



Article

Fractal Characteristics of Natural Fiber-Reinforced Soil in Arid Climate Due to Cracking

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Abstract: Fractal geometry is a geometry that focuses on irregular geometric forms and can quantitatively describe rough and uneven surfaces and interfaces. As the main material for making natural fiber geotextile, rice straw fiber can reduce the direct impact of rainfall on soil and reduce the intensity of hydraulic erosion. This study investigates whether the use of rice straw fiber as an additive to reinforce arid soil can inhibit moisture evaporation and prevent cracking. Samples with different fiber contents added (0%, 1%, 2%, and 4%) are placed in an environmental chamber to simulate the effects of an arid climatic condition and control the temperature and humidity levels. The cracking process of the samples is recorded by using a digital camera, and the parameters of the evaporation and cracking processes are quantitatively examined through digital image processing. The results show that all of the samples with fiber have a higher residual water content and can retain 31.4%, 58.5%, and 101.9% more water than without the fibers, respectively. Furthermore, both the primary and secondary cracks as well as crack networks are inhibited in samples with a higher fiber content, that is, 2% or 4% fiber contents. The samples reinforced with fiber also have a smaller crack ratio. Compared with the samples without straw fiber, the final crack ratio of the samples with 1%, 2%, and 4% fiber is reduced by 8.05%, 24.09%, and 35.01% respectively. Finally, the final fractal dimensions of the cracks in samples with fiber contents are also reduced by 0.54%, 5.50%, and 6.40% for the samples with 1%, 2%, and 4% fiber, respectively. The addition of natural fiber as an additive to reduce evaporative cracking in soil can: (1) reduce the soil porosity; (2) enhance the binding force between the soil particles; and (3) block the hydrophobic channels. Therefore, the addition of rice straw fiber to soil can effectively reduce soil evaporation and inhibit soil cracking.

Keywords: fractal characteristics; natural fiber; soil cracking; hydrophobic channels



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1. Introduction

Straw can improve the Soil structure, promote the reproduction of microorganisms, improve the aeration and permeability of soil, and enhance the self-regulation ability of soil, thus effectively reducing water and soil loss. Desiccation cracking is a common and natural phenomenon found in soil [1], which is usually caused by shrinkage due to drying [2]. Desiccation causes the formation of a network of cracks in the soil, which negatively affects the hydraulic and mechanical properties of the soil [3,4]. For example, the strength of the soil structure is reduced, the permeability of the soil is reduced due to being unsaturated but increased due to the formation of cracks [5], and the strength and water retention capacity of the soil are both reduced, thus causing various engineering and environmental problems. The advancement of urbanization has resulted in environmental degradation and pollution problems, such as those related to sanitation, waste management and availability of drinking water. Increasing urbanization has also contributed to extreme heat events due to urban heat islands because green land is covered with pavement and other surfaces that are heat retaining and absorbing [6]. The urban heat island effect has a negative impact on

various geotechnical engineering, agricultural engineering, and environmental projects [7]. Figure 1 shows the damage to agricultural land and slopes from soil cracking.

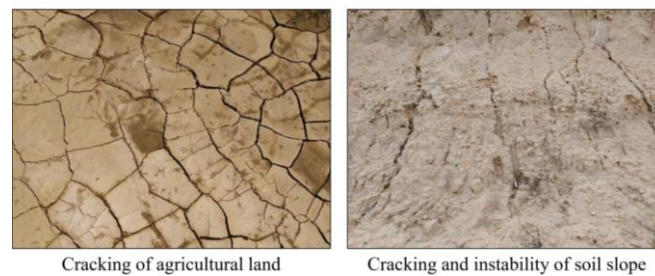


Figure 1. Damage to agricultural land and slopes from soil cracking.

Drought is a complex natural climatic cycle, and its increasing prevalence is due to the global warming effects [8]. Ongoing below-average precipitation and temperature increases are considered to be the precursors of drier-than-normal conditions [9]. Droughts have reduced agricultural production in China and are recognized as one of the costliest natural phenomena due to their widespread impacts and long duration [10,11]. They are an increasingly severe problem in the Xinjiang region of northwest China [12].

Evaporation is an important process of water balance in bare soil under arid and semi-arid conditions [13]. Zhang et al. [14] examined the impact of climate on soil moisture in the semi-arid areas of northern China and found that climate warming has reduced moisture in soil by 11.2% over the last thirty years. Moreover, it is difficult to accurately measure the water retention rate of dry soils [15]. Many techniques have been used in previous studies to estimate and predict the rate of soil evaporation, such as the one-dimensional soil models that are used to predict the effects of soil evaporation and adsorption on heat exchange between atmospheric air and surface water [16]. Qiu et al. [17] estimated soil evaporation and plant transpiration rates under arid desert conditions by using infrared remote sensing and a three-temperature model. Gong et al. [18] compared four methods to estimate soil evaporation in a site in the Guanzhong Basin in northwest China. For different methods of calculating the rate of evaporation, they found that the thermodynamic principle of the maximum increase in entropy provides the best results. Zribi et al. proposed a soil moisture estimation method based on radar satellite measurements by using ENVISAT ASAR images for a North African arid region [19].

