

Research Article

Effect of Alkali Pollutant in Influencing Crack Propagation in Soils

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Shrinkage, deformation, and cracking will occur under extreme climate conditions such as drought, due to the accumulation of salt inside the soil during the evaporation of water on the surface of the soil. In this study, the image processing method was used to quantitatively analyze the dehydration cracking process of clay polluted by alkaline pollutant sodium carbonate on the basis of experiments. The mechanism of the effect of sodium carbonate concentration on the shrinkage cracks of clay was discussed through the analysis and comparison of different concentrations of sodium carbonate samples. The results showed that the water loss and shrinkage cracks of alkaline contaminant clay were developed in different stages. Firstly, first-level cracks developed diagonally or parallel to the edge of the container, and then second-level cracks developed along the main cracks with an angle of close to 90°. Most of the third-level or higher-level cracks were approximately perpendicular to the second-level cracks or the edge of the container and developed in parallel. In the cracking stage, the water loss ratio of the sample had a good positive correlation with the surface crack ratio. The slope of the fitted curve increased with the increase of the sodium carbonate concentration. With the increase of sodium carbonate concentration, the water loss ratio and the width of first-level cracks of clayey soil decreased, and the total length and the number of cracks increased, while the surface cracking ratio increased first and then decreased.

1. Introduction

Desiccation cracking of clay on the surface is a commonly natural phenomenon, especially for expansive clays. The phenomenon is more common when the regional temperature changes or during frequent droughts and floods. When the clay is polluted, desiccation cracking not only affects soil properties, plant growth, and water transport in soil, but also brings about a series of problems related to agricultural production, engineering geology, and environmental ecological protection.

Therefore, the study of clay cracking has an important theoretical significance and application value. A great deal of experimental work has been done on the research of clay cracking. The dry shrinkage cracks of clay were studied through laboratory tests. Different drying methods were applied to analyze the relationship between solvents, material parameters, and crack morphology [1]. A series of

experiments have been carried out to study the characteristics of water evaporation, volume shrinkage, and surface crack development of saturated clay in the drying process, and the quantitative analysis is carried out by image processing technology. Meanwhile, moisture evaporation and fracture development of clay under different temperatures and dry and wet conditions were studied quantitatively [2–5]. Through the freeze-thaw test, the relationship between water loss and surface crack development was studied in clay freeze-thaw cycle, and the fractal dimension of the fracture morphology was quantitatively analyzed by using image processing technology [6]. Meantime, some scholars have studied how to reduce the development of dry shrinkage cracks in clay [7–9].

Most of the studies on the theory of dry shrinkage cracking of clay are based on fracture mechanics [10–12]. Many scholars have done research on fracture mechanics. Lachenbruch [13] used fracture mechanics to explain the

depth and spacing of thermal shrinkage cracks in permafrost and proposed a method to estimate the gap between cracks. Morris et al. [10] deduced the theoretical relationship between crack depth and soil properties. Konrad and Ayad [11] set up an ideal model based on linear elastic fracture mechanics to predict the spacing between cracks in clay shrinkage. According to the change of the state of soil in drying process, Kodikara and Costa [14] provided a reasonable framework for three-dimensional analysis of the surface shrinkage and crack formation of clay.

With the development of numerical simulation, finite element method and discrete element method are widely used to simulate the development of dry shrinkage cracks. For instance, three-dimensional discrete element is used to study the drying cracking of clay. The effectiveness of numerical simulation is verified by indoor cracking test of thin clay [15]. Hirobe and Oguni [16] simulated the process of fracture formation and established a coupling model based on drying deformation and fracture. Considering the elastic and inelastic displacement conditions, the drying shrinkage cracking of soil is simulated by discrete element program (UDEC) [17]. Combining the coupling of hydraulic characteristics and mechanical characteristics, Vo et al. [18] studied the damage and fracture laws by finite element method during the generation and development of cracks. The application of transparent visualization technology in cracks will become a trend. At present, researchers have done a lot of work on pile-soil interaction [19–21].

