

Quantitative effects of thickness and coarse-grained sand additive on soil cracking through crack parameters

Dai Nhat VO^{1,2*}

¹ Faculty of Geology and Petroleum Engineering, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam

² Vietnam National University Ho Chi Minh City, Linh Trung Ward, Thu Duc City, Ho Chi Minh City, Vietnam

* Corresponding email: nhatvodai@hcmut.edu.vn

Abstract: *In this paper, an attempt was made to evaluate the effects of thickness and coarse-grained sand additive on cracking of Kaolinite clay using digital image processing (DIP). To minimize the errors which can occur in using DIP, control point selection (CPS) technique was applied. To determine the quantity of soil cracking, images of cracked soil after converting to binary were used to quantify crack parameters by automatically applying a written program. The measurements showed that the variation of most crack parameters is described as a power function of thickness with the high regression coefficient, more than 0.99, except area of fracture, by using the fitting curve method. In addition, the variations of length of cracks, width of cracks, area of cracks, number of pattern and number of fractures are inversely proportional while those of characteristic distance as well as mean cell area are directly proportional to the percentage of coarse-grained sand additive.*

Keywords: *Kaolinite clay; DIP; CPS; thickness; coarse-grained sand additive; crack parameters*

1. Introduction

Up to now, DIP has become a powerful tool and a useful technique to apply to many researched fields [1-6]. DIP is a computerized technique by which a scene is captured electronically, digitized into a two-dimensional pixel image, and then processed so that pictorial information about the scene can be extracted. There have been several publications using DIP even in soil cracking [7-12]. Using DIP, quantitative measurements of soil cracking were quantified.

Generally, soil cracking is a natural phenomenon and frequently observed in many natural and man-made structures such as buildings, dams, etc. Cracking in soils due to drying is controlled by partly soil suctions and partly soil properties including mainly the physical and the chemical properties. Theoretical and phenomenological studies have been investigated [13,14]. Solutions for cracking due to drying have been introduced and developed based on (i) elasticity theory, (ii) the transition between tensile and shear failure, and (iii) linear elastic fracture mechanics [13]. Cracks occur when soils are restrained while undergoing volume change produced as a result of the soil suction generated within the desiccating soil matrix. A review of the available and emerging theories of desiccation cracking of clay containing some laboratory tests has been presented.

As reported in references [15-18], the results showed that cracking of clay generally depended on experiment conditions such as base material, soil density, the desiccation rate and thickness of the sample. Conditions that govern the characteristics of soil cracking may be categorized as two separate terms: extrinsic and intrinsic conditions. Extrinsic conditions fundamentally include the temperature, relative humidity, and wind velocity whereas moisture condition, structure of material, degree of packing, physical and chemical compositions, etc belong to intrinsic conditions. In addition, cracking formation also can be affected by the microbial contribution. These effects were assessed by quantifying the heterogeneity and connectivity of cracks developed following the addition of substrate differing in quantity and quality to a sandy loam soil. Furthermore, it was concluded that soil cracking has effects on the properties of clay soils.

Although there have been many studies on the theory, behavior as well as the effects of soil cracking; however, it was known obviously that the characteristics of soil cracking depend basically on the type and properties of the soil tested. The properties of the soil can be influenced considerably by the materials which were used to be added. For example, the properties of residual soil have been affected by adding the coarse-grained sand and the porosity has influenced the shear strength of granular material-clay mixture [19,20]. Nevertheless, an attempt of researching soil cracking has been required continuously, especially on Kaolinite clay because of its important role in various engineering purposes.

In this paper, the experiment was conducted on Kaolinite clay in the laboratory to present the characteristics of its cracking response. An attempt was made to evaluate the quantitative effects of the sample thickness and coarse-grained sand additive on soil cracking due to drying naturally. Images of soil cracking were captured by a digital camera and then converted to binary images. These images, subsequently, were used to quantify soil cracking by using DIP including an application of CPS technique. A program was written in Matlab software to calculate the quantity of soil cracking automatically.

2. Materials and method

2.1 Properties of materials

Figure 1 shows representatively the container used to contain the soil sample. It was made of steel and had three dimensions of 220 mm long, 165 mm wide and 50 mm in height. Before each experiment, the container was cleaned carefully and bounded by a rectangular box consisting of 4 markers for applying CPS technique (will be discussed in the next section). The rectangular box has the same ratio between sides as the container.