The drying process in soil is governed by interactions between soil and the atmosphere [20]. Soil cracks play an important role in the movement of water, pollutants, and gases by providing preferential channels for water filtration and solute transport [21–23]. At the same time, cracking can adversely affect the cohesion of soils [24]. Cracks weaken soil, which reduces its strength and stability [25]. Water can seep deeper into the soil along cracks which may cause shallow landslides [26]. To determine the effects of soil desiccation cracking, many researchers use the discrete element method established by Peron et al. [27], which can simulate cracking in the field [28]. Gui and Zhao [29] developed a distinct lattice spring model to describe the drying and cracking process of soil, and identified three key factors that affect this process: particle size, heterogeneity of the soil, and boundary conditions. In addition, a large number of experimental studies have been conducted in the laboratory to examine the characteristics of soil cracking. Julina and Thyagaraj [30] used X-ray tomography (XCT) imaging and image analysis technology to measure the changes in the volume of expansive soil due to cracking from seasonal wetting–drying cycles. Auvray et al. [31] proposed an image-processing method to determine the crack area and radial strain in the cracking process of a soil model.

Soil reinforcement and remediation techniques not only enhance the mechanical properties of soil [32], such as its shear and compressive strength and hydraulic conductivity [33–35], but also the hydraulic properties of soil, such as its water-holding capacity [36], organic matter content, etc. In semi-arid and arid lands, retaining soil moisture is a priority

for agriculture and plant growth. However, conventional methods used to retain moisture are no longer acceptable as they can be environmentally damaging. As such, new types of mulch have been examined instead of the use of traditional types of mulch for soil moisture conservation. Farzi et al. [37] examined the use of pistachio shell mulch in a semi-arid region, which has a good performance in preserving soil moisture. Cabangon and Tuong [38] used straw mulch to cover soil cracks, which not only helped to retain moisture in the soil, but also limited the development of cracks. Nyabwisho et al. [39] applied three different types of treatments in a semi-arid area of Northern Tanzania in East Africa to determine the amount of soil evaluation; among which, one is mulching. They used micro lysimeters to quantify soil evaporation and found that with mulching, soil evaporation is reduced by 28%. Mellouli et al. [40] found that a subsurface treatment of soil from semi-arid regions can retain moisture for a longer period than the control soil in column testing with the use of straw mulch and olive mill effluent on the topsoil for loamy sand soil and rock fragment mulch for stony soil. As such, natural organic matter has been increasingly used in geotechnical engineering applications because they are sustainable and environmentally friendly compared to the use of traditional synthetic fibers [41]. Here, we focus specifically on the use of natural fibers that are abundant, low in cost, degradable, and environmentally friendly [42,43].

Natural fibers have been used to increase the tensile strength of cemented soil and the compressive strength of soil [44,45]. Greeshma and Joseph [46] experimentally showed that the unconfined compressive strength of soil reinforced with 0.5% untreated rice straw is 1.94 times higher than that of soil without added fiber. Zhao et al. [47] examined the different properties of coir, jute, and water hyacinth fibers for soil reinforcement by using a Bayesian nonparametric general regression method and found that more fiber added increases the reinforcement and the cellulose in these natural fibers enhances the unconfined compressive strength. Bordoloi et al. [41] discussed the impact of jute, coir, and water hyacinth fiber-reinforced composites on the infiltration characteristics of soil and found that the rate of infiltration is increased in comparison to untreated soil. Therefore, the incorporation of natural fibers in soil can positively enhance the soil properties.

As such, this study investigates soil cracking and evaporation in the arid area of Xinjiang, China by using rice straw fibers as an additive to explore the influence of this natural fiber on soil cracking and evaporation. Using digital image processing technology, the cracking process of soil samples with different fiber concentrations is monitored in real time, and the influence of the fibers on the crack formation and expansion in different cracking stages is studied. Moreover, the variation of fractal dimensions of cracks during the evaporation process is analyzed to obtain the fiber-soil coupling mechanism in the cracking process of the samples.

2. Materials and Methods

2.1. Materials

The silty clay soil used in the experiment was obtained from a construction site in the suburbs of Urumqi, the capital city of the Xinjiang Uyghur Autonomous Region. This clay is widely distributed in the arid areas of northwest China. The site has a continental climate in the moderate temperate zone. There is a large temperature difference between day and night, and the average annual precipitation is 194 mm. There can be a large temperature difference, which can be as high as 47.8 °C and as low as −41.5 °C. Three groups of soil samples of equal size were obtained to measure their basic physical parameters under the same conditions. The moisture content of soil was obtained through a soil moisture meter. The specific gravity of the soil sample was obtained by the pycnometer method, 10 g of dried soil sample was weighed and placed in a 50 mL volumetric flask containing water. The volume of discharged water was the volume of the soil sample, and the specific gravity of the soil sample was calculated by mass-to-volume ratio. The liquid limit and plastic limit were measured by a combined liquid–plastic limit tester. A laser particle size analyzer was

used to examine the particle size of the soil samples. The basic physical properties of the soil samples are listed in Table 1.

Table 1. Basic physical properties of soil samples.

Moisture Content	Specific Gravity	Liquid Limit (%)	Plastic Limit (%)	Clay (<0.002 mm)	Silt (0.002–0.075 mm)	Silt (>0.075 mm)
22.8	2.74	36.8	18.6	12.65	8.42	78.93

2.2. Sample Preparation and Test Methods

The soil samples were air dried and crushed, and then passed through a 2 mm sieve to remove large particles such as gravel. Natural uniform straw fibers, which are 0.5–1 cm in length, dry, and free of moisture, were crushed. An amount of 10 g of straw fiber was placed in an oven at 105 °C for 3 h, then the dry straw fiber was removed and weighed again; the reduced weight is the weight of water, and the moisture content of the straw fiber is calculated. Table 2 shows the basic physical properties of the fibers used in the testing.

Table 2. Basic physical properties of rice straw fibers.