The main purpose of this study is to examine the relationship of crack with respect to evaporation and water content characteristics for the soil contaminated by the alkaline pollutant. The image processing method was used to quantitatively analyze the dehydration cracking process of clay polluted by alkaline pollutant sodium carbonate. The relationship between the cracking characteristics such as the water loss ratio and crack area ratio of the sample with time was mainly analyzed. The mechanism of the effect of sodium carbonate concentration on the shrinkage cracks of clay was discussed through the analysis and comparison of different concentrations of sodium carbonate samples.

2. Materials

The clay used in the experiment was taken from the vicinity of the domestic waste landfill. The basic physical properties are listed in Table 1. The sodium carbonate solution was selected considering the fact that carbonate ions are the main alkaline inorganic salt in the leachate of domestic waste landfill.

The soil samples were air-dried and crushed, and weighed into five rectangular glass containers with an inner diameter of 25 cm × 25 cm × 4 cm. The sodium carbonate solution with the concentrations of 0 mol/L, 0.1 mol/L, and 0.2 mol/L, 0.3 mol/L, and 0.4 mol/L was added to prepare the mud with a supersaturated water content of 133%. The samples were stirred evenly and calmly placed in natural state until dehydration cracking. The water content of the soil sample was continuously tested, and the cracking of the

sample was monitored by a digital camera during the experiment. Then, the water content and crack change of the sodium carbonate sample with different concentrations were recorded. The water loss ratio of the sample can be defined as

$$\omega = \frac{m - m_0}{m_0}, \quad (1)$$

where ω is water loss rate (%), m is soil mass (g), and m_0 is mass of dry soil (g).

The images of samples were processed by the method of Yang and Yuan [22]. The crack ratio can be defined as

$$\delta = \frac{\sum A_i}{A} = \frac{n_b}{n_b + n_w}, \quad (2)$$

where A is the surface area of the soil, A_i is the crack area of the soil surface, n_b is the crack area of the soil, and n_w is the area of the intact soil.

3. Results

The evaporation cracking process of the five groups of sodium carbonate samples is shown in Figure 1. The time to start cracking showed different trends that the sample with sodium carbonate concentration of 0.1 mol/L was the earliest, while the concentration of 0 mol/L was the latest. The crack development can be divided into three levels during the cracking process: main crack of level 1, branch crack of level 2, and level 3 crack. It also indicates that the sample has experienced three periods of cracking: early cracking, middle cracking, and late cracking.

The relationship of the water loss ratio and time, and the crack ratio and time, are shown in Figures 2 and 3. The cracking of the whole group of samples tends to be stable after 280 h. With the change of sodium carbonate solution (0.1–0.4 mol/L), the critical water loss ratio of cracking decreased first and then increased. The critical water loss ratio of cracking was 20.0%, 39.1%, 53.3%, and 64.6%, respectively. In the stage of undeveloped cracks, the soil water loss ratio changes linearly with time, and the ratio does not exceed the critical value without cracking.

The water loss increases continuously during the development period of the sample cracks. The cracks on the sample surface develop rapidly when the water loss exceeds the critical value. The cracking characteristics of samples with different concentrations of sodium carbonate were different. The dehydration cracks develop in stages with the increase of the sodium carbonate concentration. The crack morphology was dominated by level-1 and level-2 cracks; the sodium carbonate concentration is 0.1 mol/L according to the test process and the crack diagram. And the level-1 cracks are wider. The samples cut by the few undeveloped secondary cracks showed a larger surface area of the secondary. The third-level or higher-level cracks were rarely developed. With the increase of the sodium carbonate concentration, the secondary cracks began to develop significantly, the width of the surface cracks became smaller and the cutting was obvious, and the quadrilateral was the main shape.

TABLE 1: Basic physical properties of clay.

