to the moisture content.

3.2.2 Mechanical performance tests

Soil is a particularly loose material composed of particles. The stability and deterioration behaviour of this material can be estimated from its mechanical properties, including the resistance to external forces such as the shear resistance, the compression resistance and the tensile resistance. The mechanical performance tests were conducted after three dry-wet cycles, including direct shear test, unconfined compression test and tensile test. The specimens for the shear test were cut from the cubic samples due to the limited acceptable sample height of 20mm of the instrument used. Therefore, only the shear strength close to the surface of the specimens was measured while the mechanical properties of the whole cubic specimens are better represented by the compressive strength and the tensile strength.

3.2.3 Wind tunnel test

Erosion can be a common problem for monuments in deserts. Thus, the different effect of erosion response to artificial sandstorms is an effective and direct way to evaluate the salt deterioration under wet-dry cycles. The wind tunnel test was carried out in the multifunctional wind tunnel laboratory in Lanzhou University in China, with four different wind speeds, 18m/s, 21m/s, 24m/s and 28m/s, for 100s, 200s, 300s, 400s and 600s duration wind erosion. The sands used in the experiment are taken from the Tengger Desert in Minqin County of Gansu Province, China. The average particle diameter of these sands is approximate 0.288mm. In addition, the samples were weighed each time to calculate the mass loss under the different erosion conditions.

4 Results and discussion

4.1 Ultrasonic test

Soil deterioration was recorded as the P-wave velocity evolution, illustrated in Figure 2. It is seen that after the third cycle the wave velocity declines compared to after the first one, and this the more for increasing salt content. The decrease of the P-wave velocity is attributed to salt crystallisation exerting pressure on the soil material, hence causing damage. Moreover, this decrease caused by salt crystallisation accumulates with increasing cycle number as the wave velocities of the samples decreased significantly after each cycle. However, a decreasing US wave velocity for increasing cycle number was also observed for the salt free samples, indicating that swelling of clay minerals cannot be ignored. The result is consistent with the viewpoint proposed in the previous studies [10-11].

The degree of damage should be different for samples treated with different salts. According to the results of the experiments, for the single salts, the wave velocity of the sample contaminated with Na_2SO_4 is always lower than that of the one containing a similar amount of NaCl, indicating that crystallisation of the last creates less damage to the soil. The salt mixture reflects the largest damage potential to the soil material. Although the deterioration mechanism is still unknown, it ensured that the internal structure of the salt contaminated sample has changed, such as pore distribution, amount of voids and the inter-particle bonds in soil, under dry-wet cycles.

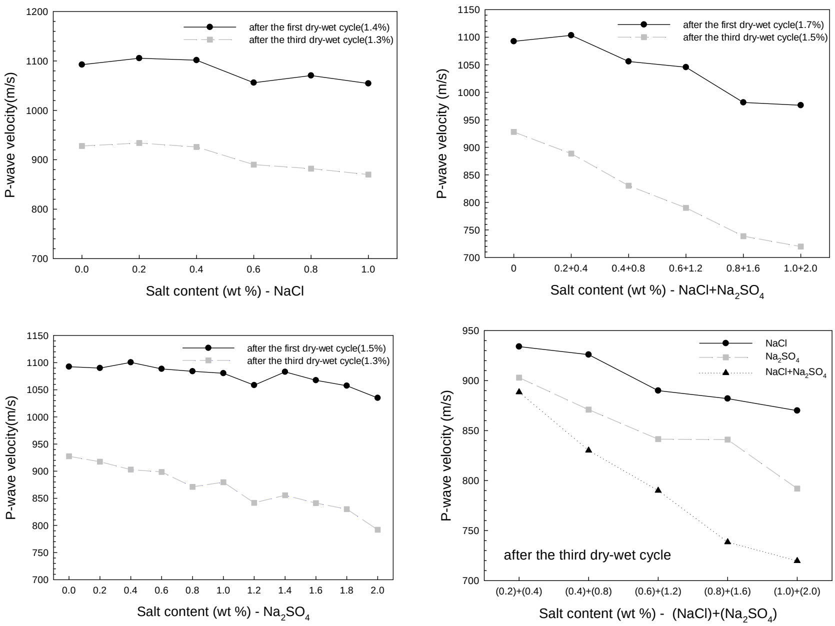

Figure 2: Relationship between P-wave velocity and salt content of the samples after different dry-wet cycles

4.2 Mechanical performance test

Different from the ultrasonic test, the degree of deterioration of the soil can be shown clearly from the results of the mechanical performance test. Figure 3 shows the relationship between mechanical strength parameters and salt content of the sample. For all samples in this experiment, the strength decreases with increasing salt content, thus, confirming the strong influence of the salt content on the magnitude of damage that was also demonstrated in the ultrasonic test.

