

## Article

# Investigation of Desiccation Cracking Behavior of Waste Carbon Fiber–Reinforced Clay Material

Fei Chen <sup>1,2</sup>, Yang Chen <sup>3,\*</sup>, Ling Li <sup>1,2</sup>, Changde Yang <sup>1,2</sup> and Binbin Yang <sup>4</sup>

<sup>1</sup> School of Mining Engineering and Geology, Xinjiang Institute of Engineering, Urumqi 830023, China; cf32@xjie.edu.cn (F.C.); ll01@xjie.edu.cn (L.L.); ycd@cumt.edu.cn (C.Y.)

<sup>2</sup> Key Laboratory of Xinjiang Coal Resources Green Mining, Ministry of Education, Xinjiang Institute of Engineering, Urumqi 830023, China

<sup>3</sup> School of Earth Sciences and Engineering, Sun Yat-sen University, Zhuhai 519082, China

<sup>4</sup> School of Civil Engineering, Xuchang University, No.88 Bayi Rd, Xuchang 461000, China; yangbinbin@xcu.edu.cn

\* Correspondence: chen2267@mail2.sysu.edu.cn

**Abstract:** Carbon fiber is a common waste building material, but its effect on the drying and cracking properties of clay materials is unknown. In this paper, crack rate and fractal dimension are used to characterize the influence of waste carbon fiber materials on the development of soil cracking. With the rise in carbon fiber content to 0.2%, 0.4% and 0.6%, the crack rate of soil cracking decreased by 7.9%, 17.3% and 23.3%, respectively, while the fractal dimension of soil cracking decreased by 2.4%, 8.7% and 21.2%, respectively. Accordingly, the critical moisture content of the soil samples increased by 33.2%, 110% and 151%, and the time of the soil constant evaporation stage decreased by 5.1%, 13.8% and 34.5%, respectively. When carbon fiber is combined with soil, carbon fiber will increase the interface bonding strength, friction and interlocking force, effectively inhibiting the cracking of soil, and it provides a channel for water transport in the soil in the early stage.

**Keywords:** waste carbon fiber; clay materials; soil; cracking behavior

**Citation:** Chen, F.; Chen, Y.; Li, L.; Yang, C.; Yang, B. Investigation of Desiccation Cracking Behavior of Waste Carbon Fiber–Reinforced Clay Material. *Buildings* **2024**, *14*, 2081. <https://doi.org/10.3390/buildings14072081>

Academic Editor: Abderrahim Boudenne

Received: 12 May 2024

Revised: 2 July 2024

Accepted: 5 July 2024

Published: 7 July 2024



**Copyright:** © 2024 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

As a high-performance, fiber-reinforced material, carbon fiber has been used in building engineering and other fields [1–3]. Carbon fiber has become a potential new pollutant due to its durability and difficult degradation and may exist in the soil for a long time after waste, which will lead to changes in soil characteristics and have a negative impact on the soil ecosystem [4]. Therefore, people have started to pay attention to its potential impact on the soil environment.

In arid areas, soil water evaporation is a concern because it directly affects soil water content and crop growth, and then leads to soil degradation and desertification [5]. With the intensification of global climate change, the problem of soil evaporation in arid areas is becoming more and more prominent, which causes concern about the soil ecological environment [6]. Soil evaporation is the process of water transfer from soil to the atmosphere. Long-term excessive evaporation of soil will lead to soil degradation and desertification. Excessive soil evaporation also leads to nutrient loss and salt accumulation in the soil, reducing soil water persistence, fertility and productivity [7–9]. At the same time, soil evaporation will also lead to the occurrence of soil surface crust and wind erosion, accelerate soil erosion and loss, and then aggravate soil poverty and desertification.

When the soil is too dry, the dry shrinkage cracking phenomenon will occur [10–13]. The dry shrinkage cracking of soil will not only have a negative impact on the ecological environment, but also have a negative impact on the geotechnical structure [14–16]. The

cracks formed by soil water loss and shrinkage will destroy the integrity of soil and degrade the physical and mechanical properties of soil, which will lead to various engineering geological problems. Soil cracking in slope engineering will make water flow into the soil more easily and reduce the soil strength faster, resulting in slope instability [17–19]. Carbon fiber as a light, high-strength, corrosion-resistant advanced material has a wide range of applications in various fields [20–22]. Carbon fiber composite material has excellent strength and stability, and by injecting carbon fiber composite material into the soil, it can strengthen the soil structure and prevent soil erosion and loss [23–25]. Since carbon fiber usually has a strong tensile strength, it is assumed that it can reduce the problem of soil cracking. Compared with traditional polypropylene fiber, carbon fiber has a higher tensile strength and elastic modulus and has excellent durability for soil improvement and is therefore very suitable. Although polypropylene fiber is cheaper than carbon fiber, a small amount of carbon fiber can significantly improve soil [24]. In addition, with the development of science and technology, the price of carbon fiber will gradually decline. The application prospect of carbon fiber in the field of soil improvement is broad.

Fractal theory is an active branch of nonlinear science, which is developed from fractal geometry [26,27]. The crack propagation mode of soil cracking has certain randomness and fractal characteristics, so the fractal theory is suitable to study the crack development process of the soil surface [28–30]. The fractal theory is used to calculate the fractal dimension of crack variation in the process of soil cracking, which can be transformed into the fractal dimension.

Dry shrinkage cracks formed by the evaporation of soil water are the main channels for soil water transport. Different carbon fiber materials can affect soil water evaporation by changing the dry shrinkage cracks and seepage paths in soil. However, the effects of carbon fiber–soil composite on evaporation characteristics and cracking mechanisms are not clear. In this paper, the effects of waste carbon fiber materials on soil evaporation were studied in a climate simulation laboratory. The cracking characteristics and mechanism of soil evaporation were investigated using image-processing technology.