Length (cm)	Width (cm)	Cellulose (%)	Hemicellulose (%)	Ash Content (%)	Water Content (%)	Tensile Strength (MPa)	Bending Strength (MPa)
0.5–1	0.2	40.5	17.8	7.25	9.2	39.6	11.6

The experiment was carried out in an environmental chamber (ZHS, Xuchang, China). The chamber is 3.5 m in length, 4.3 m in width, and 2 m in height. This chamber can simulate the effects of one or more different climates or climatic conditions. The temperature and humidity conditions can be controlled and maintained at any desired level. Figure 2 presents the images of the environmental chamber and a schematic diagram of the digital image processing procedure.

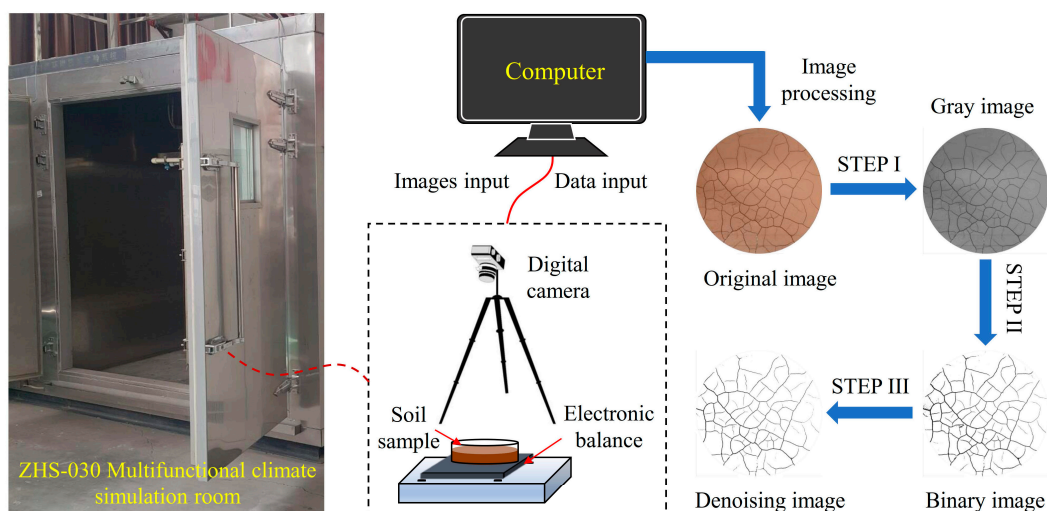


Figure 2. Images of environmental chamber and schematic of image analysis.

The test container is round and made of transparent acrylic material with a diameter of 25 cm and a height of 6 cm. Four groups of samples with different fiber contents were prepared. Group 1 does not contain any fibers, and Groups 2 to 4 have a fiber content of 1%, 2%, and 4%, respectively, and the fiber weight ratio of the sample to the total weight of soil (soil + fiber) is 1%, 2%, and 4%, respectively. The fibers were evenly mixed with the sieved soil, and then mixed with distilled water and stirred until reaching a supersaturated

state at a water content of 125%. The samples were mixed evenly and poured into the test container, and the height of the sample was limited to 5 cm, which was measured with a ruler. Considering the influence of the inner wall of the round container on the specimen cracking process, Vaseline was applied to the inner wall of the circular barrel to reduce the effect of friction on the boundaries of the specimen.

Each sample was then placed onto a scale with an accuracy of 0.001 g, and then the sample and scale were both placed in the environmental chamber. A high-definition camera was also placed on the top of the sample and the camera position was adjusted so that the camera could photograph the complete sample to provide the means to observe the initiation and development of cracks during the cracking process of the sample. The camera records the crack morphology of the surface of the sample after every three hours. When the morphology of the crack no longer changes, the evaporation process of the sample is considered to have ended.

2.3. Digital Image Processing

Digital image processing not only allows observation of the formation and development of cracks during the evaporation process, but also facilitates accurate and quantitative analyses of cracks in soil samples. The images in this study are taken with a high-definition camera which produces images with a high resolution. In the process of obtaining these high-resolution images of the cracking of the soil samples, there can be differences in the intensity and direction of the light sources when images are taken at different points in time, which can increase the amount of noise in the images. Therefore, there is a need to preprocess the raw images to remove unnecessary information, enforce data quality, and reduce variations. The digital image processing procedures for the images in this study are shown in Figure 2, which mainly consists of three steps. Step I is the conversion of the original image into a grayscale image; Step II is the conversion of the grayscale image to a black and white binary image; and finally, Step III involves the noise reduction of the binary image to provide a clear black and white image.

Color images contain much more information on color and shading, which affects the calculation of the crack characteristic parameters. Each color pixel is made up of red (R), green (G), and blue (B) color components. Therefore, the color images are first converted into grayscale images by changing the brightness. The RGB images can then be converted into grayscale with:

$$Intensity = 0.4R + 0.4G + 0.2B \quad (1)$$

The grayscale level is divided into 256 levels, which range from 0 to 255; where 0 and 255 indicate black and white, respectively.

The grayscale image of the crack edges shows an obvious step edge, so it is necessary to detect the edges. The pre-processed grayscale image can be regarded as having two regions of pixels with different grayscale values: the target and background. Therefore, it is necessary to select a reasonable threshold to identify cracks in the image. Suppose the original collected image is $f(x, y)$, the binarization image processed by the image is $g(x, y)$, and the threshold value is T :

$$g(x, y) = \begin{cases} 0, & f(x, y) < T \\ 1, & f(x, y) \geq T \end{cases} \quad (2)$$

Interference noise is found in the binary image, denoising is carried out by calculating the eight-neighbor average. The eight-neighborhood denoising method is effective for removing small noise points, and the computational cost is not large. That is, each pixel is compared to the grayscale average of eight of its neighbor pixels; if the difference is greater than a certain threshold, the pixel is noisy and replaced by the average. As such, if the threshold of a pixel is 0, which denotes noise, it is shown as a black color. If the threshold is 255, which denotes relatively isolated noise, it is shown as a white color. Therefore, the criteria used to determine image noise are as follows: a noisy pixel is black in color, and

eight adjacent pixels that surround the noisy pixel are considered to be white. An optimum threshold should be adjusted to denoise images of different binary crack networks to obtain noise-reduced images.