Kaolinite clay was mixed thoroughly with water to make a slurry of initial water content as 70%. The properties of the studied Kaolinite are shown in Table 1 and Figure 2. The slurry was, then, mixed once using a mixer to constitute a homogeneous specimen. The specimen was poured slowly and spread carefully into the container and allowed to dry naturally in the laboratory. We vary the thickness of the specimen from the smallest as 5 mm to the largest as 25 mm. As drying time increases, water in the specimen will be lost from the soil surface. Consequently, the gravimetric water content of the system will decrease. As the gravimetric water content reaches a critical value, crack initiates. After the several following days, as the development of cracking finishes completely, an image of the final cracked soil was captured by a digital camera with the experimental conditions fixed.

To investigate the effects of coarse-grained sand additives on cracking Kaolinite clay, Jumoonjin sand was used. The specific gravity of Jumoonjin sand is 2.665 and the grain-size distribution is presented in Figure 3. The sand was mixed with the mixture of Kaolinite clay and water in various ratios by weight. The sand-mixture ratios are set from 0 percent to 30 percent at an interval of 10 percent.

2.2 Digital image processing

2.2.1 Image analysis

Images of the specimen were captured by a digital camera (Olympus C-5050 zoom). To unify totally testing conditions, two 300-W halogen lamps were used and positioned at a fixed location. In addition, the camera's position was fixed to capture the whole region of the specimen. To reduce the errors which can occur in using DIP, CPS technique might be used. The procedure of CPS technique is summarized generally in Figure 4.

Firstly, the base image and the unregistered image were read automatically. To use CPS technique, the base image (Figure 5a) including the base points and the input image with the selected input points are required compulsorily. The base points are considered as four points near the corners. Figure 5b shows an example of an unregistered image consisting of the four input points. One should note that the base points and the input points are selected manually; hence, the selection must be made carefully.

Secondly, to transform the unregistered image, a type of transformation must be required. The type of transformation is used to transform the unregistered image based on the input points and the base points. The transformed image resulted from the base image (Figure 5a) and the unregistered image (Figure 5b) is presented in Figure 5c. To eliminate the effects of the border, the image was cropped to obtain the properly inside region (Figure 5d). To perform quantitative measurements in the image, the final expected image was converted to binary image.

2.2.2 Calculation of crack parameters

A part of the image is shown in Figure 6 to illustrate the definitions of fracture and pattern. As presented in this figure, cracks are denoted as black color while white color is considered as the background of cracking image. A fracture is defined by a set of pixels limited by two ends and a pattern is a set of separately continuous connected-neighbor pixels. Based on these basic definitions, several crack parameters are calculated as follows (Figure 6).

2.2.2.1 Area of cracks

Area of cracks is computed automatically by counting the total number of black pixels as shown in Figure 7a.

2.2.2.2 Length of cracks

To measure the length of cracks, the color of cracks must be converted from black to white (Figure 7b) for applying an algorithm ‘thin’ defaulted in the program. The command ‘bwmorph’ was used to calculate the length of cracks with the ‘thin’ option. Using this algorithm, cracks were thinned to lines automatically as presented in Figure 7c. Length of cracks is calculated by the sum of distances from black pixels.

2.2.2.3 Mean width of cracks

For simplicity, let us assume that the shape of the fracture is rectangular and the distribution of width at all positions on each fracture is regular. Consequently, the mean width of cracks is defined as a ratio of area of cracks to length of cracks.

2.2.2.4 Number of patterns and number of fractures

Generally, after initiating, cracks will develop toward both directions at their tips. When it touches either another crack or the border of the container, it stops increasing its length. As a result, that constitutes a new pattern and a new fracture in the system of cracks. As mentioned above, the number of patterns and number of fractures are determined by counting the total pattern and fracture in the system of cracks respectively.

2.2.2.5 Characteristic distance

We define the characteristic distance between fractures as below:

$$l = \sqrt{\frac{A}{N}}$$

where A is the area of the whole image region and N is the number of patterns.

2.2.2.6 Mean cell area

To characterize the size of pattern resulting from soil cracking, mean cell area is calculated by a ratio of area of patterns to number of patterns.