G_s specific gravity	ω_L Liquid limit	ω_P Plastic limit	I_P Plastic index	Soil particle composition		
				Clay composition	Silt composition	Sand composition
2.74	34.8	17.1	17.3	58	32	10

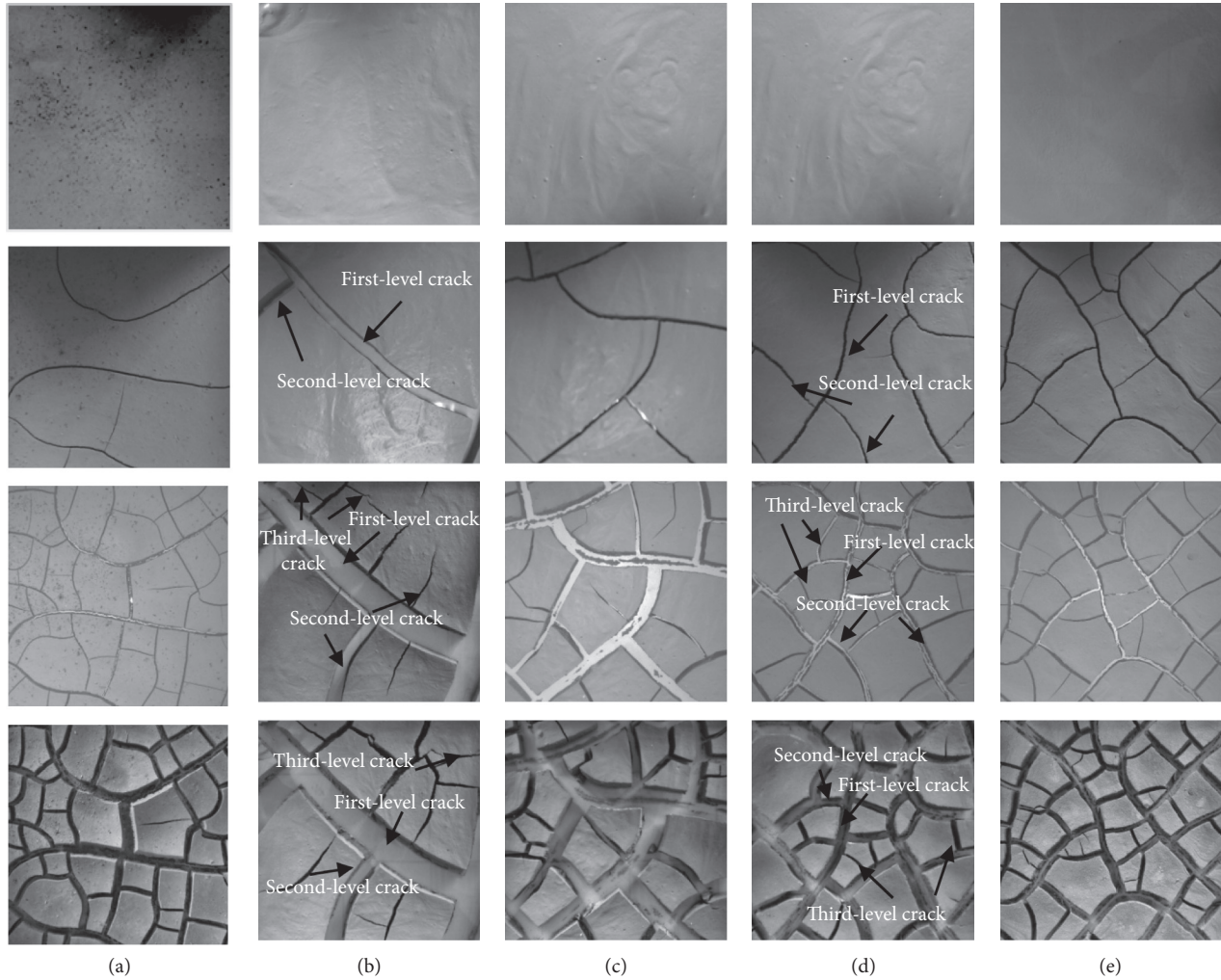


FIGURE 1: Different stages of water loss cracking of clay with sodium carbonate: (a) 0 mol/L. (b) 0.1 mol/L. (c) 0.2 mol/L. (d) 0.3 mol/L. (e) 0.4 mol/L.