2.4. Calculation of Crack Characteristic Parameters

The crack ratio and fractal dimension of the samples during the process of evaporative cracking are calculated to quantitatively obtain the changes in the crack characteristics. The crack ratio of the samples is calculated by using:

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

where μ is the crack ratio of the sample, $\sum S_c$ is the total projected area (cm^2) of the crack on the surface of the sample, and S is the surface area (cm^2) of the sample without any cracks.

In this study, the fractal dimension is used because it is a measure to quantify the self-similarity of objects in images [48]. There are many methods to calculate the fractal dimension, such as size, slit island, and box-counting methods, etc. The fractal dimension can be used to measure the irregularity of cracks during the cracking process of the samples. The box-counting method is one of the most common methods used because it has been proven effective and can be applied to any dimensional set. Given a box of side length r , if B is defined as a finite set and $N(r)$ is the number of sets that are needed to cover B with a length of r , the fractal dimension D_B can be calculated by using:

$$D_B = -\lim_{r \rightarrow 0} \frac{\log N(r)}{\log r} \quad (4)$$

where D_B is the fractal dimension.

The variation of the water content of the sample was reflected by using a scale indicator, which recorded the variation every two hours and calculated by using:

$$\omega = \frac{m - m_0}{m_0} \quad (5)$$

where ω is the water content of the sample, m is the current mass of the sample, and m_0 is the dry mass of the sample after evaporation takes place.

The evaporation rate is obtained by calculating the rate of change of the water content per unit time as follows:

$$E = \frac{\Delta m}{\Delta t} \quad (6)$$

where E represents the evaporation rate, (g/h); Δm is the difference in water content in the sample after three hours has lapsed, g; and Δt is the time interval, which is 3 h in this study.

2.5. Structural Characteristics Model of Soil Reinforced with Natural Fibers

Figure 3 shows the conceptual soil model reinforced by using natural fibers. The three-phase system of the soil in the natural state is shown in Figure 3a,b, which shows the natural straw fibers added for testing. Figure 3c shows the idealized model of natural fibers mixed into the soil. The volume of air, water, and soil in the three-phase system of soil in the natural state is defined as V_A , V_W , and V_S , respectively.

In its natural state without fiber additive, the void ratio of the soil, e_n , can be calculated from:

$$e_n = \frac{V_{A+W}}{V_S} = \frac{V_A + V_W}{V_S} \quad (7)$$

where V_{A+W} , V_A , V_W , and V_S are the volume of air and water, the volume of air, volume of water, and the volume of soil solid, respectively.

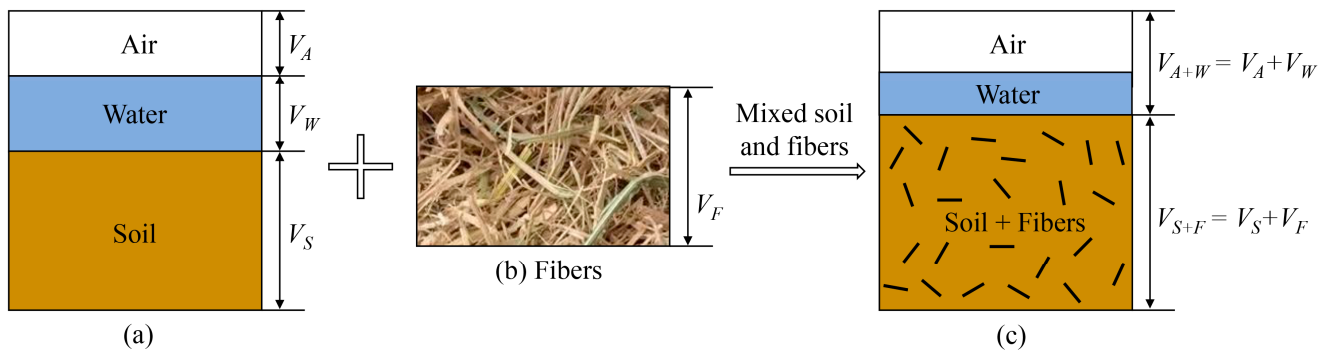


Figure 3. Schematic of reinforcement of soil with rice straw fibers: (a) soil (b) fibers, and (c) mixed soil and fibers.

The compacted fiber volume is assumed to be V_F . After fiber is added to the soil, the volume of soil and fiber is defined as V_{S+F} , and the expression for the void ratio of the reinforced soil is:

$$e = \frac{V_{A+W}}{V_{S+F}} = \frac{V_A + V_W}{V_S + V_F} \quad (8)$$

Divided Equation (8) by V_S gives:

$$e = \frac{(V_A + V_W)/V_S}{(V_S + V_F)/V_S} = \frac{e_n}{1 + V_F/V_S} \quad (9)$$

3. Experimental Results

3.1. Effect of Natural Fibers on Soil Evaporation

Figure 4 plots the water contents and evaporation rate of the samples with time. The initial water content of the four samples (which have different fiber contents (0%, 1%, 2%, and 4%), respectively) is the same or 100%. They were prepared and placed in the environmental chamber for a total of 160 h. After 160 h elapsed, the water contents of the samples with a fiber content of 0%, 1%, 2%, and 4% are 3.18%, 4.18%, 5.04%, and 6.42%, respectively. Compared to the sample without any fibers, the samples with 1%, 2%, and 4% fiber contents can retain 31.4%, 58.5%, and 101.9% more water, respectively. In these tests, the final volume of water in the samples shows a positive correlation with the fiber content. Therefore, adding rice straw fibers to the soil samples in this study can effectively increase their water holding capacity.

