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# Short Communication

# Fractal analysis of cracking in a clayey soil under freeze-thaw cycles



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# A R T I C L E I N F O

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# ABSTRACT

Under extreme climate conditions, clayey soils experience not only seasonal drying and wetting but also frequent freezing and thawing. Cracking would also occur in clayey soils under freeze–thaw cycles, but now less academic attention has been paid on this issue. In this study, a series of laboratory tests were conducted on a clayey soil to investigate the cracking behaviors under freeze–thaw cycles. Water loss, surface crack initiation and propagation processes were monitored after each freeze–thaw cycle. By using the image processing technique, the crack patterns were described and then quantitatively analyzed on the basis of the fractal dimension concept. It was found that for the tested clayey soil subjected to freeze–thaw cycles, the surface crack pattern slowly evolves from an irregularly rectilinear pattern towards a polygonal or quasi-hexagonal one; and the water loss, closely related to the sample thickness, plays a significant role in the process of the clay cracking; Upon cyclic freezing–thawing, the fractal dimension is well correlated to the surface crack ratio in a logarithmic equation. Fractal dimension is clayey soils under freeze–thaw in a logarithmic equation. Fractal dimension is clayey soils under freeze–thaw cycles.

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#### 1. Introduction

Cracking is a common natural phenomenon that occurred in clayey soils and significantly impacts the mechanical and hydraulic behaviors of soils. In practical engineering applications, clay-rich soils are widely used for the construction of lining and covering systems because of their low permeability and high cation exchange capacity. The development of cracks in liners and covers will provide preferential flow paths for water infiltration and dramatically increase the hydraulic conductivity, resulting in the failure of anti-seepage systems. In addition, cracks will induce zones of weakness in a soil mass, leading to the reduction of the soil shear strength and the increase of the soil compressibility (Saada et al. 1994). Moreover, cracks will probably cause the instability of slopes (Gao et al. 2015), foundations (Lozada et al. 2015), embankments (Spencer 1968; Dyer et al., 2009) and other structures related to clayey soils. Therefore, better understanding of soil cracking formation and development can facilitate the analysis of a wide spectrum of geotechnical, environmental and geological problems.

Development of cracks may be attributed to various processes including desiccation and shrinkage (Yesiller et al. 2000; Tang et al. 2008), drying and wetting (Tang et al. 2011a; Asahina et al. 2014), freezing and thawing (Chamberlain and Gow 1979), syneresis (Pratt 1998), differential settlement (Viswanadham and Rajesh 2009), and penetration by vegetation roots (Whiteley and Dexter 1983; Sinnathamby et al. 2013; Li et al. 2016). Among them, cracks induced by the first three processes are mainly related to atmospheric conditions, which significantly influence the long-term behaviors of earthworks. Many laboratory experiments, field tests and numerical simulations have been conducted to investigate the phenomenon of desiccation cracking of clayey soil (Morris et al. 1992; Konrad and Ayad 1997; Péron et al. 2009; Li and Zhang 2011; Amarasiri and Kodikara 2013; Costa et al. 2013; DeCarlo and Shokri 2014a, 2014b). Desiccation cracks, induced by sustained water loss to the atmosphere from a drying material, often occur on the surface of clayey soils. Drying results in shrinkage and subsequent cracking of the soil. When a clayey soil is subjected to repeated wetting and drying, the crack surface becomes more irregular and coarse, and the segments of short and narrow cracks increase prominently (Tang et al. 2008).

In cold and arid regions, clayey soils are subjected to not only desiccation and seasonal wetting–drying, but also frequent freezing–thawing. Damages due to cyclic freezing–thawing can present various forms, in which the most common ones are cracking and spalling (Andersland and Al-Moussawi 1987; Czurda and Hohmann 1997; Yarbaşı et al., 2007). It has been found that the permeability of fine-grained soils changes under freezing and thawing (Chamberlain and Gow 1979). A network of cracks resulting from the ice lenses during freeze–thaw cycles appeared to be the primary causes of the larger hydraulic conductivities of soils (Benson and Othman 1993). The mobilization of colloid and colloid-associated contaminants could also increase under frequent freeze–thaw cycles in a fractured soil, where preferential flow paths are prevalent