With the increase of the sodium carbonate concentration, the final area crack ratio increased first and then decreased. The length and width of the level-1 cracks were relatively large and mostly through the whole sample based on the crack morphology. The included angle between the level-2 and the level-1 cracks was about 90° . Most of the third-level cracks were approximately parallel to the level-1 cracks, and more evenly distributed on the surface of the sample. The soil samples composed of the primary and secondary cracks were mostly irregular quadrilaterals. The large ones in the center were divided by the level-1 and level-2 cracks, while the small ones were divided by the higher level crack. Most of the angles between the cracks were mostly close to 90° .

3.1. The Characteristics of Water Loss Rate and Cracks Development. In the cracking test, the relationship between the water loss rate and fracture (surface fracture rate, cracking soil blocks, fracture width and length) had to be analyzed.

Figure 4 shows the relationship between the water loss ratio and the number of soil cracking blocks. With the increase of the water loss ratio, the number of soil blocks of samples with different concentrations of sodium carbonate increased, while the number of soil blocks increased significantly when the sodium carbonate concentration is zero. The number of soil blocks decreased first and then increased with the increase of sodium carbonate concentration. Figure 5 shows the relationship between the crack ratio of the

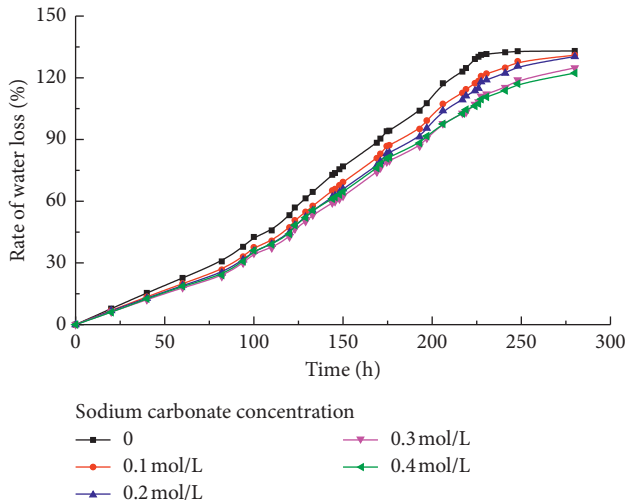


FIGURE 2: The curves of water loss rate and time of soil contaminated by sodium carbonate.

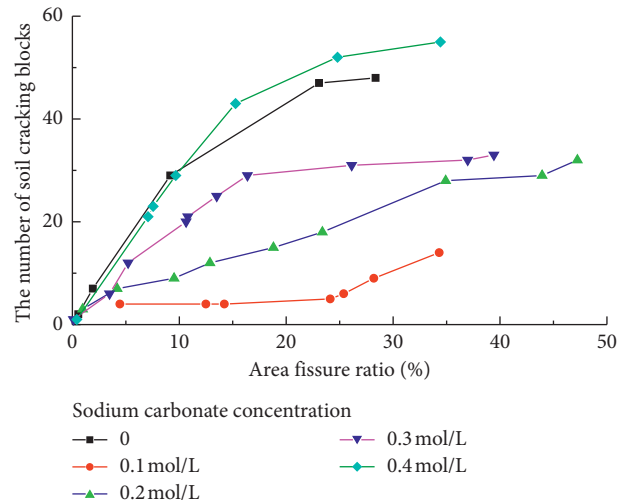


FIGURE 5: Relationship between the crack ratio and the number of cracking blocks of the soil.

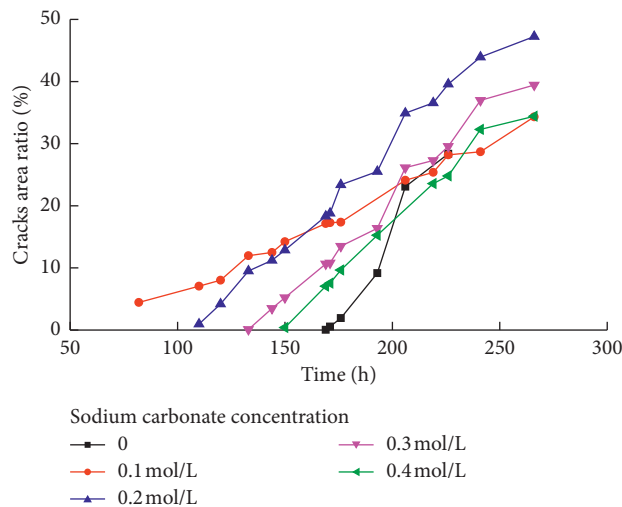


FIGURE 3: The curves of area-fissure rate and time of soil contaminated by sodium carbonate.