In Figure 4, the evaporation process of the four samples with time can be divided into three stages. Stage I is a constant rate of evaporation. The duration of Stage I for the sample without fibers is 69 h, while for the samples with 1%, 2%, and 4% fibers, the durations are 60 h, 66 h, and 63 h, respectively. This shows that the addition of fibers can effectively reduce the constant rate of evaporation. The evaporation rate of the sample in this stage is high and constant. Stage II is a rapid decrease in the rate of evaporation. The duration of the evaporation of the sample without fibers is 138 h, in which Stage II consists of 69 h. The duration of the evaporation of the samples with 1%, 2%, and 4% fibers is 144 h, 141 h, and 141 h, in which Stage II consists of 84 h, 75 h, and 78 h, respectively. The results show that the addition of fibers can effectively prolong the stage in which there is a decrease in evaporation, and the evaporation rate shows an obvious downward trend. Stage III involves residual evaporation, in which the evaporation rate of the sample decreases slowly and tends to stop.

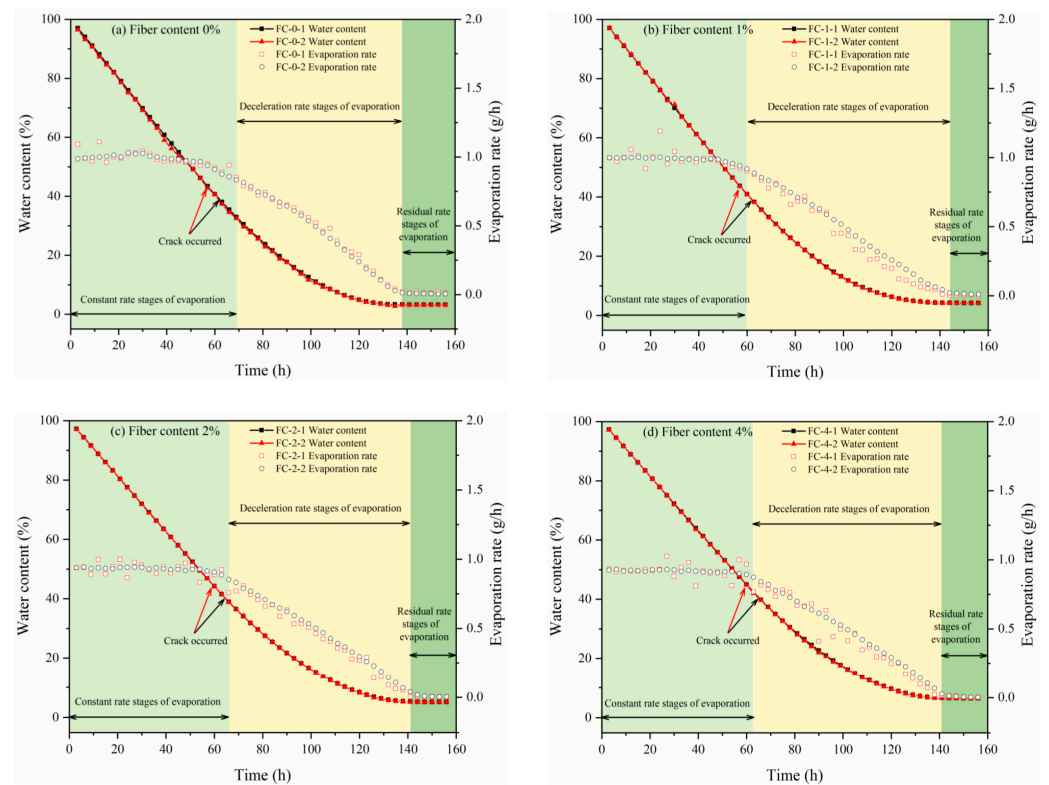


Figure 4. Water contents and evaporation rate of samples with time.

3.2. Crack Morphology

Figure 5a shows the cracking process of the samples. The evolution of the cracking process can also be examined in three stages. Stage A is the initial cracking stage, in which the crack width is narrow, and the cracks are confined to a small area of the sample. Stage B is the accelerated cracking stage, which shows the progressive development of the primary cracks and the gradual appearance of secondary cracks. Stage C is the end of the cracking stage, in which the sample cracks are large, deep, and wide. After that, the crack ratio reaches the maximum value, and the morphology of the cracks does not change. As Figure 5a shows, the primary cracks are mainly formed in Stage A, while the secondary cracks emerge and gradually expand perpendicular to the primary cracks. In Stage C, the cracks gradually cross each other to form a crack network. To determine the influence of fiber addition on the formation of cracks, the morphology of the samples was analyzed at the end of the cracking or after 156 h. The crack morphology of the sample without fibers is evident for both the primary and secondary cracks. The addition of 1% fiber mainly affects the number and range of the secondary cracks and crack network but has no effect on the primary cracks. As for the samples with 2% and 4% fibers, the fibers have an effect on both the primary and secondary cracks, and the crack network in that the crack propagation is effectively inhibited.

