Effects of fly ash on the evaporation and cracking characteristics of soda soil

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Data available on request from the authors.

Abstract: Soil salinization seriously affects the movement of water in soil which then affects soil stability and sustainability in industrial and agricultural development. Fly ash, one of the most discarded solid wastes from coal-fired power plants, has been widely used as a recycled resource in recent years. In this study, the basic components of soda soil have been investigated through laboratory experiments. Soda soil samples with different amounts of fly ash are tested to study the changes in the characteristics of the material due to changes in water content and evaporation rate during drying. Changes in fractal and crack intensity factor (CIF) are calculated based on digital image processing technology. The results show that the residual water content of soda soil increases from 8.55% to 16.22% with increases in the fly ash content. Fly ash can improve the water retention capability of soda soil, with a rate of increase of 89.68%. The average length of the surface cracks gradually decreases with increase in fly ash content, which indicates that fly ash can effectively inhibit the development of surface cracking in soil. The rate of cracking is an important measure for characterizing the development of cracks by measuring the area of the cracks. The crack area gradually decreases with increase in the fly ash content with different rates of cracking. The rate of cracking with a fly ash content of 10% is relatively slow, which indicates that 10% fly ash can effectively reduce cracking in soda soil thus resulting in a high residual water content. Therefore, the water retention capability of the soda soil in the current study can be improved with an optimal fly ash content of 10% to 15%.

Keywords: soda soil; fly ash; crack; evaporation; water retention capability

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1. Introduction

Water and salt in soil migrate to the surface at the same time during soil degradation under the influence of salt and alkali. Water in the soil evaporates into the atmosphere, while salt accumulates at the surface. High rates of evaporation cause the upward movement of groundwater along with increase in the depth of soil capillary such that the concentration of soluble salts in the soil and groundwater gradually increases with increased water content, which results in the surface accumulation of salt and soil salinization (Abtahi 1977). High salt and alkali contents are the main causes of soil degradation in arid and semi-arid lands. Soil salinization seriously affects the sustainable development of agricultural land (Choudhury et al. 2014). On the one hand, excessive salt and alkali substances cause the hardening of soil which results in the degradation of permeation and ventilation characteristics and other soil properties, which affects the absorption of nutrients and respiration of crops. On the other hand, the increase in salt content will affect the absorption of other ions by plants, thus resulting in uneven distribution of nutrition (Rengasamy 2010). This results in soda soil, which is a kind of soil that is harmful or directly inhibits plant growth, due to high concentrations of soluble salts (Shainberg et al. 1981). Soda soils have high pH and it is formed as a result of carbonate accumulation under poor Ca^{2+} and Mg^{2+} conditions.

Soda soil can cause damage to both plants and the soil structure (Chaudhari et al. 2008). Soda soil mainly contains sodium carbonate (Na_2CO_3) and sodium bicarbonate ($NaHCO_3$), which not only corrode the roots of plants, but also make it difficult for plants to absorb water due to the increase in soil salinity. Large amounts of sodium ions ($Na^{+)}$ will destroy the structure of the cell membrane of the roots, which causes a large overflow of nutrients into the cell, thus resulting in the lack of plant

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nutrients and delaying the discharge of sodium out of the cell membrane (Bharti et al. 2017; Priyanka et al. 2020). Moreover, a considerable amount of Na^+ in soda soil can be adsorbed by the soil adsorption complex, which causes high levels of hydrophilicity and dispersibility of the soil colloids, thus resulting in clogging of the soil pores with poor gas exchange. The contact between soil particles and the cementation of the soil structure become unstable. Due to changes in temperature and the effects of wet and dry cycles, water bearing calcium carbonate crystals will eventually form, which leads to the expansion of the soil and thus uneven settlement of building foundations (Zhao et al. 2016). Soda soil can be mainly improved by removing the salt in the soil. However, the salt concentration is usually lower than that during a drought, which not will only affect crop production, but also increase the soil salinization (Singh et al. 2018). Additives can be used to improve the soil by reducing the rate of the evaporation of water which will restore agriculture and improve land use (Srivastava et al. 2016).