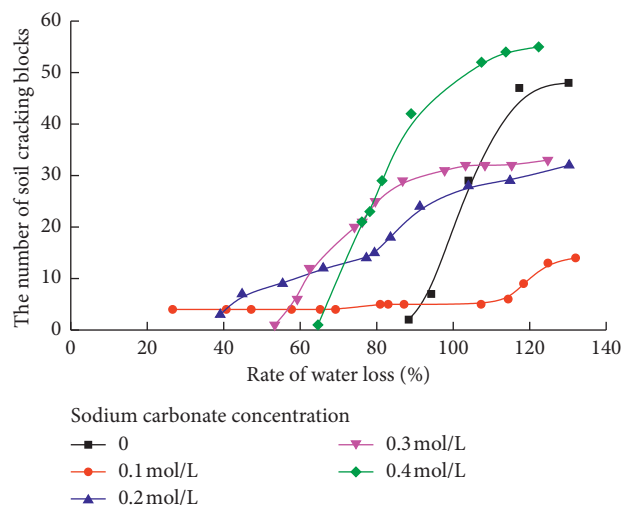


FIGURE 4: Relationship between the water loss ratio and the number of cracking blocks of the soil.

sample and the number of cracked blocks. The results indicated that the crack ratio of the sample with different pollution degrees was approximately linearly positively correlated with the number of cracked blocks. Figure 6 shows the relationship between the crack ratio of the soil and the crack length. The peak length of samples with different concentrations varied greatly. The peak length decreased first and then increased with the increase of sodium carbonate concentration, which is consistent with the development of crack ratio and sodium carbonate concentration.

3.2. *Effect of the Sodium Carbonate Concentration on the Development of the Cracks.* With the increase of sodium carbonate concentration, the duration of crack development showed a parabolic change, increasing first and then decreasing. Meanwhile, the size of the final cracking ratio also shows the same rule (Figure 7). Figure 7 shows that the soil sample with the concentration of 0.1 mol/L showed the greatest impact. And the water loss ratio of clay gradually decreased and tended to be gentle. The large sodium carbonate concentration showed little effect on the water loss ratio (Figure 8). The crack ratio increased first and then decreased with the sodium carbonate concentration under the same water loss ratio according to the dynamic development of cracks. A larger value of the crack ratio was obtained when the concentration is about 0.2 mol/L (Figure 9). The effect of sodium carbonate on the number of cracking blocks and cracking length of the soil shows the same rule that the more blocks of the soil, the longer the final crack length will be.

The clay needs a large water loss ratio that the soil body began to crack when the clay contains no pollution or the pollution concentration exceeds 0.4 mol/L. A small water loss ratio may cause the rapid cracking when the pollutant concentration is low. The cracking occurred earlier with a low sodium carbonate concentration; however, the crack development ratio was slow with the occurrence of the water

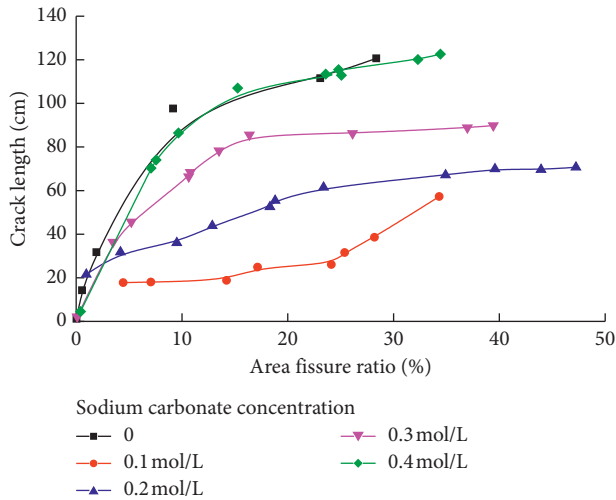


FIGURE 6: Relationship between the crack ratio and the crack length of the soil.