## 2. Materials and Methods

### 2.1. Materials

This study evaluates the effects of different carbon fiber materials on soil evaporation and cracking. Carbon fiber is a type of high-performance composite material, which is not only a waste material of construction engineering, but also has the characteristics of a high specific modulus and chemical-corrosion resistance. The carbon fiber contents used in this test are 0%, 0.2%, 0.4% and 0.6%. Table 1 shows the basic parameters of carbon fiber. The surface of carbon fiber is smooth and there are no obvious bumps, burrs or grooves (Figure 1).



**Figure 1.** Carbon fiber.**Table 1.** Basic parameters of carbon fiber.

| Diameter ( $\mu\text{m}$ ) | Density ( $\text{g}\cdot\text{cm}^{-3}$ ) | Elongation (%) | Tensile Strength (MPa) | Tensile Modulus (GPa) | Elongation at Break (%) |
|----------------------------|-------------------------------------------|----------------|------------------------|-----------------------|-------------------------|
| 8                          | 1.78                                      | 1.9            | 5920                   | 298                   | 2.04                    |

The soil samples in this experiment were taken from Hua County, Anyang City, Henan Province. The basic properties of the soil samples are shown in Table 2. Hua County is located in the former route of the Yellow River and belongs to the alluvial plain of the Yellow River, which is a part of the North China Plain. The terrain is flat and the soil is soft. The average annual temperature is 13.7 °C, the annual precipitation is 634.3 mm, the annual evaporation is 1931.4 mm and the frost-free period is 200 days. The geographical location of the sample is 114°31'01" E, 35°33'14" N, and the altitude is 62.13 m. The sample belongs to the subclass of tidal loam soil. The sampling depth of the soil sample is 0~20 cm.

**Table 2.** Basic properties of the soil samples.

| Density ( $\text{g}\cdot\text{cm}^{-3}$ ) | Moisture Content (%) | Plasticity Index | pH  | Organic Matter (%) | Total Nitrogen (%) | Available Phosphorus (ppm) | Available Potassium (ppm) |
|-------------------------------------------|----------------------|------------------|-----|--------------------|--------------------|----------------------------|---------------------------|
| 1.86                                      | 16.5                 | 24.2             | 8.1 | 0.87               | 0.057              | 4                          | 155                       |

## 2.2. Methods

Before the test, dried soil samples (less than 2 mm) with removed gravel and plant roots were placed in square glass containers measuring 40 × 40 × 5 cm. The 200 g soil sample previously sealed was successively added to each glass container with different contents of carbon fiber to make it into a mud with 100% moisture content. The samples were thoroughly mixed with a glass rod and then left to ensure that the carbon fiber was fully mixed with the mud. To study the effect of different carbon fiber content on the evaporation and cracking characteristics of the soil samples, four groups of mud with different carbon fiber content were set up, and each group was set up with control test samples. The prepared sample was weighed and photographed in real time to observe the evaporation rate and dry shrinkage crack growth of the soil sample. The soil samples were tested in a climate simulation laboratory environment with a constant temperature of 25 °C and a relative humidity of 50%.

Based on the change in the weight of the soil sample, the moisture content  $w$  and the average evaporation rate  $E_v$  of the real-time sample of the soil sample can be calculated as follows:

$$E_v = \frac{\Delta m}{t} \quad (1)$$

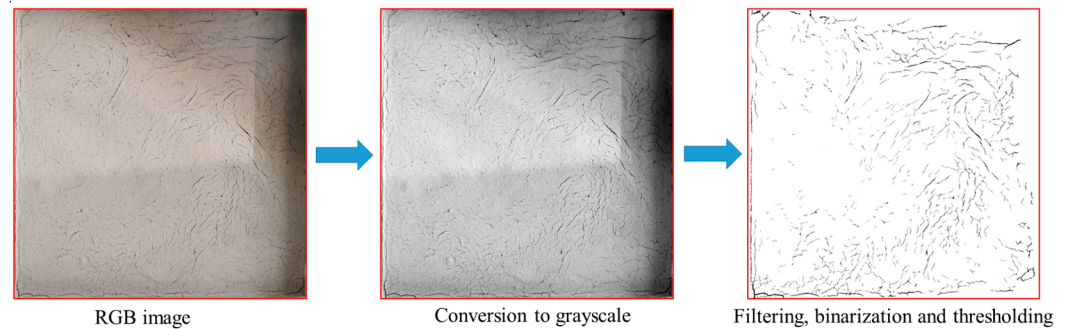
$$w = \frac{m_0 - \Delta m}{m_d} \quad (2)$$

where  $t$  is evaporation time (h),  $\Delta m$  is the change in sample weight (g),  $m_0$  is the initial weight of water in the sample (g),  $m_d$  is the weight of dry soil (g), and  $w$  is the water content (%).

In the process of this experiment, the images obtained from the experiment were analyzed quantitatively after grayscale, binarization and noise reduction. The method of image processing is shown in Figure 2. The crack rate and fractal dimension of the samples during evaporation are calculated to quantitatively obtain the changes in the crack characteristics. The crack rate of the samples is calculated using

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

where  $\mu$  is the crack rate of the sample (%),  $S_c$  is the total crack area of the surface area of the sample ( $\text{cm}^2$ ) and  $S$  is the surface area of the sample ( $\text{cm}^2$ ).



**Figure 2.** The method of image processing.

Fractal has three elements (shape, chance and dimension) and can be used to solve problems that cannot be described in traditional geometric methods. Simple formulas are used to describe very complex things, so fractal theory is often used to describe “irregular” graphics and segmented graphics [31,32]. The mathematical tool used in fractal theory is fractal geometry and the two basic features of fractal geometry are self-similarity and scale invariance [33–35]. Fractal dimension is often expressed as a quantitative parameter of self-similarity and scale invariance, and is a mathematical measure used to describe the complexity of fractal sets. Self-similarity refers to the statistical similarity between a part and a whole in terms of function and shape [36]. Dimensions are integers, but fractal dimensions change continuously, and there is a difference between the two. The importance of fractal dimensions lies in the fact that they can be defined in terms of data and can be approximated by experimental means. Fractal dimension quantifies the self-similar property of fractals and is also the main basis for distinguishing chaos from other motion forms. Fractal dimension is based on the idea of scale measurement. For the convenience of expression, the finite set is a compact set of metric space [37]. This assumption is widely representative, because most of the geometric objects with fractal properties encountered in practical problems can be used as mathematical models by the compact set of Euclidean metric spaces.