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(Mohanty et al. 2014). According to the study by Pardini et al. (1996), the ice lenses formed during the freezing period tend to segregate the soils and the segregating forces cause the breakage of the micro-fissures existing in the soils, which are transformed into a great number of irregular and rounded pores and the soil structures are readjusted in micro- and macro-scales. Akagawa and Nishisato (2009) proposed that fractures or cracks would take place in a soil when the ice pressure exceeds the tensile strength of the frozen soil and such rupture of the pore-ice framework in the soil is necessary for the initiation of the ice lenses. Bhreasail et al. (2012) applied the synchrotron micro-computed tomography (CT) to study the microstructures of frozen soils and found that the micro-cracks and longer cracks were orientated parallel to the freezing front, affecting both the frozen soil's mechanical properties and permeability. During the thawing period, the fissures and cracks still exist due to the previously frost-induced plastic deformation, although part of the porosity is affected by the slaking of aggregates (Hohmann-Porebska 2002).

However, previous researchers mainly focused on the detrimental effects and the frost mechanism of clayey soils under freeze–thaw cycles. Few attempts have been made to investigate the evolution of cracks induced by freeze–thaw cycles, especially the quantitative assessment of such cracking behaviors. Owing to climate change and extreme weather events, the phenomenon of freezing–thawing has become as common as the wetting–drying, and its detrimental effects on earthworks have gradually aroused public concerns.

In this study, a series of laboratory cyclic freezing-thawing tests were conducted on a clayey soil to investigate the evolution of the surface cracks. The variation of the water contents, the initiation and propagation of the cracks were monitored during the freeze-thaw cycles. A quantitative method to characterize the crack patterns by combining the image processing with the fractal dimension concept was developed, which was then applied to quantitatively investigate the evolution of the cracks together with the water loss and the number of freeze-thaw cycles.

## 2. Laboratory freezing-thawing tests

#### 2.1. Preparation of clay samples

As swelling/expansive soils contain active clay minerals like montmorillonite and illite, they have quite high swell-shrink potentials and are more prominent in cracking. Compacted expansive soils are often used as impervious liners in canals and cover materials in waste disposal landfills (El-Sohby et al. 1995; Kayabali 1997; Kaya and Durukan 2004). The cracking in expansive soils resulting from freeze-thaw cycles in cold regions has aroused attentions by some researchers (e.g., Andersland and Al-Moussawi 1987). In this study, the clay samples were prepared with an expansive soil, which was taken from the construction field of a water transfer project in North China. The physical properties of the tested expansive soil are listed in Table 1.

The clay samples were prepared in three procedures. First, the expansive soils were air-dried, lightly crushed by use of a rubber hammer and sieved through a 2.0 mm mesh. Water was added into the sieved soil and mixed thoroughly by hand until the soil has the water content close to its liquid limit (62.0%). The mixed soil was cured for about 24 h

Table 1Physical properties of the tested clayey soil.

Soil property	Value
Specific gravity, Gs	2.59
Liquid limit, $L_L$ (%)	62.0
Plastic limit, $L_P$ (%)	39.0
Shrinkage limit, L <sub>S</sub> (%)	13.8
Plasticity index, P <sub>1</sub>	23
USCS classification	CH

in order to make the moisture in the soil as uniform as possible. Then, the mixed soil was poured into three open-faced rectangle containers with a length of 360 mm and a width of 270 mm. The three containers were designed to have different depths of 5 mm, 10 mm and 20 mm so that the effect of soil layer thicknesses on the cracking behavior may be investigated. A thin layer of petroleum jelly (Vaseline) was pasted on the inner walls of the containers to reduce the boundary friction. To eliminate the air bubbles within the clay samples, the containers were slightly vibrated for about 3 min. Finally, the clay sample surfaces were smoothed lightly with a grafter to obtain a uniform thickness.

#### 2.2. Freezing-thawing tests

Fig. 1 shows the experimental set-up for the cyclic freezing-thawing tests, which was developed by Li et al. (2013). The tests were performed in a closed system where drainage was closed and no additional water was permitted to enter into the sample during the tests, as done by Dirksen and Miller (1966). In a closed system, the freezing front cannot achieve continuous water supply during freezing because the rate of the downward frost penetration is generally faster than that of the upward moisture transportation (Wong and Haug 1991). In this study, the cyclic freezing-thawing test was performed by freezing the clay sample for 12 h at a temperature of -20 °C and then thawing the clay sample for 12 h at room temperature of about 25 °C. That is to say, one freezethaw cycle lasted for 24 h. As the surface of each clay sample was open to air during the test, the moisture evaporation from the sample was permissible. After every freeze-thaw cycle, each clay sample was weighted by using an electronic scale with a precision of 0.5 g and the corresponding water content of the sample was calculated. The freezing-thawing test for each sample was ended until the change of its water content was very small (less than 0.1%). Changes in humidity were not measured during the testing process.