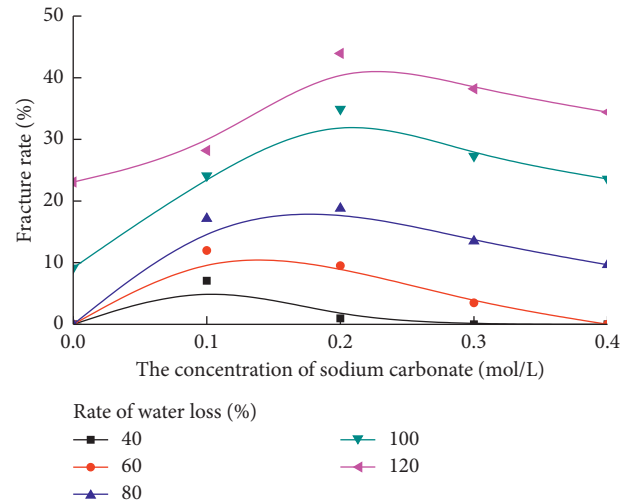


FIGURE 9: Relationship between the sodium carbonate concentration and the crack ratio.

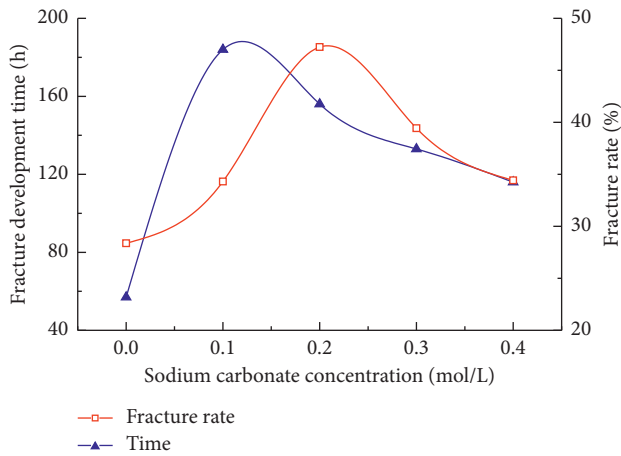


FIGURE 7: Relationship between the sodium carbonate concentration and the duration.

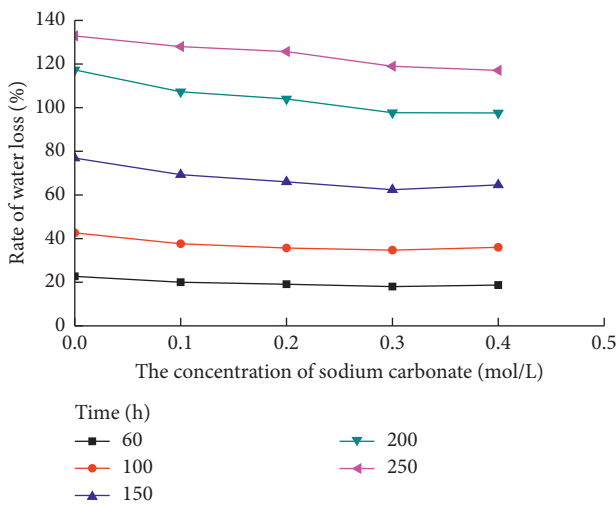


FIGURE 8: Relationship between the sodium carbonate concentration and the water loss.

loss according to the later stage of cracking. The number of blocks produced by the crack was small. The secondary crack was undeveloped in the later stage while the primary crack mainly changed in the deepening and widening process, which is also verified in Figure 1. The number of crack blocks and the crack length of the contaminated soils showed an increase trend with the increase of the pollution concentration (Figures 10 and 11).

4. Discussion

4.1. Clay with No Pollution. Clay that has not been polluted by the sodium carbonate pollution has the largest water loss ratio, and the stage characteristics of cracking of the sample are the most obvious. Before cracking, the soil was in a supersaturated state that no cracks occurred. The speed of water loss was related to the surface area of the container; the water loss ratio remains unchanged (Figure 2). The supersaturated water and free water in the soil were lost in the first stage, leading to a higher relative water content where no cracks occurred. When the soil water loss ratio exceeded 88% (corresponding to the sample water content of 45%), the soil began to crack. The soil water content is still greater than the liquid limit; however, the sample surface has cracked as the water moves downwards under the action of gravity. The surface water content is lower than that of the whole which caused the early cracks.