According to the number of dark pixels in the crack region of the sample, the fractal dimension  $D$  of the crack is calculated. The box count size is defined as follows:

When  $r$  goes to 0, there is

$$N(r) \propto r^{-D} \quad (4)$$

If and only if there is a positive number  $k$  that makes

$$\lim_{r \rightarrow 0} \frac{N(r)}{r^{-D}} = k \quad (5)$$

Take the logarithm of both sides of the equation and calculate it

$$\lim_{r \rightarrow 0} (\log N(r) + D \log r) = \log k \quad (6)$$

To wit

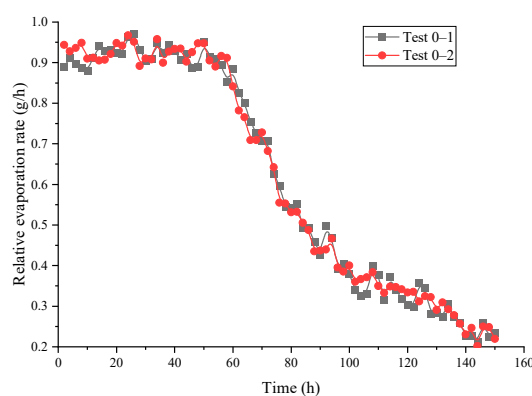
$$D = \lim_{r \rightarrow 0} \frac{\log N(r)}{\log(1/r)} \quad (7)$$

where  $N(r)$  is the number of boxes containing the crack and  $r$  is the length of the side of the box.

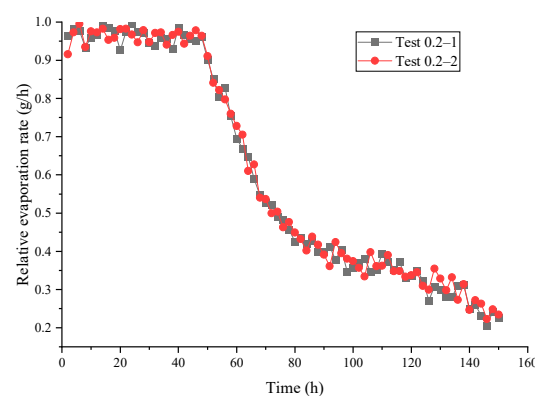
### 3. Results

#### 3.1. Sample Evaporation Characteristics

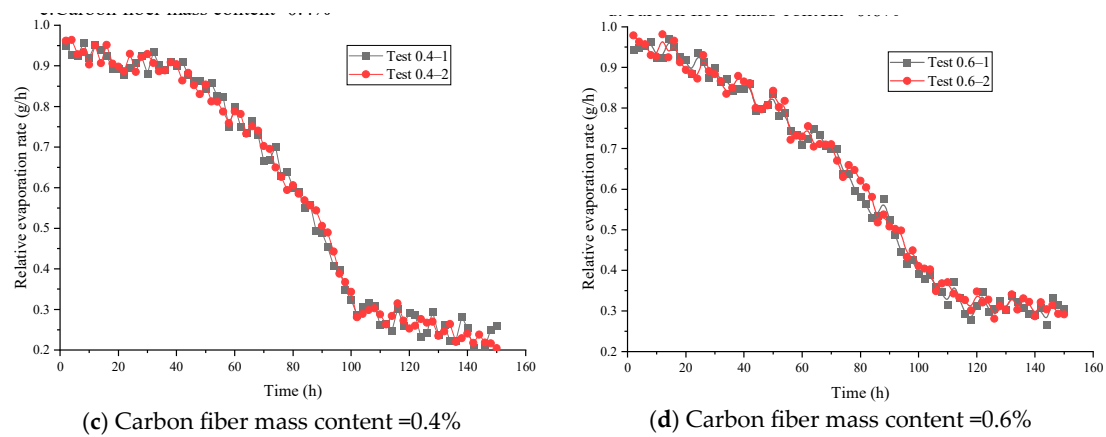
The direct result of evaporation is to reduce the moisture content of soil, which leads to the change of physical–mechanical properties of soil and induces various engineering geological problems and environmental geological problems. Due to the high proportion of hydrophilic clay minerals, the occurrence state of pore water and its pore structure are much more complex than that of sandy soil. Moreover, during the evaporation process, viscous soil will significantly shrink, deform or even crack, which has an important impact on water migration. As shown in Figure 3, evaporation usually starts from the soil surface, when the sample is in a saturated state, so it is mainly surface free water evaporation and the initial evaporation rate is large. As shown in Figure 3a, the evaporation rate of the sample without adding carbon fiber is divided into three stages (constant evaporation stage, deceleration evaporation stage and equilibrium stage) [38]. With the rise in carbon fiber content (Figure 3b–d), the constant evaporation stage time of the sample becomes shorter. With the increase in carbon fiber content from 0.2% to 0.6%, the constant evaporation stage time of the sample decreases by 5.1%, 13.8% and 34.5% respectively. In this process, the latent heat transferred to the soil by the external environment is completely used to supplement the heat consumed by free water evaporation. The soil temperature and the atmosphere temperature reach a relative balance and the vapor pressure gradient between the soil and the atmosphere is basically unchanged. As evaporation proceeds, the cracking of the clay further promotes evaporation. For clay, free water is the first to evaporate when drying, and the evaporation rate in the soil gradually transitions from the constant rate stage to the deceleration rate stage. With the rise in carbon fiber content, the deceleration evaporation time of the sample decreases by 6.25%, 3.75% and 2.25%, respectively.