3. Results and discussion

3.1 The effects of thickness on crack parameters

Test results indicate that the soil thickness has a significant influence on the resulting crack parameters. This is first illustrated in Figure 8 for length of cracks, mean width of cracks and area of cracks. It is clear that as thickness increases length of cracks decreases significantly with a regular trend. It is suggested that the variation can be described by a function. Experimentally, in cracking for Kaolinite clay, length of cracks is described as a power function of thickness as shown in Figure 8a by using fitting curve method. A high regression coefficient, more than 0.99, strongly proves the validity of the expression. Nevertheless, different from the length of cracks, areas of cracks calculated from various thicknesses seem to be the same as given in Figure 8b. It concludes that the quantity of area of cracks is not dependent on the soil thickness. As a result of the variations of length and area of cracks, the relationship between thickness and mean width of cracks obeys a power law. The resulting relation is presented in Figure 8c consisting of a high value of regression coefficient.

In addition, Figure 9 gives other considerations of crack parameters influenced by thickness of the soil specimen. They are shown in Figures a, b, c and d for number of patterns, number of fractures, characteristic distance and mean cell area, respectively. As can be seen from Figures 9a and 9b, the number of patterns and number of fractures decrease as thickness increases. A new pattern and a new fracture are constituted by either an apparition of a new crack or a connection of a crack to another. Hence, decreasing length of cracks with an increase of the soil thickness results in a decrease of number of pattern and number of fractures with an increase of thickness. Similar to the variations of length and mean width of cracks, the variations of number of pattern and number of fractures give the regular trends. These trends are fitted by power functions as shown in Figures 9a and 9b, respectively. The regression coefficients are also high.

As defined above, characteristic distance was calculated by square root of ratio between the total area of the image region and number of patterns; therefore, a smaller thickness produces a small characteristic distance. It might be expected that the variation of characteristic distance can, also, be described as a power function of thickness. It is found experimentally to have a good observed relation, a power law, between thickness and characteristic distance. Figure 9c presents the experimentally observed relation in this study by using the fitting curve method through high value of regression coefficient.

Finally, as with most relationships between thicknesses and crack parameters discussed above, mean cell area varies regularly with thickness, described by a power function as given in Figure 9d. It is easy to

understand this result. First, the mean cell area was computed as the area of pattern divided by the number of patterns. Second, areas of cracks with various thicknesses are the same. Therefore, combining these two reasons explains why mean cell area increases with an increase of thickness. Figure 9d shows a power variation between them.

3.2 The effects of coarse-grained sand additive on crack parameters

The effects of coarse-grained sand additive on crack parameters including length of cracks (Figure 10a), area of cracks (Figure 10b) and width of cracks (Figure 10c). As coarse-grained sand was mixed with fine-grained clay, the macro pores around the sand particles were filled by clay particles. This results in better contact between coarse- and fine-grained particles comparing to that between the fine- and fine-grained particles. Therefore, the appearance of weak planes where cracks can occur will become decreasingly with higher percentage of coarse-grained sand added. Consequently, as can be seen from Figures 10a and 10b, as a higher percentage of coarse-grained sand was added to Kaolinite clay, length of cracks and area of cracks will decrease.

Because length of cracks as well as area of cracks decrease with an increase of coarse-grained sand additive in percentage, so it is likely that mean width of cracks does not decrease clearly as percentage of coarse-grained sand additive increases as shown in Figure 10c. This also can be explained by an addition of coarse-grained sand leading to an increase in the width of cracks. However, if we consider a maximum width of the largest fracture, it presents the same trend of variation as coarse-grained sand is added. That means the maximum width of fracture decreases with higher coarse-grained sand added (Figure 10c).

Additionally, decreasing the length of cracks as well as area of cracks lead to a decrease of number of pattern and number of fractures as shown in Figures 11a and 11b, respectively. Consequently, as a result, characteristic distance together with mean cell area will increase with a high percentage of coarse-grained sand added. Figures 11c and 11d present these experimental variations for the studied materials.

4. Conclusions

The soil thickness influenced significantly the quantitative measurements of cracking described through crack parameters. Among them, length of cracks, area of cracks and width of cracks have been known as the principal parameters. Length of cracks decreased as the thickness increased while area of cracks appeared to be constant. This results in an increase of mean width of cracks as the soil thickness increases. Conclusively, most of the variations of crack parameters with the soil thickness are described by power functions, except area of cracks, by using the fitting curve method. The high regression coefficient, more than 0.99, strongly proves the validity of the suggestion.