With the appearance of early cracks, the contact area between soil and air increases, and the water loss of the sample enters the second stage, shown as the slope of the curve in Figure 2. And the cracks on the sample surface developed rapidly in stages. When the water loss is greater than 110%, the volatilized water of the sample changed from free water to bound water which is more difficult to volatilize, so that the water loss ratio decreased in the later period. The shrinkage rate of the soil increased as the increase of the soil water loss ratio, matrix suction, and negative pore pressure at the cracking stage. The soil began to crack when it exceeded

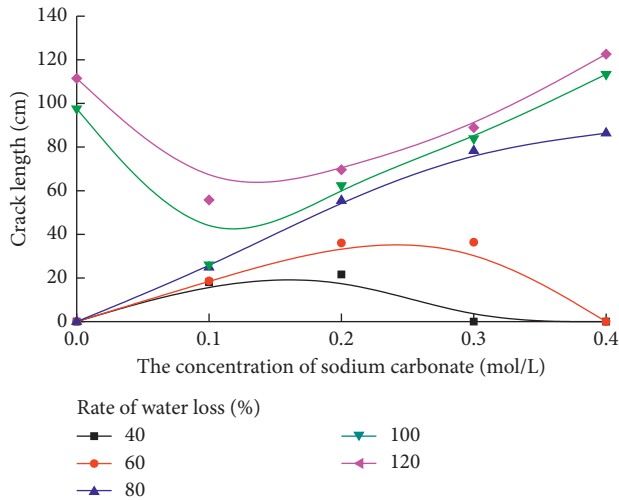


FIGURE 10: Relationship between the sodium carbonate concentration and the total length of the cracks.

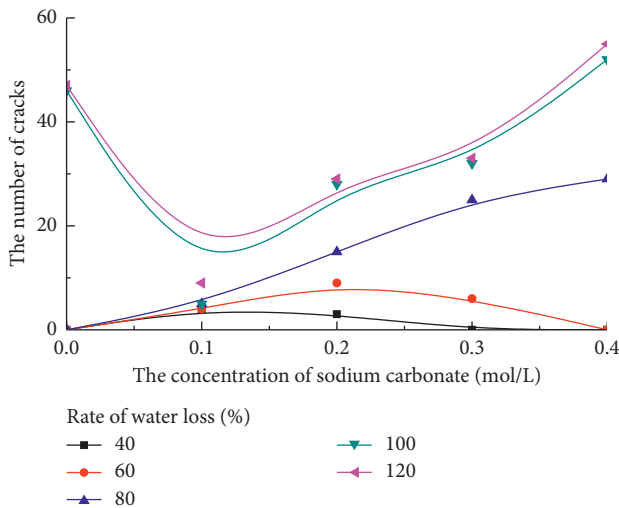


FIGURE 11: Relationship between the sodium carbonate concentration and the number of crack blocks.

the tensile strength of the soil. And the cracked area of the soil and number of cracked blocks increased as the increase of the water loss ratio.

In the third stage, the water loss of the soil no longer increased, and the crack morphology was relatively fixed. The free water and weakly bound water of the soil were volatilized, and the matrix suction and shrinkage of the soil were close to the maximum.

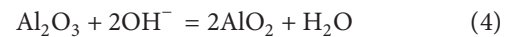
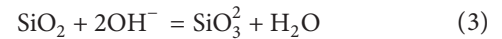
4.2. Clay Contaminated with the Sodium Carbonate. In the clay with sodium carbonate, the development of desiccation cracks is different from that of natural clay. The most important is that as the concentration of sodium carbonate increases, the initial cracking loss rate increases gradually, the final crack rate increases, and the number of crack blocks increases. The influence mechanism of sodium carbonate on

clay is mainly reflected in the following three aspects (other development processes are similar to uncontaminated soils).