(a) Carbon fiber mass content = 0%

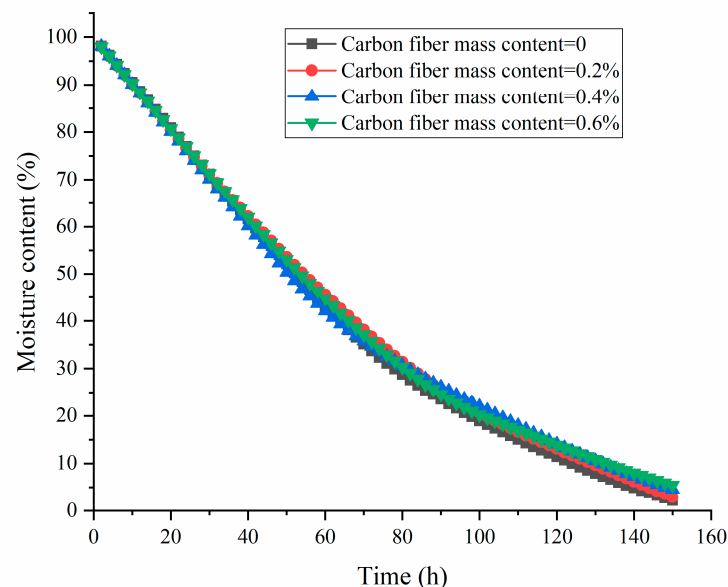


(b) Carbon fiber mass content = 0.2%



**Figure 3.** Change of the relative evaporation rate of the sample over time.

With the passage of drying time, the water available for evaporation in the soil becomes less and less and the connectivity of pore water decreases gradually. At the same time, the pore gases are increasing and penetrating each other. The sample without carbon fiber entered the equilibrium evaporation stage at the earliest, when the water absorption and evaporation rate of the sample reached the equilibrium, and the water content of the test remained basically unchanged. As shown in Figure 4, with the rise in carbon fiber content in the sample, the critical moisture content in the equilibrium state of the sample increased by 33.2%, 110% and 151%.



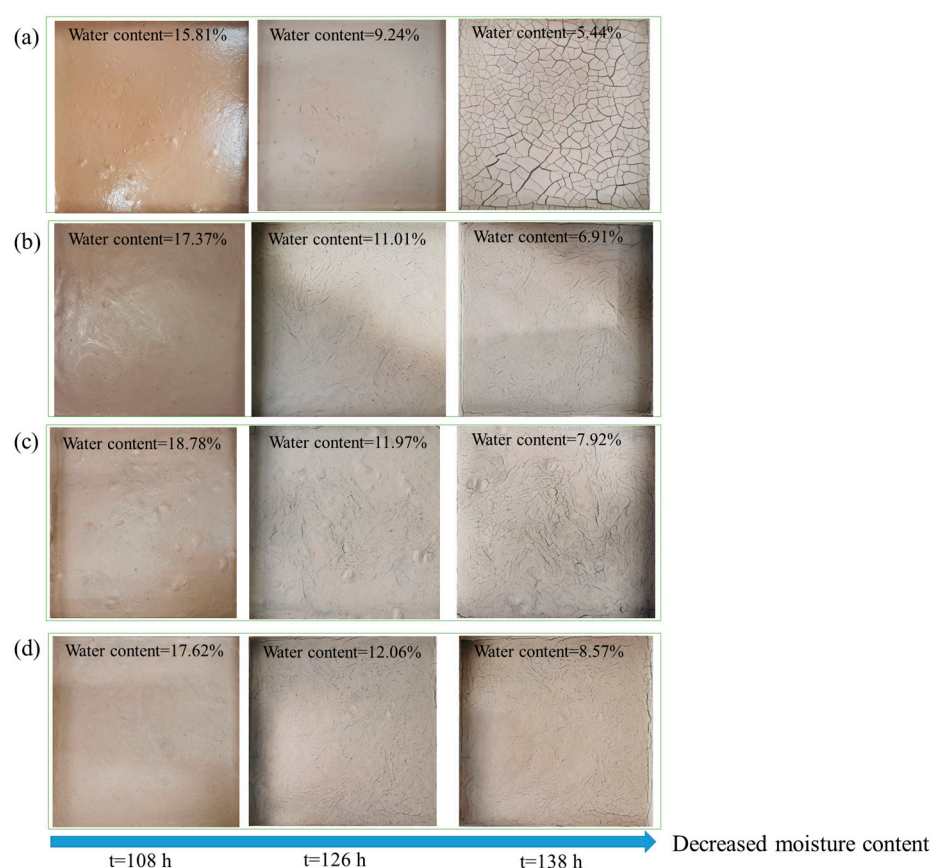
**Figure 4.** Change of the moisture content of the sample over time.

### 3.2. Sample Cracking Behavior

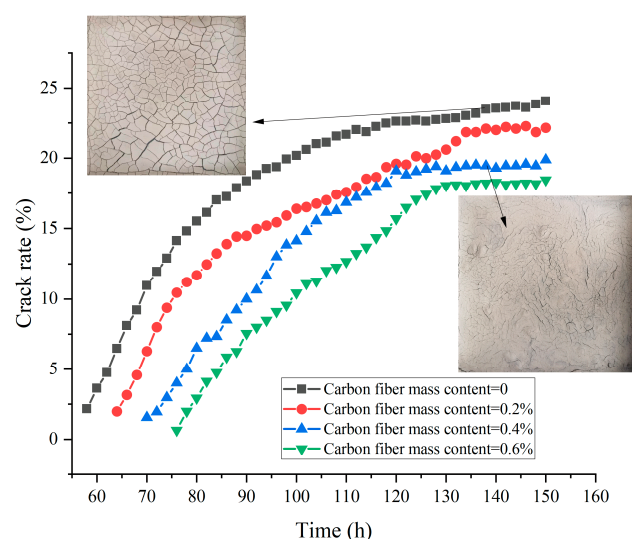
As a type of porous medium material composed of solid, liquid and gas, the volume shrinkage of soil mainly depends on the change of water content. The volume shrinkage of soil in the drying stage is actually a gradual increase in soil compactness. The deformation occurs under the action of internal force and the deformation mechanism is very different from the soil compaction under the action of external force. For the initially saturated soil, the pores are filled with water. When the relative humidity in the atmosphere is lower than the relative humidity in the soil, the water molecules in the pores will escape into the atmosphere through the soil surface, resulting in evaporation. With the continuous evaporation, due to the action of surface tension, the soil particles will move closer to

each other, and the pore diameter will decrease, which is manifested as the shrinkage deformation of the soil volume on the macrolevel. As shown in Figure 5, with the decrease in soil water content during the test, the degree of soil cracking gradually increased.