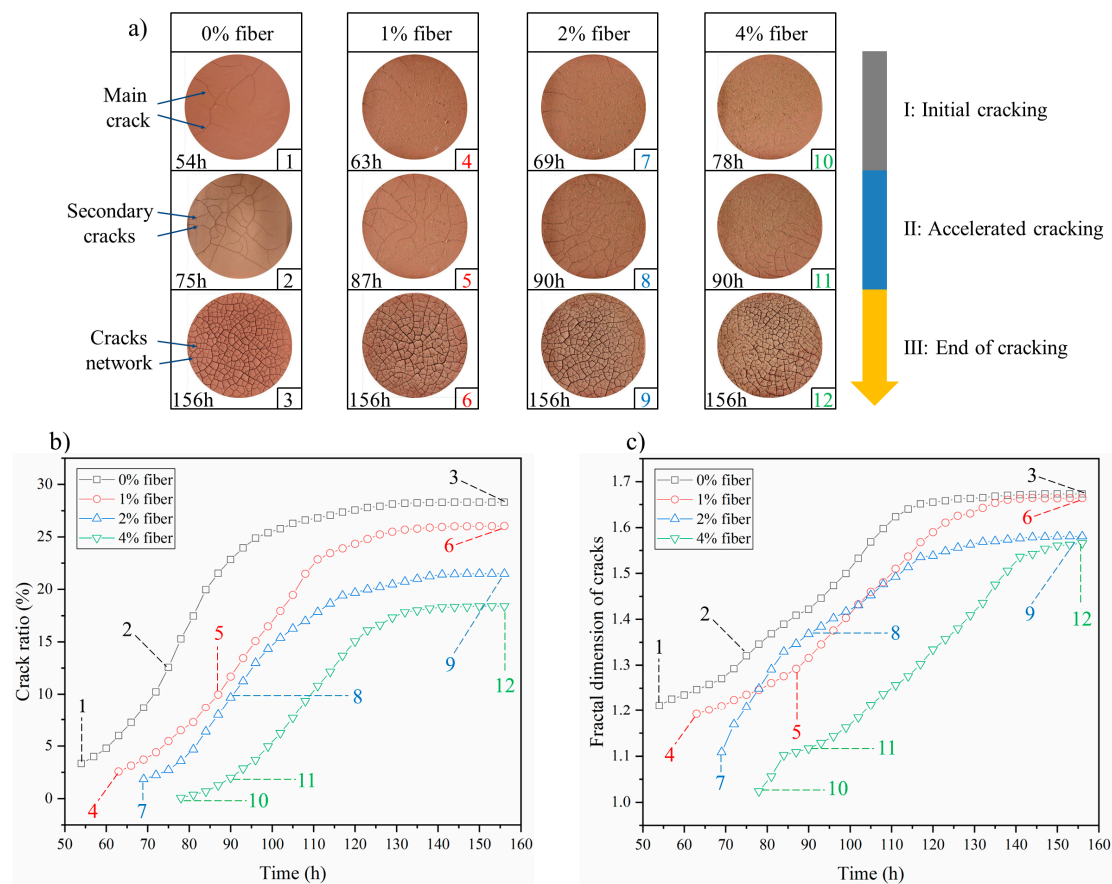


Figure 5. Changes in characteristics of crack parameters: (a) Cracking process of the sample, (b) crack ratio of samples with time, and (c) fractal dimension of samples with time.

3.3. Variations in Crack Characteristic Parameters

Figure 5b shows the changes in the crack ratio with time during the cracking process of the samples. The sample without fibers cracks first at 54 h. The initial cracking time of the samples that contain 1%, 2%, and 4% fibers was delayed by 9 h, 15 h, and 24 h, respectively, compared to the sample without fiber. Considering Figure 5a, the initial crack ratio of the sample without fibers is the largest, and the initial crack ratio of the sample with 1%, 2%, and 4% fiber decreases successively. During the entire cracking process, the crack ratios of the four samples increase with time. When cracking is ceased, the final crack ratio of the sample without fibers is 28.31%, and that of the samples with 1%, 2%, and 4% fibers is 26.03%, 21.49%, and 18.4%, respectively. Compared to the sample without fibers, the crack ratios are reduced by 8.05%, 24.09%, and 35.01%, respectively. From the cracking of the sample to the decrease in the crack ratio with time, the main reason for the result is due to the early initiation of cracking and the increase in cracking of the samples later on. The secondary cracks and crack network are mainly inhibited when the sample has 1% fiber, as mentioned above, while both the primary and secondary cracks and the crack network are inhibited for the samples with 2% or 4% fiber. Therefore, the crack ratio of the sample with 1% fiber is obviously smaller than that of the sample that contains 2% or 4% fiber. The results show that an increase in fiber content inhibits soil cracking.

Figure 5c shows the changes in the fractal dimension with time during the cracking process. The fractal dimension of the samples at the initiation of cracking is defined as the initial fractal dimension. The initial fractal dimension of the sample without fibers is larger than that of the samples with fibers. The initial fractal dimensions of the cracks in samples with 0%, 1%, 2%, and 4% fibers are 1.212, 1.192, 1.109, and 1.024, and the final fractal dimensions are 1.673, 1.664, 1.581, 1.566, respectively. The final fractal dimensions

of the cracks in the samples with 1%, 2%, and 4% fiber are reduced by 0.54%, 5.50%, and 6.40%, respectively, compared to that of the sample without fiber.

According to the changes in the crack ratio with time and the fractal dimension with time of the four samples, the crack ratio and fractal dimension of the samples with 1%, 2%, and 4% fiber are smaller and lower than that without fibers, respectively.