Furthermore, the quantity of soil cracking was also affected by the addition of coarse-grained sand. As the percentage of coarse-grained sand added increases, crack parameters can either increase or decrease depending on the characteristic of their definitions. In summary, length of cracks, width of cracks, area of crack, number of pattern and number of fractures vary inversely proportional to high percentage of coarse-grained sand additive while those are directly proportional in cases of characteristic distance and mean cell area.

Tables and Figures (with descriptions)

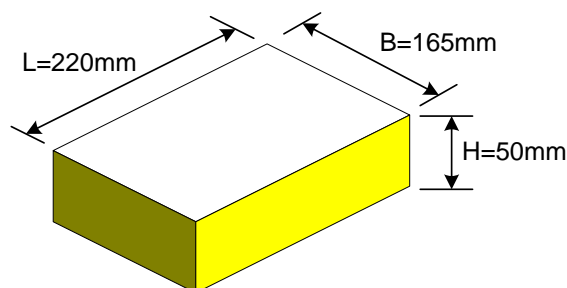


Fig. 1. Dimensional illustration of the container

Tab. 1. Properties of Kaolinite clay

Clayey soil	<i>Liquid Limit</i>	<i>Plastic Limit</i>	<i>Plasticity Index</i>	<i>Specific gravity</i>
	<i>LL (%)</i>	<i>PL (%)</i>	<i>PI (%)</i>	G_s
Kaolinite	42.07	25.40	16.67	2.646