Fly ash plays an important role in the improvement of soda soil. Fly ash has the potential to improve soil since it contains a large amount of calcium, silicon and aluminum (Kumar et al. 2017; Matsi and Keramidas 2001; Riehl et al. 2010). Fly ash can improve the physical, chemical and biological properties of degraded soil. It is a readily available source of microscopical and macroscopical plant nutrients. The addition of fly ash changes the porosity, bulk density and expansion rate of soda soil. Fly ash contains a large volume of silicate minerals and carbon particles with a porous structure. The pH of soda soil can be reduced by adding acidic fly ash which contains trioxides, insoluble hydroxides and dissociable acids that are formed during hydrolysis. Fly ash in the soil is beneficial to plant growth. Phosphorus, potassium and calcium in fly ash cause a series of biological reactions when mixed with soil which promote plant growth. It is feasible to use fly ash to improve

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acidic soil (Matsi and Keramidas 2001). Fly ash is produced in large quantities and one of the most discarded solid wastes from coal-fired power plants (Borowski and Ozga 2020), and not made available everywhere. Fly ash can also take up a lot of land resources, pollute surface and subsurface water resources, and cause damages to the environment (Ahmaruzzaman 2010; Bhattacharya and Kim 2016). The use of waste is encouraged around the world to reduce the use of traditional materials that emit greenhouse gases and consume large amounts of energy. Using fly ash as a soil stabilizer by improving the strength of the soil is not only a cost saving measure in an engineering project, but also helps to reduce environmental pollution (Pathan et al. 2003).

Soil cracking due to evaporation is a complicated process. Cracking has an important influence on the characteristics of soil for plant growth and the movement of water and solutes in the soil (Shokri et al. 2015; Peron et al. 2009). Soda soil is prone to cracking in rainfall areas that have a high rate of evaporation due to the high salt content which increases the moisture content of the soil and leads to more surface erosion, as shown in Figure 1. Due to the high $NaHCO_3$ and Na_2CO_3 contents in soda soil, the level of beneficial microorganism species activities and the amount of microorganisms are reduced, which leads to the deterioration of the physical characteristics of the soil and changes in the microorganism structure (Semenov et al. 2017; Shi et al. 2019). Soil cracking increases the rate of evaporation which changes the surface water runoff and the movement of water, nutrients and microorganisms in the soil. This affects the absorption of beneficial nutrients by the root system of plants, reduces crop yield, pollutes the groundwater and reduces the water available for irrigation. Although fly ash is a promising agent that may improve the properties of soil for agricultural use, unfortunately, the effects of fly ash on the evaporation and cracking characteristics of soda soils have

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not been studied in detail.

To gain a more in-depth understanding of the effects of fly ash on soda soil, a laboratory testing program on soil samples taken from the City of Shihezi, Xinjiang, China, is carried out in this study. The soil is mixed with different amounts of fly ash and the water content is measured during the drying of the samples. The fractal and crack intensity factor (CIF) are calculated based on digital images of the soil surface during evaporation. The water retention capabilities and cracking characteristics of the soda soil due to the addition of fly ash are also explored.

2. Test materials and testing methods

2.1 Test materials

Soil samples for the experiments were obtained from Shihezi City. Shihezi City is located in the Xinjiang Uygur Autonomous Region in western China as shown in Figure 2. The saline-alkali soil is distributed widely in the region. There are different types of soils with high concentrations of salt due to the complex geological processes that have been under the influence of the arid climate and closed inland basin. Typical natural moisture content of the soil is around 0.18%.

The studied area has a typical temperate continental climate with long cold winters and short hot summers. Temperatures are lower in the north parts and higher in the south parts of the studied area. The highest temperatures during the year are found in July, with an average temperature of 25.1°C to 26.1°C. The annual precipitation is about 125.0-207.7 mm. Shihezi City has abundant sunshine, with annual sunshine hours ranging from 2721 to 2818 hours and more sunshine in the northern region. A subsurface soil profile of the sampling site in Shihezi City is shown in Figure 3. The samples were obtained at a depth of about 10-15 cm. The soil samples were broken into pieces by using a wooden

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hammer and then dried. They were then sieved through a standard 2 mm sieve. The amount of salt and other chemical compounds of the soil were measured and are listed in Table 1. Fly ash was taken from nearby coal fired power generation plants for Shihezi City. The fly ash has a density of 2.5 g/ml and a specific surface area of 3,380 - 5,430 m^2/g. During storage and disposal of the solid waste from the power plant, leachate, which contains hazardous and harmful substances, may pollute the environment. The chemical compositions of the leachate, with its potential impact on water quality, are important in determining whether the waste is hazardous. The chemical composition of the fly ash is shown in Table 2. Based on the leachate experiments of the fly ash from the power plant, Table 3 compares the heavy metal concentrations from the leachate of the fly ash with acceptable standards. It can be seen that the fly ash used in this experiment has acceptable levels of heavy metals.