As shown in Figure 5c, after 90 h of evaporation and cracking, the fractal dimensions of cracks in samples with 0%, 1%, 2%, and 4% straw fibers are 1.421, 1.316, 1.362, and 1.115, respectively. Figure 6 shows the fitted curves of the fractal dimension of the cracks at 90 h. According to Formula (4), the opposite of the slope of the fitted curve is the fractal dimension.

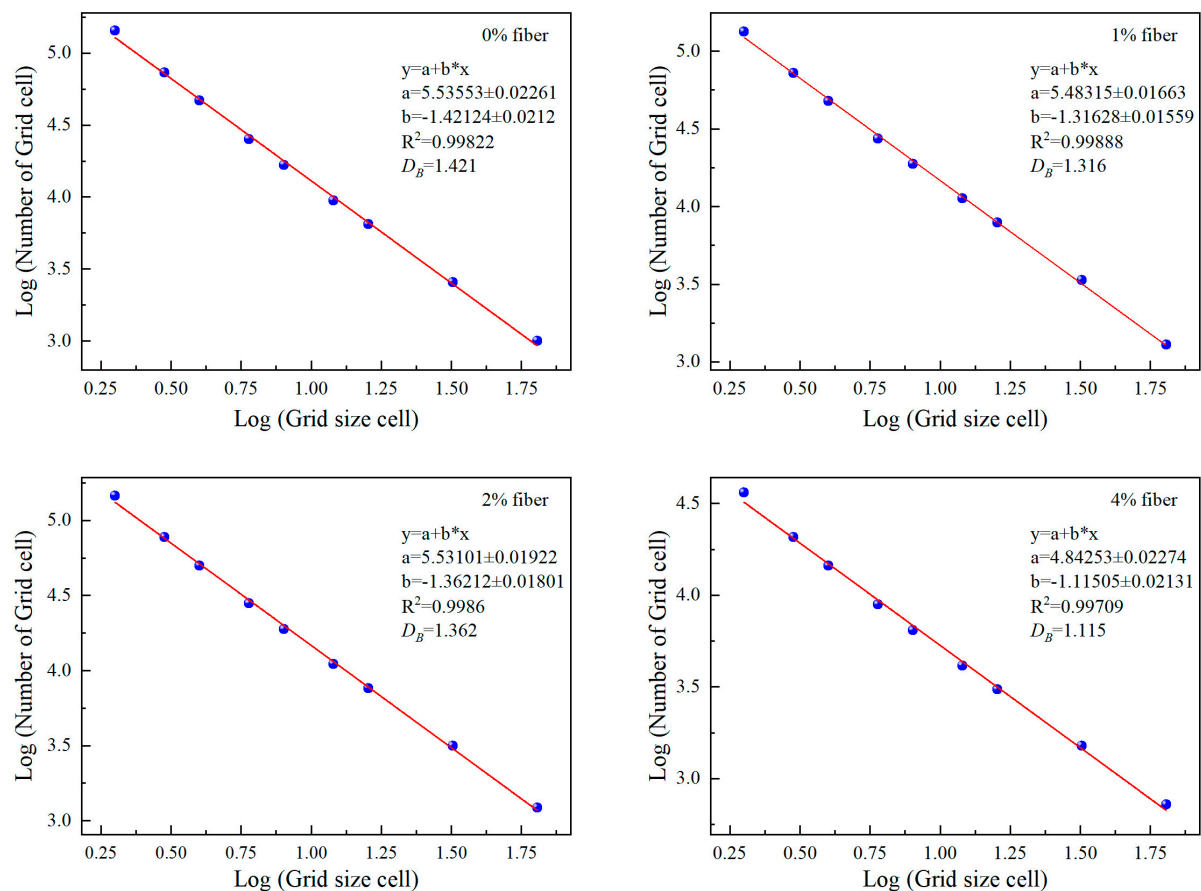


Figure 6. The fitted curves of the fractal dimension of the cracks at 90 h.

4. Discussion of Results

Mechanism of Reduction of Soil Evaporation and Cracking with Natural Fiber Additive

It can be seen from Equation (9) that the void ratio of the reinforced soil is negatively correlated to the volume ratio of the fiber to the soil solid (V_F/V_S). When V_F/V_S is larger, e is smaller. If V_F/V_S tends to 0, e tends to e_n . If V_F/V_S is smaller, e is larger, and as V_F/V_S approaches infinity, e approaches zero.

Therefore, maintaining a reasonable fiber-to-soil volume ratio is the key to obtaining the optimal void ratio. According to Equation (9), the void of the samples is decreased with an increase in the fiber contents of 0%, 1%, 2%, and 4%. After evaporation takes place, the residual water contents of the samples with 0%, 1%, 2%, and 4% fiber are 3.18%, 4.18%, 5.04%, and 6.42%, respectively. The results are not only related to the absorption capacity of the fibers, but they also show that a higher void ratio is more conducive to evaporation in the soil.

This study shows that the addition of natural fiber to soil will inhibit soil evaporation and cracking. The mechanism behind this reduction in soil evaporation and cracking is shown in Figure 7. At the initial stage of evaporation, the sample contains fibers, soil, water, and air, and the fibers are randomly distributed in the soil. With the evaporation of water, the sample shrinks horizontally and vertically, and the amount of shrinkage increases with the evaporation rate. The actual effect and schematic diagram of the fiber-reinforced soil samples are shown on the left side of Figure 7. With the decrease in moisture, the cracks gradually propagate from the surface of the sample to the fibers, and the fibers are embedded on both sides of the crack. At this time, the fiber and soil act as a “skeleton structure”, which can effectively limit soil cracking due to the friction between the fibers and the soil. The fiber provides tensile resistance to reduce further widening of the crack. The right side of Figure 7 shows how the fibers reduce soil evaporation in the schematic diagram of the initial water movement. When the water movement path is blocked by the fibers, the migration of water is impeded, which not only increases the length of the water flow channel but also reduces the cross-sectional area available for water flow. Coupled with the water absorption ability of the natural fibers, the moisture content in the sample with fibers is therefore higher than that in the sample without fibers. At the end of the evaporation process, only residual water and air remain in the sample.