#### 2.3. Observation of crack patterns

During the tests, cracks that occurred in the sample surfaces were observed by using a simple image acquisition technique, which has also been used to observe clay cracking under desiccation and cyclic wetting–drying by some researchers (e.g., Tang et al. 2010, 2011a, 2011b; Xue et al. 2014). At the end of each freeze–thaw cycle, the surface of each sample was pictured by using digital camera to capture the crack patterns. The camera lens was fixed parallel to the sample surface with a suitable distance to ensure the sample totally within the shooting range. It is noted that the interval between the weighting of the sample and its picturing should be as short as possible (less



Fig. 1. Image of experimental set-up for the freezing-thawing tests.

than 30 s) to minimize the influence of the environment temperature. For this purpose, the digital camera was set up on a frame and the weighting and the automatic picturing were carried out simultaneously, as shown in Fig. 2.

## 3. Fractal analysis

The fractal concept proposed by Mandelbrot (1977) is an effective method to describe the complex phenomena with properties of selfsimilarity and self-organization in nature. It has been used to characterize root systems of rice plants (Wang et al. 2009), frost crystal formation (Liu et al. 2012), micro-structural damage analysis (Abdul Hassan et al., 2014), desiccation cracking (e.g., Baer et al. 2009; Vallejo 2009; DeCarlo and Shokri 2014a), rill evolution on loess slope (Zhang et al. 2016), etc.

In this study, the crack patterns that developed on the clay surface exhibit a hierarchical network structure that is fractal at a statistical level. Thus, in order to quantify the possible fractal property, the fractal dimension concept was applied to analyze the crack patterns of the clay samples under freeze–thaw cycles. The crack patterns, obtained from the digital images, were firstly processed by use of MATLAB software, and then a program was developed to determine the corresponding fractal dimensions.

#### 3.1. Processing of digital images

Images taken by the digital camera were originally true color in a RGB format, which can only provide some sense impression on the cracking behavior. To quantitatively analyze the geometric characteristics, e.g., the width, length, number and distribution of cracks, it is necessary to process the digital images. By taking the image of the 20 mm thick sample at the end of the freezing-thawing tests as an example, the typical procedure of digital image processing is explained (cf. Fig. 3), which includes two steps: 1) the color image (Fig. 3(a)) of the crack patterns was converted into a gray one (Figs. 3(b), 2) the gray image was further changed into a binary one (Fig. 3(c)) with the threshold division method. After the process, the cracks and aggregates were simply distinguished in a blackwhite image, in which the black lines and the white areas represent the crack networks and the aggregates, respectively. During the threshold division process, the threshold should be optimized to make the binary images as clear as possible. If the image pixels are less than the threshold, they were set to be 0; otherwise, they were set to be 1. The optimized threshold can be calculated by the maximum variance difference method, which was originally proposed by Otsu (1975), and has been implemented into MATLAB software in the function of "Graythresh". A digital image is originally saved in magnetic disks in a matrix form. After the threshold division, the elements in the matrix are converted into only the numbers of 0 and 1. Thus, it is easy to use the converted matrix to calculate the geometric parameters of the binary images, such as the fractal dimension and the surface crack ratio (defined later).



Fig. 2. Schematic of experimental set-up used for crack observation.

## 3.2. Calculation of fractal dimensions

The fractal analysis is mainly to determine the fractal dimension,  $D_{F}$ . Different from Euclidean (topological) dimension of a space, D, the irregular, complex shapes with fractal characteristics generally have non integral dimension. There are different definitions for a fractal dimension, such as similarity dimension, Hausdorff dimension, packing dimension and divider dimension as well as box-counting dimension (Feder 1988). Among these definitions, the box-counting dimension is most popularly used because it is easily programmed and applicable for patterns with or without self-similarity (Peitgen et al. 2004). In this study, the box-counting dimension was used. Each image is covered by a sequence of grids of descending sizes and for each of the grids, two values are recorded: the number of square boxes intersected by the image, N(r), and the side length of the squares, r. The regression (negative) slope  $D_B$  of the straight line formed by plotting log(N(r))against log(r) indicates the degree of complexity, or fractal dimension. The linear regression equation used to estimate the fractal dimension is as shown in Eq. (1).

$$\log N(r) = \log(C) - D_B \log(r) \tag{1}$$

where *C* is a constant; N(r) is proportional to  $r^{-D_B}$  (Mandelbrot 1983; Falconer 2004).