2.2 Experiments

The soil sample that was sieved through a 2 mm sieve and fly ash were dried for 24 hours in an oven at a temperature of 105°C. Six groups of samples with different fly ash contents (0, 5%, 10%, 15%, 20%, and 25% by weight) were prepared to study the influence of fly ash on the evaporation and cracking of soda soil. The soil and fly ash were evenly mixed and distilled water was added to the mixture to produce a saturated mud with a water content of 100%. The soil samples were placed in an open cylindrical glassware with an inner diameter of 20 cm and a height of 4 cm . Drying was conducted in an oven at a constant temperature with an accuracy of 0.1°C. An electronic balance with an accuracy of 0.01 g and the soil samples were placed in the oven to record the weight changes which were used to calculate the evaporation rate E_r and the average water content of the samples. The evaporation rate is calculated as follows:

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$$E_r = \frac{\Delta m}{S \bullet \Delta t} \qquad (1)$$

where S is the surface area of the soil samples, Δt is the change in time during evaporation, and Δm is the changes in the water mass.

A digital camera (D7100, Nikon, Ayutthaya, Thailand) was placed directly above the sample and pictures were taken once every hour to observe the development of cracking during evaporation. The experimental setup and images of the sample surface are shown in Figure 4. As seen in the figure, the color image is converted to grayscale to improve the contrast between the cracked and non-cracked surfaces or Steps 1 to 2. The grayscale image is then converted to a black and white binary image in order to identify the cracks, or Steps 2 to 3. The binary image is further processed to reduce the image noise for a more identification of the crack lines, or Steps 3 to 4. During the drying process, the net weight of the glass container, total weight of the soil sample and the glass container, soil sample, cracked image and accumulated drying time were recorded to a computer.

In order to characterize the crack development, fractal dimension is used to provide a quantitative measure of surface cracks. Fractal dimension is a space filling process of complex shapes, which is used to measure the irregularity of complex shapes (Mandelbrot 1985). Statistical methods are necessary to characterize the crack behavior and describe the distribution characteristics of the relative parameters. The fractal dimension is determined by a method called the differential greyscale method. In this study, the characteristic parameters of the of CIF surface crack networks and fractal dimension are introduced to characterize the development of cracks. The minimum grayscale number of the image region, N(r), has a side length r and a dimension of r×r×r. The fractal dimension, D, of the image and *N(r)* has the following relationship :

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$$\begin{cases} N(r) * r^{D} = 1 \\ \log N(r) = -D \log r \end{cases} \quad (2)$$

The CIF is a characteristic parameter of the surface crack networks, which is defined as:

$$CIF = \frac{S_c}{S} \quad (3)$$

where S is the surface area of the soil sample and S_c is the surface area of the cracks.

3 Experimental results

3.1 Effect of fly-ash on the rate of evaporation

Figure 5 shows the changes in the water content of the soil samples and the rates of evaporation with different fly ash contents. The water content with different fly ash contents gradually decreases with time and eventually becomes stable with non-zero water contents as shown in Figure 5a. The evaporation characteristics of the samples can be divided into three stages: Stage 1 - initial evaporation, Stage 2 - decreasing evaporation, and Stage 3 - residual evaporation or extremely low evaporation. Figure 5a shows that the water content of a soil sample with no fly ash decreases rapidly in Stage 1 with a high rate of evaporation. With increase in the amount of fly ash, the initial evaporation rate first decreases and then increases. The soil sample with 10% fly ash has the lowest initial rate of evaporation and the water content slowly decreases over time. The soil sample with 20% fly ash has an initial evaporation rate slightly higher than the one without fly ash. However, the soil sample with 10% fly ash has the longest Stage 1, which is 10 h longer than the other soil samples. In Stage 2, soil samples with different fly ash contents are found to have different longevity. The soil sample with 10% fly ash has the shortest longevity and quickly reaches Stage 3. In Stage 3, the residual water content increases with increase in the fly ash content, and the addition of fly ash significantly reduces the evaporation capacity of soil water. With increases in the amount of fly ash, the evaporation capacity of

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soil decreases. It is seen that 10% fly ash can effectively reduce the amount of evaporation.