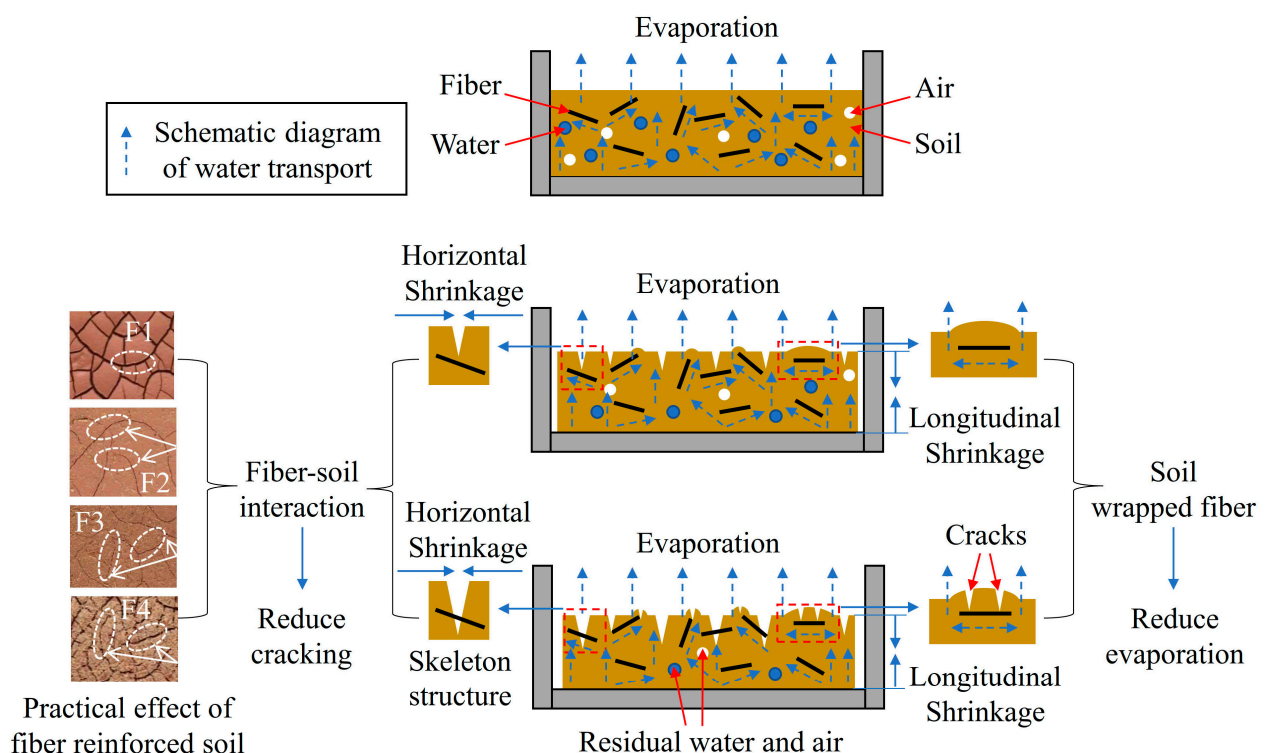


Figure 7. The mechanism through which rice straw fibers reduce soil evaporation and cracking.

5. Summary and Conclusions

In this paper, drying tests of samples with 0%, 1%, 2%, and 4% fiber have been carried out. The parameters for the evaporation and cracking processes of soil samples are quantitatively measured by using digital image processing. The changes during the process in the evaporation rate, crack ratio, and fractal dimension with time of the samples with different fiber contents are examined, and the influence of the fiber content on the surface cracks of the soil samples is analyzed. Finally, the mechanism for reducing the rate of evaporation and cracking of fibers is discussed. The following conclusions are made accordingly:

1. At the end of the evaporation process, the residual water contents of the samples with 0%, 1%, 2%, and 4% fiber are 3.18%, 4.18%, 5.04%, and 6.42%, respectively. All of the samples with fiber content have a higher residual water content than the sample without fibers; they can retain 31.4%, 58.5%, and 101.9% more water, respectively.
2. The surface morphology of the soil is composed of primary and secondary cracks which form a crack network. The sample with 1% fiber mainly inhibits the expansion of the secondary cracks and crack networks, but does not affect the expansion of the primary cracks. However, samples with 2% or 4% fiber can prevent the initiation of both primary and secondary cracks as well as crack networks.
3. At the end of the cracking process, the final crack ratios of the samples with 0%, 1%, 2%, and 4% fiber are 28.31%, 26.03%, 21.49%, and 18.4%, respectively. Evidently, rice straw fibers used as additives can reduce the crack ratio of the samples with 1%, 2%, and 4% fiber by 8.05%, 24.09%, and 35.01%, respectively.
4. The final fractal dimensions of the samples with 0%, 1%, 2%, and 4% fiber are 1.673, 1.664, 1.581, and 1.566, respectively. This shows that the addition of 1%, 2%, and 4% rice straw fiber reduces the fractal dimension by 0.54%, 5.50%, and 6.40%, respectively.

The findings in this study show that rice straw fiber used as a soil reinforcement in arid soil can retain moisture content and prevent desiccation cracking.

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