For a binary image, the pixel-covering method can be used to estimate the box-counting dimension (e.g., Feng and Zhou 2001; Zhuang and Meng 2004; Tang and Wang 2012). The matrix of a binary image is divided into a series of sub-matrices with a certain rank k, and then the number of non-zero matrix N(k) is counted, where k and N(k)are equivalent to r and N(r) in Eq. (1), respectively. The processing procedures of the box-counting method were programmed with MATLAB software. Table 2 gives a comparison of the fractal dimensions of some typical images calculated by the MATLAB code with their corresponding theoretical values (after Zhu and Ji 2011). The good agreement between them shows the feasibility of the MATLAB code for the box-counting method. Fig. 4 gives the estimation of fractal dimensions for the images of the three different thick samples at the end of freezing-thawing tests, corresponding to their final crack patterns. It is seen that the linear regressions for the three different thick samples have very high correlation coefficients  $R^2$  greater than 0.99 and the obtained final fractal dimensions *D*<sub>B</sub> are 1.6200, 1.5929 and 1.5897 for the 5 mm, 10 mm and 20 mm thick samples, respectively.

#### 4. Results and discussion

#### 4.1. Crack patterns

A series of typical crack patterns were captured from the digital camera during the tests. Similar crack patterns were observed in the three samples with different thicknesses. Fig. 5 shows the typical crack patterns for images of the 10 mm thick sample after different freeze-thaw cycles. It is found that the cracks developed roughly in three stages during the freezing-thawing tests:

(1) Crack initiation stage. During the first five freeze-thaw cycles, the water inside the sample migrated from the unfrozen zones towards the surface of the cooling clay sample, leading to the sustained growth of ice lenses near the sample surface. When the clay sample thawed, the ice lenses near the surface gradually melted into a number of watermarks, and no obvious cracks could be visually observed on the sample surface. However, it is speculated that the micro-fissures might be induced inside the clay sample as a result of the repeated formation of the ice lenses during the freeze-thaw cycles. After six freeze-thaw cycles, some random cracks were visually captured on the sample surface, which were short, fine and irregularly rectilinear.



Fig. 3. Procedures of digital image processing.

- (2) Crack propagation stage. With the increase of freeze-thaw cycles, the cracks gradually developed and finally covered on the whole sample surface, accompanying with the increase of the crack widths, especially for the early-initiated cracks. Such a propagation process continued approximately to the 17th freeze-thaw cycle. Thereafter, few cracks were further developed except the increase of the widths for the existing cracks.
- (3) Crack stabilization stage. A relatively stable crack pattern was obtained after 21 freeze-thaw cycles, with no obvious changes both in the number and width of the cracks. The final crack pattern basically presented an interconnected polygonal network.

In the aforementioned three stages, it is observed that the surface cracks slowly evolve from an irregularly rectilinear pattern towards a polygonal or quasi-hexagonal pattern, which is somewhat analogous to the form of distinct arrays of interconnected polygons (referred as patterned ground) in a particularly cold and arid region on Earth, the Dry Valleys of Antarctica, as reported by Sletten et al. (2003).

#### 4.2. Change of water contents

Before the freeze-thaw tests, the initial water contents of the clav samples were measured by the oven-drying method. As stated previously, at the end of each freeze-thaw cycle, the sample was weighted and the corresponding water content was then determined. The variation of water contents of the three samples with the number of freeze-thaw cycles can be seen from Figs. 6 or 7. With the increase of the freezethaw cycles, the water contents of the samples firstly decreased (i.e. water loss) at a nearly constant rate and then tended to a constant residual value. The thinner the soil layer is, the faster the water loss is. Although the decreasing rates of the water contents for three samples are different, the residual water contents are approximately the same value of 14.0%, which is close to the shrinkage limit (13.8%) of the tested clay (see Table 1). The numbers of freeze-thaw cycles to reach the residual water content are 11, 21 and 50 for the 5 mm, 10 mm and 20 mm thick samples, respectively. For the 10 mm thick sample, the crack patterns have no significant change after 21 freeze-thaw cycles, as shown in Fig. 5. Therefore, it can be deduced that the clay cracking

#### Table 2

Comparison of calculated fractal dimensions with the corresponding theoretical values.