Figure 5 shows the overall dynamic process of soil surface cracking. The initial cracks are not connected to each other and appear uneven. With the rise in the test time, the water loss rate of the clay increased, and the cracks became longer, wider and deeper, and intersected into a network (Figure 5a). During the test, all the cracks in Figure 5a were fully developed after 138 h of evaporation. There were 56 cracks of different shapes on the surface of the sample, among which 12 large cracks were affected by the boundary effect, and the cracks were square after stable growth. This is usually formed due to the location of the primary crack and develops almost perpendicular to the direction of the primary crack. After drying, the primary and secondary cracks combine to form a final crack network on the test surface. At the same time, the observation shows that the direction of development of almost all new cracks tends to intersect with the original crack at right angles, which can be explained by the crack growth criterion. At present, the scientific community believes that the soil cracking is caused by the tensile stress caused by the matrix suction exceeding the shear strength of the soil, and the suction and tensile strength are two important factors limiting the soil cracking [39,40]. Soil cracks usually first appear where the tensile stress is concentrated on the surface. When cracks appear, the environmental tensile stress is released, and the direction of the maximum tensile stress is parallel to the existing crack, and the crack always tends to develop along the direction of the normal maximum principal stress. Therefore, the new crack will be perpendicular to the existing crack. As shown in Figure 5a, the soil mass on both sides of the crack has obvious displacement along the edge of the soil block. The length of the crack is much longer than that of other sections, indicating that its density is much higher than that of other sections, and its displacement trend is toward the middle of the block region. In other areas far from the edge of the crack, there is little or no displacement of the clod. Due to the independent development of each block, most of the soil also moves in the block to which it belongs. With continuous drying, cracks gradually increase, and the number of blocks formed by the soil gradually decreases. The displacement direction of the soil particles also changes with the division of the original area of the block, but the displacement vector of the soil particles in each area of the block always points to the central area of the block. Figure 6 shows that the crack development trend of the soil samples with different carbon fiber content is similar. With the gradual evaporation of water, the crack rate of soil gradually increases. The crack rate of soil decreases with the increase in carbon fiber content. With the increase in carbon fiber content, the final crack rate of the sample was reduced by 7.9%, 17.3% and 23.3%, respectively.



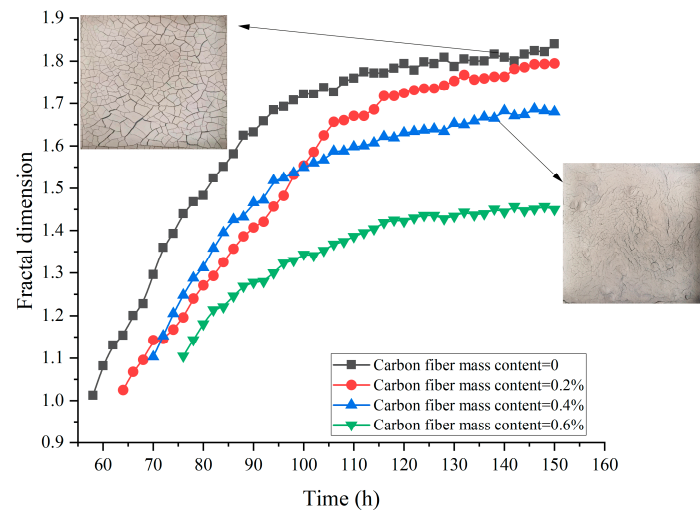
**Figure 5.** Cracking process of the sample: (a) carbon fiber mass content =0%; (b) carbon fiber mass content =0.2%; (c) carbon fiber mass content =0.4%; (d) carbon fiber mass content =0.6%.



**Figure 6.** Crack rate characteristics of the sample over time.

With the decrease in moisture content of the sample, the size and number of cracks increase. Soil cracks have strong nonlinear characteristics. Previous studies have shown that soil surface cracks conform to the “self-similarity” required by fractal theory, so the cracks of samples of different scales have similar fractal distribution rules [38]. As shown in Figure 7, the fractal dimension of the image during the specimen cracking process was calculated. With the decrease in the water content of the sample, the fractal dimension of the sample increases gradually. The sample without carbon fiber was the first to crack, and the fractal dimension of the initial crack was small, only 1.025. However, with the

decrease in the water content of the sample, the fractal dimension of the sample increased at the highest rate, and the cracking of the sample continued for more than 92 h. With the rise in carbon fiber content, the cracking duration of the samples decreased by 15.2%, 31.5% and 54.3%, respectively. Carbon fiber has the effect of reinforcing bars in the sample, which increases the surface tension of the sample. With the rise in carbon fiber content, the fractal dimension of the final cracking of the sample decreases by 2.4%, 8.7% and 21.2%, respectively.