Comparing the tensile strength and the compressive strength of samples contaminated with NaCl, Na_2SO_4 and their mixtures, respectively, similar results are obtained as with the ultrasonic test. Samples prepared with the salt mixtures have the lowest strength, followed by those mixed with Na_2SO_4 while NaCl shows the lowest destruction potential.

However, there is a slight difference in the shear strength. The cohesion of samples prepared with the salt mixture is higher than that of the samples containing pure Na_2SO_4 when the content is less than 1.2%. This is an apparent contradiction to the results of the compression and tensile tests. However, the reasonable interpretation of this difference is simply that the shear parameter was determined on smaller specimens (2 cm height) that were cut from the cubic ones. Therefore, the shear measurements only represent the deterioration closed to the surface of the cubic samples. In other words, the degree of deterioration in the samples is inhomogeneous from the interior to the surface. Low RH (relative humidity) promotes rapid evaporation, driving the flow through the pores to the surface. Thus, the salt normally crystallises on the exterior surface or near the surface of the sample. Due to the presence of NaCl, the solubility of Na_2SO_4 in the mixture is lower than that of the single salt, so it can be that the precipitation of Na_2SO_4 occurs at greater depths, resulting in less damage close to the surface of the specimens where the shear measurements were carried out.

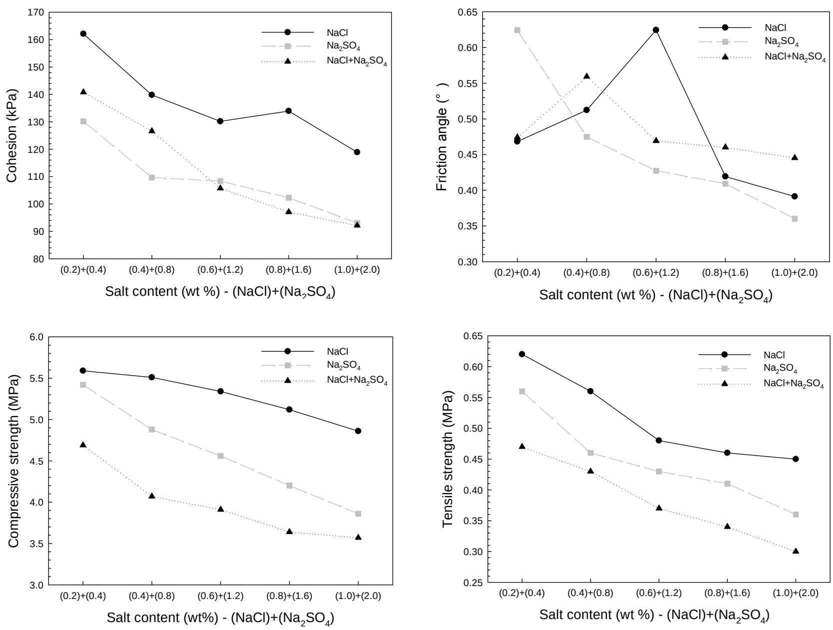

Figure 3: Relationship between mechanical strength parameters and salt content of the samples

In addition, the angle of internal friction of the soil, another important shear performance parameter usually used to describe the friction shear resistance of soil, exhibits an increasing trend at first and then decreases with increasing salt content. The value of the friction angle depends on the roughness of the contact surface between particles and the compactness of the soil. Salts precipitated in the pores can increase the roughness of the contact surface between adjacent particles, while crystallisation pressure decreases the compactness of the soil as well. Therefore, when the salt content is smaller, the friction angle increases due to the filling of the pores with growing salt crystals, whereas in case of larger salt contents, the reduction of the compactness is primarily controlling the angle of internal friction.

4.3 Wind tunnel test

The following observations should be considered in order to evaluate the influence of the salt content on the erosion response of relic soils under dry-wet cycles. Erosion is usually considered as a minor problem for stone monuments or sculptures. However, the mass loss of soil due to the erosion is an obvious result of its loose structure. Moreover, typical soil, they crumble very easily under an external force such as salt crystallisation pressure. Therefore, the mass loss during wind tunnel tests reveals the deterioration combining salt crystallisation and erosion.

Apparently，the mass loss is largely dependent on the speed of wind-sand flow and time of duration (Figure 4). This means that the greater the wind speed and the longer the duration, the more serious the mass loss. On the contrary, the mass loss is low when the wind speed is low with short time of duration. Thus, the deterioration caused by the erosion can not be ignored for the earthen relics.