Image	Theoretical $D_B$ (after Zhu and Ji 2011)	Calculated D <sub>B</sub>	Relative error	Image pixels
	1.000	0.9965	0.35%	520 × 518
	1.465	1.4344	2.09%	$890\times894$
	1.585	1.5452	2.51%	483 × 420
	1.6309	1.6400	0.56%	975 × 845
	1.8928	1.9265	1.78%	1024 × 1024
	2.000	1.9987	0.07%	512 × 512



Fig. 4. Estimation of fractal dimensions for the images of the three different thick samples at the end of freezing-thawing tests.

will no longer develop when the water content of the sample approaches to the shrinkage limit.

During freezing and thawing, on one hand, the desiccation induced by freeze-thaw cycles leads to the creation of micro cracks in the soil blocks, on the other hand, water loss leads to a reduction of the pores and thus to a hardening of the soil (Aubert and Gasc-Barbier 2012). Water loss in soil layers is mainly attributed to two physical processes: water evaporation and ice sublimation (Jong and Kachanoski 1988). Water evaporation occurs throughout the whole process of freezing and thawing, while ice sublimation mainly occurs during the freezing process. When a fine-grained soil is frozen at the freezing point (e.g., 0 °C for pure water), not all water within the pores freezes owing to the effects of capillary and surface adsorption (Anderson and Morgenstern 1973). If the soil is continuously cooled to a temperature below its freezing point, the bound water inside the soil begins to freeze, resulting in the significant decrease of the pore water pressure and the generation of a relatively large negative pore water pressure (referred



Fig. 5. Cracks on the surface of the 10 mm thick sample after different freeze-thaw cycles.

to as frost-induced suction) (Williams 1966; Zhang et al. 2015). The frost-induced suction promotes the moisture migration during the freezing process and then enhances the ice sublimation. From the view point of thermodynamic, as stated by Ozawa (1997), the moisture migration during soil freezing is caused not by a mechanical force but by a thermodynamic tendency to increase entropy in a whole system which has been kept in a non-equilibrium state. This freezing state initiates from the sample surface and gradually penetrates into the sample interior. As the three clay samples in this study have different thicknesses of 5 mm, 10 mm and 20 mm, the paths of the moisture migration during the freezing process are different. The thinner the soil layer is, the faster the moisture migration is. Therefore, for the thinner clay sample, water loss during the freezing and thawing is faster, easily reaching the residual water content.

## 4.3. Surface crack ratio

The surface crack ratio ( $R_{SC}$ ), the ratio of the surface area of cracks to the total area of the sample, is usually used to quantitatively describe the cracks on the sample surface. In this study, it is determined by counting pixels on the binary crack patterns and calculated as

$$R_{\rm SC} = 100N_B / (N_B + N_W)(\%) \tag{2}$$

where  $N_B$  and  $N_W$  are the numbers of black pixels and white pixels in the binary image, respectively.



Fig. 6. Variations of surface crack ratio as well as water content with number of freezethaw cycles.



Fig. 7. Variations of fractal dimension as well as water content with number of freeze-thaw cycles.

Fig. 6 shows the variations of surface crack ratio  $R_{SC}$  as well as water content w with number of freeze-thaw cycles for the three clay samples. As can be seen, the surface crack ratio  $R_{SC}$  of each clay sample firstly increases with the increasing freeze-thaw cycles and then tends to a stable value, which well corresponds to the decrease of water content w. The maximum  $R_{SC}$  takes place at the residual water content. The thinner clay sample has a relatively higher value of  $R_{SC}$  and the cracks can be observed in fewer numbers of freeze-thaw cycles. For the 5 mm thick clay sample, the initial cracks with a value of  $R_{SC}$  = 3.64% were observed under three freeze-thaw cycles and the maximum value of  $R_{SC}$  is about 12.0% after 11 freeze-thaw cycles; for the 20 mm thick clay sample, the initial and the maximum values of  $R_{SC}$  decrease to 0.51% and 11.0%, respectively, and the corresponding numbers of freeze-thaw cycles increase to 16 and 50. This is because the moisture migration pathways and the transfer of thermal energy in clay samples under freeze-thaw cycles are significantly affected by the thicknesses of the samples, which in turn influence the surface crack rates and water loss rates in clayey soils.