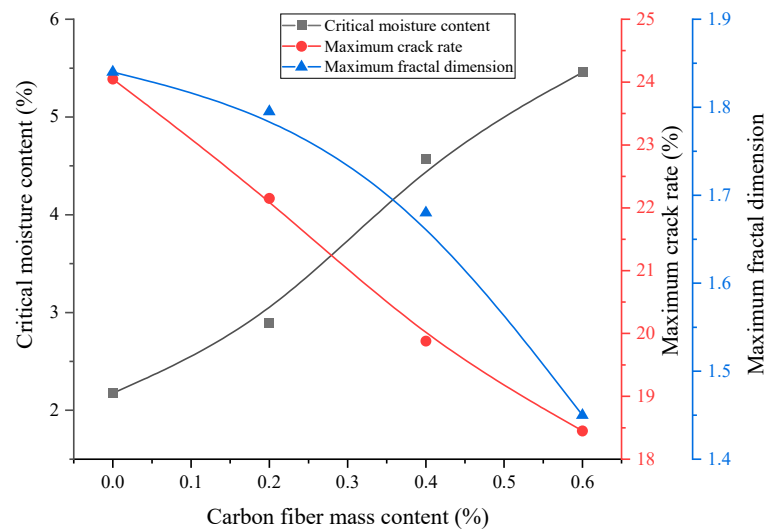


**Figure 7.** Fractal characteristics of sample cracking over time.

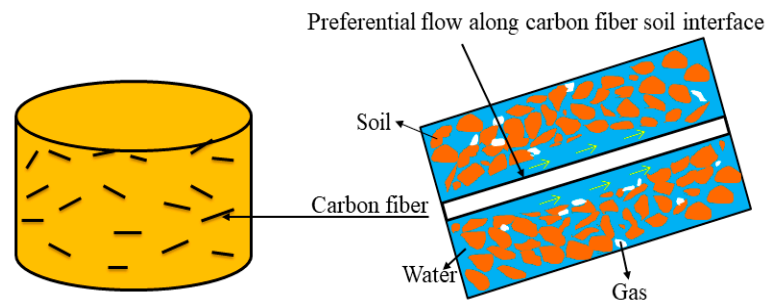
#### 4. Discussion

With the gradual evaporation of water, a liquid-bending surface appears between surface soil particles and, correspondingly, the distance between soil particles decreases, resulting in soil shrinkage [41]. Soil containing more clay minerals has stronger shrinkage; that is, the greater the degree of cracking. With the continuous evaporation of water, the tensile stress in the soil gradually accumulates, and when the tensile stress exceeds the tensile strength of the soil, dry shrinkage cracks begin to form [42,43]. In the process of evaporation, soil generally forms dry cracks first in the part with high water content in the nearby region [44]. Since the bonds within aggregates are stronger than the bonds between aggregates, soil cracks are generally located at the boundaries of different aggregates in the soil [45]. This experiment shows that the evolution of soil cracks is generally divided into three stages as follows: the cracks increase slowly at first, then rapidly and finally the cracks are stable.

As shown in Figure 8, the addition of carbon fiber can raise the critical moisture content of the soil sample and reduce the crack rate and fractal dimension of the sample. The experimental results show that the soil with a higher carbon fiber content usually has better water-retention performance. Although carbon fiber itself does not have water absorption, it can be used to store water in the soil by increasing the pores and channels of the soil; therefore, carbon fiber can effectively slow the evaporation rate of soil water. This means that in arid regions, carbon fiber can help the soil hold water for longer, providing a continuous water source for plants, thereby reducing evaporation pressure on the soil. When the carbon fiber binds to the soil, the path of the water in the soil changes and the water migrates along the carbon fiber in the soil section (Figure 9). This is why the duration of the constant evaporation stage of the soil decreases with the rise in the carbon fiber content.

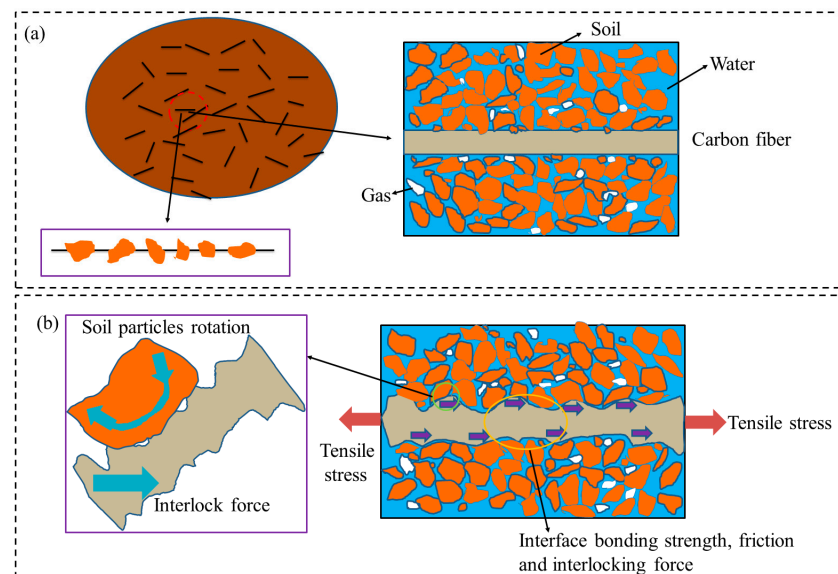


**Figure 8.** Change characteristics of critical values of the different carbon fiber samples.



**Figure 9.** Schematic diagram of soil and carbon fiber evaporation.

In addition, when carbon fiber is combined with soil, it can also improve the stability of soil [23,46], reduce the cracking phenomenon of soil and reduce the fractal dimension of the samples. At the same time, the application of carbon fiber can reduce the degree of soil cracking to a certain extent, thereby further increasing the water retention of the soil. When the carbon fiber is combined with the soil mass, the carbon fiber will interact with the soil mass to form more carbon fiber crossing points and raise the interface bonding strength, friction and interlocking force between the soil mass and carbon fiber (Figure 10). Such a close combination can inhibit the cracking of the soil mass [47]. At the same time, carbon fiber itself has excellent tensile strength [47], which can effectively prevent soil cracking caused by shrinkage. With the same mass of carbon fiber, the low density of carbon fiber ensures that more carbon fiber is present at a fixed content. The increase in the amount of carbon fiber helps to further strengthen the mechanical action between the carbon fiber and soil, restrain the cracking of soil and increase the water retention of soil.



**Figure 10.** Cracking mechanism diagram of soil and carbon fiber: (a) diagram of soil and carbon fiber; (b) diagram of the mechanical action of soil and carbon fiber.