3.2 Effects of fly ash on desiccation crack development of soil

Cracks started to appear when the water content of the sample decreases to a certain amount. The shape and size of the cracks can be used as an indication of stress and strain characteristics in the soil. The hydraulic properties of the soil are affected by the geometry of the crack network (Albrecht and Benson 2001). The width, length, depth, and curvature of the cracks govern the transport rate and velocity of the solutes and microorganisms in the soil. The distribution and connectivity of the cracks affect the flow paths, thereby controlling the water diffusion in the soil, which in turn affects crop growth and production. The fractal dimension and crack growth rate can be therefore used to quantitatively describe the crack characteristics of a sample.

Figure 6 shows the calculated fractal dimension and CIF with time for different fly ash contents. The cracking characteristics of the samples can be divided into three stages: Stage Ⅰ- initial cracking, Stage Ⅱ- accelerated cracking, and Stage Ⅲ – stabilization as shown in Figure 6c. With increases in the fly ash content, the fractal dimension and rate of increase of the CIF decrease with time. The fractal dimension is mainly characterized by the length of the crack. As shown in Figure 6a, the lengths of the cracks decrease with increased fly ash content which means that the fly ash can effectively inhibit crack growth. The rate of the crack growth is mainly calculated from the changes in the crack area which depends on the fly ash content. As shown in Figure 6b, the CIF decreases with increased fly ash content. The soil sample with a 15% fly ash content has the slowest crack development which is reflected by the smallest value of the CIF. Therefore a fly ash content of 10% can effectively reduce the cracking of soda soil. Figure 7 shows the relationship between the fractal dimension and CIF and water

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content. It is seen that the cracking of the sample increases with decreases in the water content. With a reduced water content, the CIFs with different fly ash contents are basically the same. However, the fractal dimension is quite different. Fly ash can therefore effectively inhibit the crack growth and reduce the crack length in soda soil.

Figure 8 shows the relationship between the rate of evaporation and the rate of change of the fractal dimension and CIF. Figure 8a shows that the fractal dimension begins to increase in Stage 2. When the fly ash contents are equal to 10% and 15%, the increase in the fractal dimension has the longest delay with the smallest value. Figure 8b shows that the CIF begins to increase at the point when the rate of evaporation decreases rapidly. The increase in CIF has the longest delay at a fly ash content of 10%.

4 Microscopic examination of fly ash using SEM and discussion of results

The water retention capacity of soda soil is affected by the microstructure of the fly ash. Fly ash is a byproduct of burning coal above 1500°C. The carbon and hydrocarbons in the coal are heated at high temperatures which generates a large amount of gas that affects the internal structures and forms of the network of silicate with other compounds. Pores are formed and connected between particles which form numerous channels and the fluid transportation network. To understand the micro structure of the fly ash, a Regulus 8100 scanning electron microscope (SEM) was used to examine the pore structure of the fly ash from coal field emissions. The highest resolution of the SEM is 0.8 nm and 0.7 nm under the 1 kV and 15 kV deceleration modes respectively. To prepare the sample for viewing under the SEM, the samples were first uniformly coated with gold. Subsequently, images with different magnifications were acquired by using different objective lens. Then the images were processed to identify the

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distribution of the pore structures.