# 4.4. Fractal dimension

The fractal dimensions  $D_F$  of the crack patterns in different freezethaw cycles for each clay sample were estimated by using the boxcounting method. Fig. 7 shows the variations of fractal dimension  $D_F$ as well as water content w with the number of freeze-thaw cycles. It can be seen that the computed fractal dimensions of the three clay samples during cyclic freezing-thawing are within the theoretically allowable range of 1.0 and 2.0. The fractal dimension of each sample increased with the increasing of freeze-thaw cycles until the corresponding water content decreased to its residual value. When the residual water content was approached, the maximum fractal dimensions of the clay samples with thicknesses of 5 mm, 10 mm and 20 mm were approximately 1.6200, 1.5929 and 1.5897, respectively, as estimated in Fig. 4. Similar to the surface crack ratio *R<sub>SC</sub>*, the thinner clay sample also has a relatively higher value of  $D_F$ . As previously described, the fractal dimension  $D_F$  can be used to evaluate the spatial distribution of cracks, the density of cracks, and the tendency of the crack traces to fill the area in which they are embedded. The results in Fig. 7 suggested that the successive freezing-thawing increase the complexity, density, roughness and interconnectivity of clay surface cracks. As shown in Fig. 4, this phenomenon is more prominent in a thinner clay layer (i.e., the 5 mm thick clay sample in this study), resulting in a faster increase of the corresponding fractal dimension with a higher maximum value.

As investigated above, the surface crack ratio  $R_{SC}$  and the fractal dimension  $D_F$  of the three clay samples during the cyclic freezing–thawing have been discussed separately. By comparing Fig. 6 with

$$D_F = a \cdot \ln(R_{SC}) + b \tag{3}$$

where *a* and *b* are the two regression coefficients with the values of 0.1872 and 1.144, respectively. The fractal dimension  $D_F$  is well correlated to the surface crack ratio  $R_{SC}$ , with the regression coefficient  $R^2 = 0.987$ .

#### 5. Conclusions

Laboratory experiments were performed on three clay samples with different thicknesses to investigate the cracking behaviors under cyclic freezing-thawing. Crack patterns were observed under different freeze-thaw cycles, which were quantitatively analyzed using the fractal dimension concept. The relationships among crack pattern, water loss, number of freeze-thaw cycles, surface crack ratio and fractal dimension were investigated and discussed. For the tested clayey soil in this study, the main conclusions were drawn as follows:

- (1) The development of clay cracks under cyclic freezing-thawing can be roughly divided into three stages: crack initiation, crack propagation and stabilization stages. The surface crack pattern slowly evolves from an irregularly rectilinear pattern towards a polygonal or quasi-hexagonal one.
- (2) Water loss during cyclic freezing-thawing is attributed to water evaporation and ice sublimation. The cracking is accompanied with water loss and will no longer develop until water content of the clay sample decreases to the soil shrinkage limit. Water loss is closely related to the sample thickness. The thinner clay sample has a faster water loss, and cracks easily occur.
- (3) The degree of cracking in the samples under cyclic freezingthawing is reflected in the fractal dimension  $D_F$ . The evolution of the fractal dimension  $D_F$  with the number of freeze-thaw cycles is similar to that of the surface crack ratio  $R_{SC}$ . The fractal dimension  $D_F$  is well correlated to the surface crack ratio  $R_{SC}$ , which can be expressed in a logarithmic equation. Therefore, the fractal dimension  $D_F$  can be used as a quantitative index to analyze the crack behaviors of clays under cyclic freezingthawing.



Fig. 8. Correlation between fractal dimension and surface crack ratio for clay samples under freeze-thaw cycles.

Cracking behaviors in clays under extreme atmosphere conditions are very complicated and difficult to be described comprehensively. In this study, the two-dimensional digital photography was used, so that the roughness of the surface cracks and the interior cracks were not taken into consideration. Further studies need to be conducted to investigate the cracking behaviors in clayey soils under freeze-thaw cycles, such as the effect of soil types, freezing temperatures and in-situ conditions.

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