## 5. Conclusions

Carbon fiber has many excellent properties and has developed broad application prospects in recent years. In this study, the evaporation cracking process of carbon fiber-modified soil was studied, and it was found that waste carbon fiber can increase the water retention capacity and crack resistance of soil. With the increase in carbon fiber content to 0.2%, 0.4% and 0.6%, the critical moisture content of the soil samples increased by 33.2%, 110% and 151%. Due to the change of water path in soil when carbon fiber is combined with soil, the duration of the soil constant evaporation stage is reduced by 5.1%, 13.8% and 34.5%, respectively. With the rise in carbon fiber content to 0.2%, 0.4% and 0.6%, the crack rate of soil cracking decreased by 7.9%, 17.3%, and 23.3%, respectively. With the rise in carbon fiber content, the fractal dimension of cracks decreased gradually. When the carbon fiber content is 0.2%, 0.4% and 0.6%, the fractal dimension of cracking is reduced by 2.4%, 8.7% and 21.2%, respectively. When carbon fiber is combined with soil, carbon fiber will interact with soil to form more carbon fiber interleaving points to raise the interface bonding strength, friction and interlocking force between the carbon fiber and soil. This close combination can inhibit the cracking of soil and further increase the water retention of soil. The application of carbon fiber in the field of soil cracking resistance and water retention is a new idea.

**Author Contributions:** F.C.: Conceptualization, writing, revise. Y.C.: methodology, check. L.L.: experiment. C.Y.: analysis. B.Y.: analysis. All authors have read and agreed to the published version of the manuscript.

**Funding:** The authors would like to acknowledge financial support from the Outstanding Young Talents Training Plan by Xuchang University, the Natural Science Foundation of Henan under Grant No. 222300420281, the Key Scientific Research Project of Colleges and Universities in Henan Province (CN)(21A410003) and the National Natural Science Foundation of China (52364021).

**Data Availability Statement:** The data sets generated during the current study are available from the corresponding author upon reasonable request.

**Conflicts of Interest:** The authors declare no competing financial interests.

## References

1. de la Rosa, P.; González, M.d.I.N.; Prieto, M.I.; Gómez, E. Compressive behavior of pieces of wood reinforced with fabrics composed of carbon fiber and basalt fiber. *Appl. Sci.* **2021**, *11*, 2460.

2. Li, H.; Liebscher, M.; Zhao, D.; Yin, B.; Du, Y.; Yang, J.; Kaliske, M.; Mechtcherine, V. A review of carbon fiber surface modification methods for tailor-made bond behavior with cementitious matrices. *Prog. Mater. Sci.* **2023**, *132*, 101040.
3. Mostert, C.; Bock, J.; Sameer, H.; Bringezu, S. Environmental assessment of carbon concrete based on life-cycle wide climate, material, energy and water footprints. *Materials* **2022**, *15*, 4855.
4. Chen, Y.; Wei, X.; Yang, X.; Song, G.; Dou, W.; Chen, J.; Qian, Y.; Han, L. Will the aging products of soil-reinforcement fibers stress plant growth and soil health? *Chemosphere* **2023**, *338*, 139464.
5. Shoba, P.; Ramakrishnan, S. Modeling the contributing factors of desertification and evaluating their relationships to the soil degradation process through geomatic techniques. *Solid Earth* **2016**, *7*, 341–354.
6. Chang, I.; Prasidhi, A.K.; Im, J.; Shin, H.-D.; Cho, G.-C. Soil treatment using microbial biopolymers for anti-desertification purposes. *Geoderma* **2015**, *253*, 39–47.
7. Piotrowski, J.; Huisman, J.A.; Nachshon, U.; Pohlmeier, A.; Vereecken, H. Gas permeability of salt crusts formed by evaporation from porous media. *Geosciences* **2020**, *10*, 423.
8. Van Asten, P.; Barbiéro, L.; Wopereis, M.; Maeght, J.-L.; Van der Zee, S. Actual and potential salt-related soil degradation in an irrigated rice scheme in the Sahelian zone of Mauritania. *Agric. Water Manag.* **2003**, *60*, 13–32.
9. Bringedal, C.; Schollenberger, T.; Pieters, G.; Van Duijn, C.; Helmig, R. Evaporation-driven density instabilities in saturated porous media. *Transp. Porous Media* **2022**, *143*, 297–341.
10. Andrushia, A.D.; Neebha, T.M.; Umadevi, S.; Anand, N.; Cashell, K.A. Shrinkage crack detection in expansive soil using deep convolutional neural network and transfer learning. *KSCE J. Civ. Eng.* **2022**, *26*, 4202–4213.
11. Basson, M.S.; Ayothiraman, R. Effect of human hair fiber reinforcement on shrinkage cracking potential of expansive clay. *Bull. Eng. Geol. Environ.* **2019**, *79*, 2159–2168.
12. Izzo, M.Z.; Miletić, M. Sustainable improvement of the crack resistance of cohesive soils. *Sustainability* **2019**, *11*, 5806.
13. Yang, B.; Chen, Y.; Zhao, C.; Li, Z. Effect of geotextiles with different masses per unit area on water loss and cracking under bottom water loss soil conditions. *Geotext. Geomembr.* **2024**, *52*, 233–240.
14. Stewart, R.D.; Abou Najm, M.R. Field measurements of soil cracks. *Soil Sci. Soc. Am. J.* **2020**, *84*, 1462–1476.
15. Izzo, M.Z.; Miletić, M. Desiccation cracking behavior of sustainable and environmentally friendly reinforced cohesive soils. *Polymers* **2022**, *14*, 1318.
16. Jin, L.; Yang, B.; Yuan, S. Investigation of evaporation and cracking of soil reinforced with natural and polypropylene fibers. *J. Nat. Fibers* **2022**, *19*, 9547–9561.
17. Wei, Y.; Zhang, S.; Zhang, Y.; Zhou, X.; Dai, Z.; Zheng, H.; Li, Z.; Cai, C. Analytical modelling of desiccation crack depth estimation for granitic soils. *J. Hydrol.* **2024**, *629*, 130539.
18. Hassanikhah, A.; Miller, G.A.; Cerato, A.B. A method to predict desiccation crack depth in a compacted clayey soil. *Can. Geotech. J.* **2022**, *59*, 526–537.
19. Xing, X.; Nie, W.; Chang, K.; Zhao, L.; Li, Y.; Ma, X. A numerical approach for modeling crack closure and infiltrated flow in cracked soils. *Soil Tillage Res.* **2023**, *233*, 105794.
20. Li, X.; Wang, X.; Zhao, Q.; Wan, L.; Li, Y.; Zhou, Q. Carbon fiber enhanced bioelectricity generation in soil microbial fuel cells. *Biosens. Bioelectron.* **2016**, *85*, 135–141.
21. Mohseni Ghaleh Ghazi, F.; Zakerabbasali, S.M.; Karimi, G. Exploring the relationship between soil thermal conductivity and frostbite prevention: A comprehensive modeling and experimental approach. *Model. Earth Syst. Environ.* **2024**, *10*, 45–59.
22. Orbanich, C.J.; Dominguez, P.N.; Ortega, N.F. Strengthening and repair of concrete foundation beams with carbon fiber composite materials. *Mater. Struct.* **2012**, *45*, 1693–1704.
23. Cui, H.; Jin, Z.; Bao, X.; Tang, W.; Dong, B. Effect of carbon fiber and nanosilica on shear properties of silty soil and the mechanisms. *Constr. Build. Mater.* **2018**, *189*, 286–295.
24. Bao, X.; Huang, Y.; Jin, Z.; Xiao, X.; Tang, W.; Cui, H.; Chen, X. Experimental investigation on mechanical properties of clay soil reinforced with carbon fiber. *Constr. Build. Mater.* **2021**, *280*, 122517.
25. Gao, L.; Zhou, Q.; Yu, X.; Wu, K.; Mahfouz, A.H. Experimental study on the unconfined compressive strength of carbon fiber reinforced clay soil. *Mar. Georesour. Geotechnol.* **2017**, *35*, 143–148.
26. Su, Z.; Zhou, F.; Liang, J.; Liu, A.; Wang, J.; Liang, J.; Chen, B.; Yang, J. Fractal theory based identification model for surface crack of building structures. *Eng. Struct.* **2024**, *305*, 117708.
27. Wang, L.; Tang, S. Investigation and Application of Fractals in Civil Engineering Materials. *Fractal Fract.* **2023**, *7*, 369.
28. Xu, P.; Mujumdar, A.S.; Yu, B. Fractal theory on drying: A review. *Dry. Technol.* **2008**, *26*, 640–650.
29. Lu, Y.; Liu, S.; Weng, L.; Wang, L.; Li, Z.; Xu, L. Fractal analysis of cracking in a clayey soil under freeze–thaw cycles. *Eng. Geol.* **2016**, *208*, 93–99.
30. Baer, J.; Kent, T.; Anderson, S. Image analysis and fractal geometry to characterize soil desiccation cracks. *Geoderma* **2009**, *154*, 153–163.
31. Louati, F.; Trabelsi, H.; Jamei, M.; Taibi, S. Impact of wetting-drying cycles and cracks on the permeability of compacted clayey soil. *Eur. J. Environ. Civ. Eng.* **2021**, *25*, 696–721.
32. Martinez, F.; Ojeda, A.; Manríquez, H. Application of fractal theory to describe the morphological complexity of large stream networks in Chile. *Water Resour.* **2022**, *49*, 301–310.
33. Tian, Y.; Cui, G.; Morris, H. Digital imaging based on fractal theory and its spatial dimensionality. *Fractals* **2020**, *28*, 2040014.