Physical properties: the addition of Na^+ in sodium carbonate changed the original electric double layer structure of the clay layer. The surface of clay particles is usually negatively charged, and the clay particles adsorb cation ions due to the adsorption effect of ionic electrostatic force. However, the hydration ability of Ca^{2+} and Mg^{2+} is small, and the binding water film formed is thin on the surface of the particles, so the distance between them is close and attractive, and the force needed for cracking is also large. Under the environment of Na_2CO_3 erosion, the clay is alkaline, which increases the adsorption of Na^+ . The adsorption of Na^+ on the clay particle surface is related to the cation of clay particles. Although Na^+ has a small radius, it has a large radius of hydration, resulting in thickening of the double layer structure on the surface of the clay particles and reducing the gravitational pull between the particles. As a result, the clay with sodium carbonate is cracked at a lower water loss rate. However, when the concentration increases, excess Na_2CO_3 will precipitate, which will accumulate on the clay particle surface, so that the effect of Na^+ in sodium carbonate will be reduced.

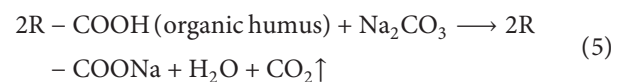
Chemical properties: after the clay is eroded by Na_2CO_3 , a series of chemical reactions occur, and some insoluble carbonates are formed, and filled in the clay pores, which is the main reason for the decrease of the water loss rate of the clay by sodium carbonate.

In addition, the free oxides SiO_2 and Al_2O_3 in clay will react chemically in an alkaline environment and produce meta silicate and meta aluminate:



Meta silicate and meta aluminate have a strong viscosity, which makes the soil difficult to crack. It is one of the main reasons for the secondary crack development of low concentration sodium carbonate pollution soil. This is one of the main reasons why secondary cracks are not developed in clay by the low concentration sodium carbonate.

Other aspects: organic humic acid substance is an important part of the clay, these humus have a large anion exchange capacity, and Na_2CO_3 has the function of decomposing the organic substance (R represents the organic carbon chain).



The decomposed R-COO^- is more hydrophilic than R-COOH , and R-COO^- is more easily contact with clay cations. The other end of RCOO^- is oriented towards the aqueous solution, the charge is reversed in the clay, and the electronegativity increases, which forms the diffusion

electric double layer with Na^+ in the solution, and effectively increases the colloid stability and shortens the distance between the clay particles. This is also one of the reasons why the initial clay is not easy to crack.

But too much RCOO^- is like lubricating oil, which increases the mobility between the clay particles. And with the increase of sodium carbonate concentration, the content of humic acid in clay decreased, and the flocculation structure of clay changed to the dispersion structure, which is the main reason for the increase of the cracking rate with the concentration of sodium carbonate in the later period.

5. Conclusion

Through the drying shrinkage cracking test of alkali contaminated clay, the characteristics and laws of crack development are revealed. It provides a reference for the study of physical and mechanical properties of contaminated clay, and provides a theoretical basis for related engineering construction.

- (1) The dehydration cracking of contaminated clayey soil can be divided into three stages: before, during and after cracking. In the cracking stage, the water loss ratio of the sample is positively correlated with the surface crack rate. As the concentration of sodium carbonate increases, the slope of the fitted line of the water loss ratio and the crack rate increases. In the process of cracking, primary cracks are developed along the diagonal of the container or parallel to the edge of the container, and then secondary cracks are developed vertically, and the angle between the cracks is generally close to 90° . Most of the third-level cracks or higher-level cracks are approximately perpendicular to the second-level cracks or container walls and develop in parallel. The main cracks have a large cutting soil area and are irregular polygons. The secondary cracks are divided into irregular quadrilaterals with a small area.
- (2) With the increase of sodium carbonate concentration, the water loss ratio of cohesive soil decreases, the width of the primary cracks decreases, the total length of cracks and the number of cracking blocks increase, while the surface crack rate tends to increase first and then decrease. In low-concentration sodium carbonate contaminated soil, secondary cracks do not develop. With the increase of the concentration, secondary cracks develop and the development process and gradually approach uncontaminated clay soil.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

There are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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