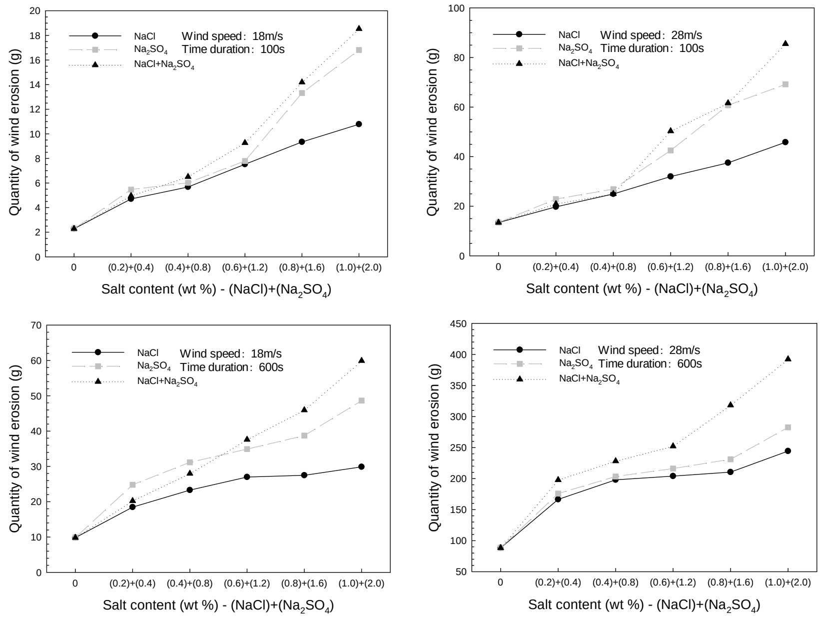

Figure 4: Relationship between quantity of wind erosion and salt content of the samples

However, for the same conditions (wind speed and duration), the effect of increasing wind erosion on samples with increasing salt content is striking.

The maximum mass loss due to the salt weathering is several times that of the salt free sample. It is also observed that the mass loss rate of the same sample decreases with increasing time duration under constant wind speed (Figure 5). In other words, the outmost zone of the sample is more deteriorated and less resistant to erosion. Therefore, salt crystallisation not only deteriorates the soil but also makes the samples inhomogeneous.

Moreover, according to the experimental results of the mechanical performance, the degree of deterioration is determined by the crystallisation behaviour of different salts as well, which is consistent with the results obtained in the wind tunnel experiment. In the beginning, the erosion process is largely controlled by the Na_2SO_4 content (Figure 4). With increasing mass loss, the influence of the salt mixture is obvious.

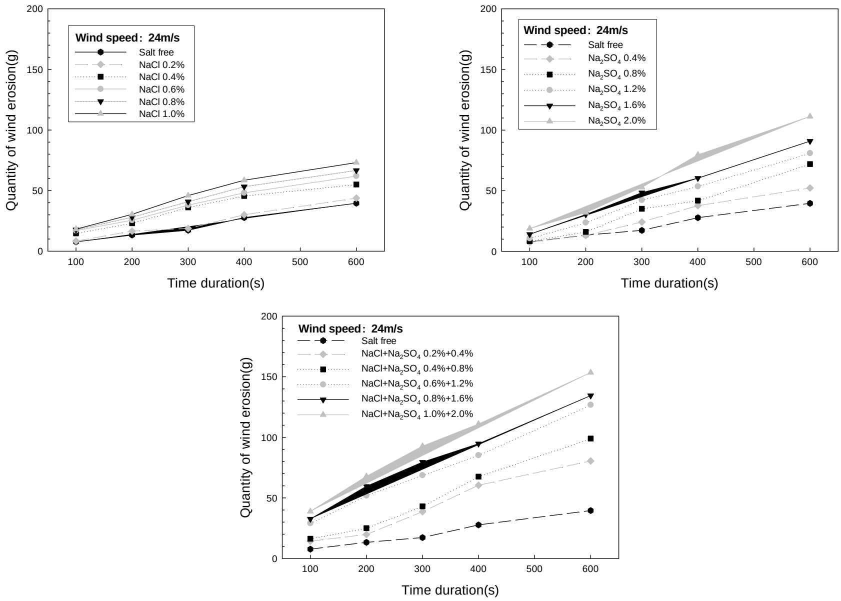

Figure 5: Relationship between quantity of wind erosion and time duration

5 Conclusions

To investigate the salt deterioration of salt contaminated soil under dry-wet cycles, an experimental program was conducted to test the mechanical performance and erosion characteristics of salt contaminated specimens. In addition, the deterioration process was monitored by means of ultrasonic tests. The factors of salt content and type of salts were considered. From the results presented and discussed above, the following conclusions can be drawn.

1) The dependence of the degree of deterioration on the salt content is obvious. Moreover, a mixture of Na_2SO_4 and NaCl added to the sample has the largest damage potential while the crystallisation of NaCl caused the lowest damage to the soil.
2) The deterioration caused by salt crystallisation accumulated with increasing cycle number. However, the presence of swelling clay minerals also causes damage during dry-wet cycles that cannot be ignored.
3) It is found that the degree of deterioration in the samples is inhomogeneous from the interior to the surface. Most serious deterioration is at the surface of the samples due to salt crystallisation. Na_2SO_4 contributed most to the surface weathering of the soils while NaCl played a minor role in the weathering.

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