34. Su, X.; Ren, B.; Huang, Z. Permeability analysis of fractured-vuggy carbonate reservoirs based on fractal theory. *Fractals* **2022**, *30*, 2250144.
35. Zhang, X.; Peng, F.; Lin, Z.; Long, M. A coverless image information hiding algorithm based on fractal theory. *Int. J. Bifurc. Chaos* **2020**, *30*, 2050062.
36. Yao, J.; Sun, B. Fractality of evolving self-similar networks. *Physica A* **2019**, *515*, 211–216.
37. Lombardini, L. Fractional perimeters from a fractal perspective. *Adv. Nonlinear Stud.* **2019**, *19*, 165–196.
38. Zhang, Y.; Gu, K.; Li, J.; Tang, C.; Shen, Z.; Shi, B. Effect of biochar on desiccation cracking characteristics of clayey soils. *Geoderma* **2020**, *364*, 114182.
39. Sun, Y.; Li, Z.; Zhang, X.; Huang, Q.; Wu, Y.; Xie, J. Experimental study on tensile strength of granite residual soil during drying and wetting. *Geomech. Energy Environ.* **2024**, *37*, 100523.
40. Wei, Y.; Tang, C.-S.; Zhu, C.; Cheng, Q.; Lu, Y.; Li, L.; Tian, B.-G.; Shi, B. Influence of desiccation during freeze-thaw cycles on volumetric shrinkage and tensile strength of compacted clayey soils. *Eng. Geol.* **2024**, *334*, 107513.
41. Yang, B.; Liu, J.; Zhao, X.; Zheng, S. Evaporation and cracked soda soil improved by fly ash from recycled materials. *Land Degrad. Dev.* **2021**, *32*, 2823–2832.
42. Yesiller, N.; Miller, C.J.; Inci, G.; Yaldo, K. Desiccation and cracking behavior of three compacted landfill liner soils. *Eng. Geol.* **2000**, *57*, 105–121.
43. Murray, I.; Tarantino, A. Mechanisms of failure in saturated and unsaturated clayey geomaterials subjected to (total) tensile stress. *Geotechnique* **2019**, *69*, 701–712.
44. Zeng, H.; Tan, C.; Zhu, C.; Vahedifard, F.; Cheng, Q.; Shi, B. Desiccation cracking of soil subjected to different environmental relative humidity conditions. *Eng. Geol.* **2022**, *297*, 106536.
45. Li, J.H.; Zhang, L.M. Study of desiccation crack initiation and development at ground surface. *Eng. Geol.* **2011**, *123*, 347–358.
46. Gao, L.; Hu, G.; Chen, J.; Ren, K.; Zhou, Q.; Yu, X. Dynamic properties of carbon-fiber-reinforced clay soil. *Soil Mech. Found. Eng.* **2018**, *55*, 317–324.
47. Wang, L.; Shao, G. Test research on flexural strength of soil-cement reinforced with carbon fibers. *Case Stud. Constr. Mater.* **2023**, *19*, e02280.

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.