Figure 9 shows the SEM images of the soda soil with different fly ash contents. As shown in the figure, the fly ash can significantly change the porosity of the soil sample. Small amounts of fly ash that fill the small pores in the soil results in a decrease in the porosity. With increases in the fly ash content, the micropores in the soil also increase which leads to an increase in the porosity. With increases in the drying time, less water is available for evaporation in the soil, the connectivity of the pores is reduced, and the amount of capillarity of the water is gradually decreased. Moreover, water is mainly distributed in some of the relatively small pores and greatly constrained by the soil particles. Meanwhile, more and more pores with gases are connected to each other, and the evaporation of the water in the soil is gradually dominated by water vapor diffusion, which mainly occurs in the later stages of evaporation. Fly ash is like a sandy soil that contains large pores and small clay size particles. The mixing of soil and fly ash changes the porosity of the material which helps to agglomerate the soil particles. Figure 10 shows the maximum fractal dimension, particle size distribution and the organic carbon content with different amounts of fly ash. As shown in Figure 10a, the maximum CIF first decreases and then increases, and then decreases with increases in the fly ash content, while the maximum fractal dimension first decreases and then increases. Particle size analyses were performed on soil samples with different fly ash contents using a Bettersize 2000 laser particle sizer. Figure 10b shows the changes in the particle size with different fly ash contents. The classification of the material changes from a loamy clay to clay loam when the fly ash content exceeds 15%. Due to heating, the soil organic carbon is oxidized, which produces a potassium dichromate standard solution in sulfuric acid. The excess potassium dichromate is then titrated with ferrous sulfate. The amount of organic carbon is

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calculated from the amount of ferrous sulfate consumed. The reaction follows the following formula:

$$\begin{cases} 2K_2Cr_2O_7 + 3C + 8H_2SO_4 \rightarrow K_2SO_4 + 2Cr_2(SO4)_3 + 3CO_2 + 8H_2O \\ K_2Cr_2O_7 + 6FeSO_4 + 7H_2SO_4 \rightarrow K_2SO_4 + Cr_2(SO4)_3 + 3Fe_2(SO4)_3 + 8H_2O \end{cases} \quad (4)$$

Figure 10c shows that the organic carbon content in the soil decreases with increases in the fly ash content. The residual water content shows an increasing trend with fly ash content with the highest rate of increase at a content of 10%. The soil organic carbon content decreases by 7.4% and 9.6% with fly ash contents of 10% and 15%, respectively, while the residual water content increases by 29.2% and 35.2%, with fly ash contents of 10% and 15%, respectively. In Stage 3, the soil evaporation and water adsorption reach an equilibrium condition during drying, which suggests that the residual water content can be used to measure the water retention capacity of the soil under drought conditions with no rainfall. Therefore, the optimal fly ash content to enhance the water retention capacity of the soda soil in the studied area is between 10% and 15%.

5 Conclusions

Fly ash is a recyclable material which has been widely used in many applications in recent years. In this study, the cracking characteristics of soda soil due to evaporation with different fly ash contents have been examined. The results show that the residual water content of soda soil increases from 8.55% to 16.22% with increases in the fly ash content. This represents an increase in the water retention capacity of the soda soil by 89.68% ((16.22% - 8.55%)/8.55%). The crack length gradually decreases with more fly ash, which indicates that fly ash can effectively inhibit the crack growth in soil. The rate of cracking mainly reflects the crack development in the soil. The crack area gradually decreases with more fly ash, and the development characteristics of the rate of cracking for different fly ash contents are different. The development of cracks with a fly ash content of 10% is relatively slow, which

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indicates that soda soil with a fly ash content of 10% can effectively reduce cracking of the soil. However the residual water content greatly increases at this fly ash content. Therefore, the soda soil in the studied area requires an optimal fly ash content of 10% to 15% for maximum improvement in the water retention capacity of the soil.

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List of tables

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Table 1: List of salt content and other chemical compounds of the soil sample

pH	Salt content (%)	Organic matter (%)	Ionic concentration (mg/kg)					
			Na^+	Ca^{2+}	Mg^{2+}	Cl^-	HCO_3^-	CO_3^{2-}
10.1	3.98	0.98	1000	250	170	120	2553	500

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Table 2: Chemical composition of fly ash

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3
Content (%)	55	29	8.45	3.3	1.5	1.6	0.7	0.45

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Table 3: Heavy metal concentration in fly ash leachate

Heavy metal	Cr	Pb	Zn	Cu
Heavy metal concentration in leachate (mg/Kg)	0.008	0.009	0.024	0.006
Acceptable level of heavy metal in leachate (mg/ Kg) Soil environmental quality-Risk control standard for soil contamination of agricultural land (GB15618-2018)	800	400	200	50

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