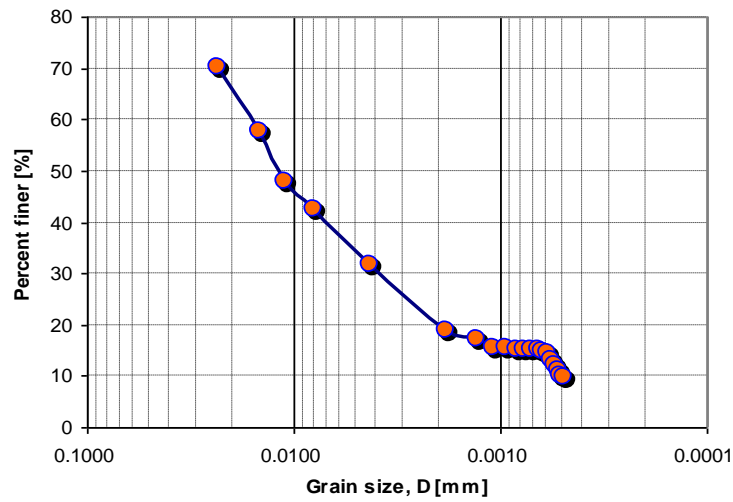


Fig. 2. The grain-size distribution curve of Kaolinite clay

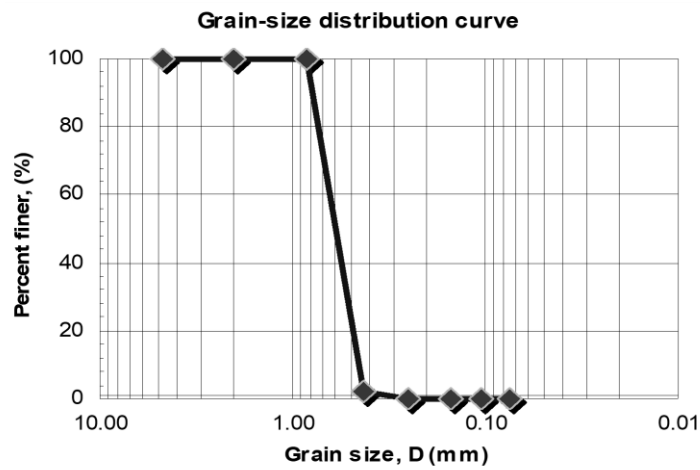


Fig. 3. The grain-size distribution curve of Jumoonjin sand studied

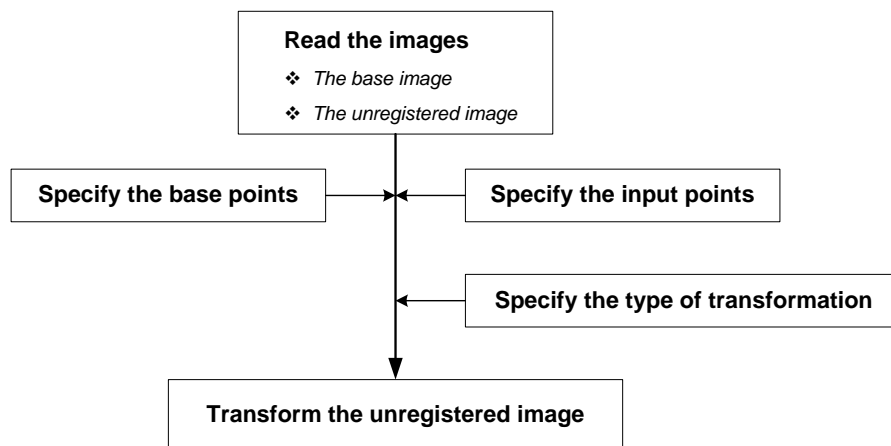


Fig. 4. Illustration of control point selection (CPS) technique

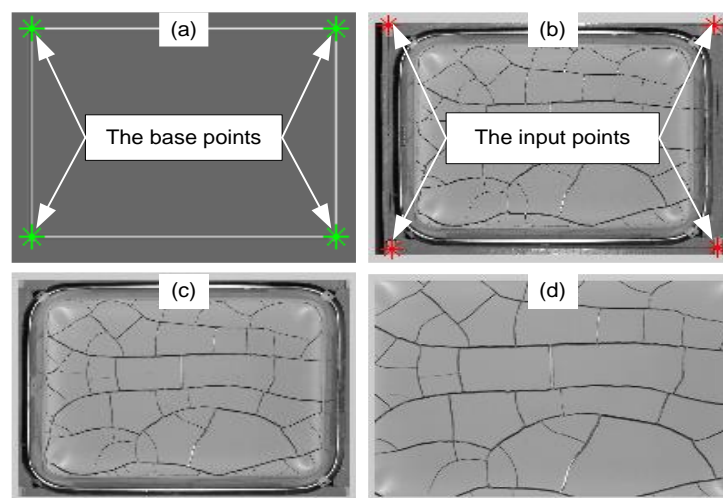


Fig. 5. Transformation of the unregistered image: (a) the base image and points, (b) the unregistered image and the input points, (c) the transformed image, and (d) the finally expected image

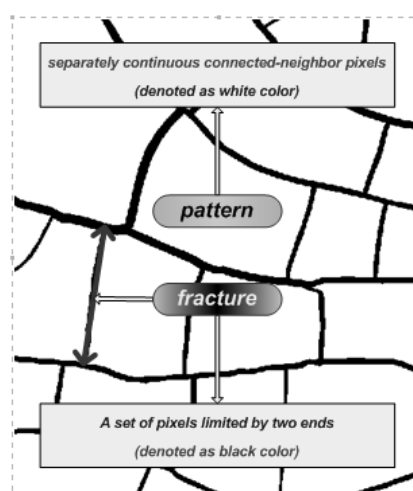


Fig. 6. Definitions of fracture and pattern

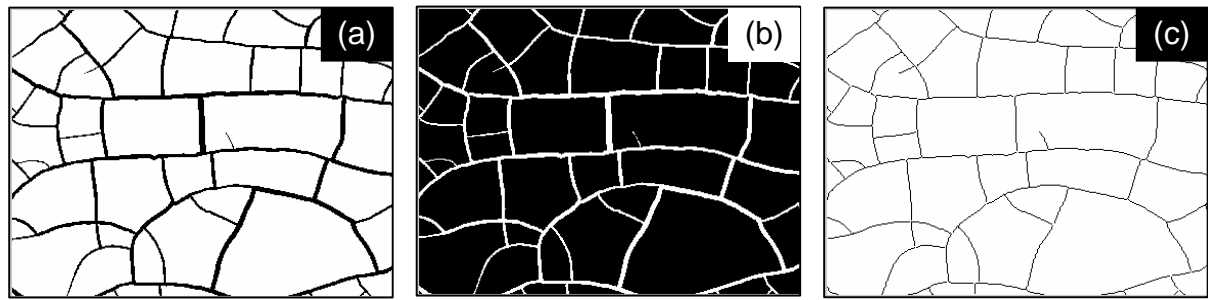


Fig. 7. Images for calculating area of cracks and length of cracks: (a) area of cracks, (b) converted image, and (c) length of cracks.

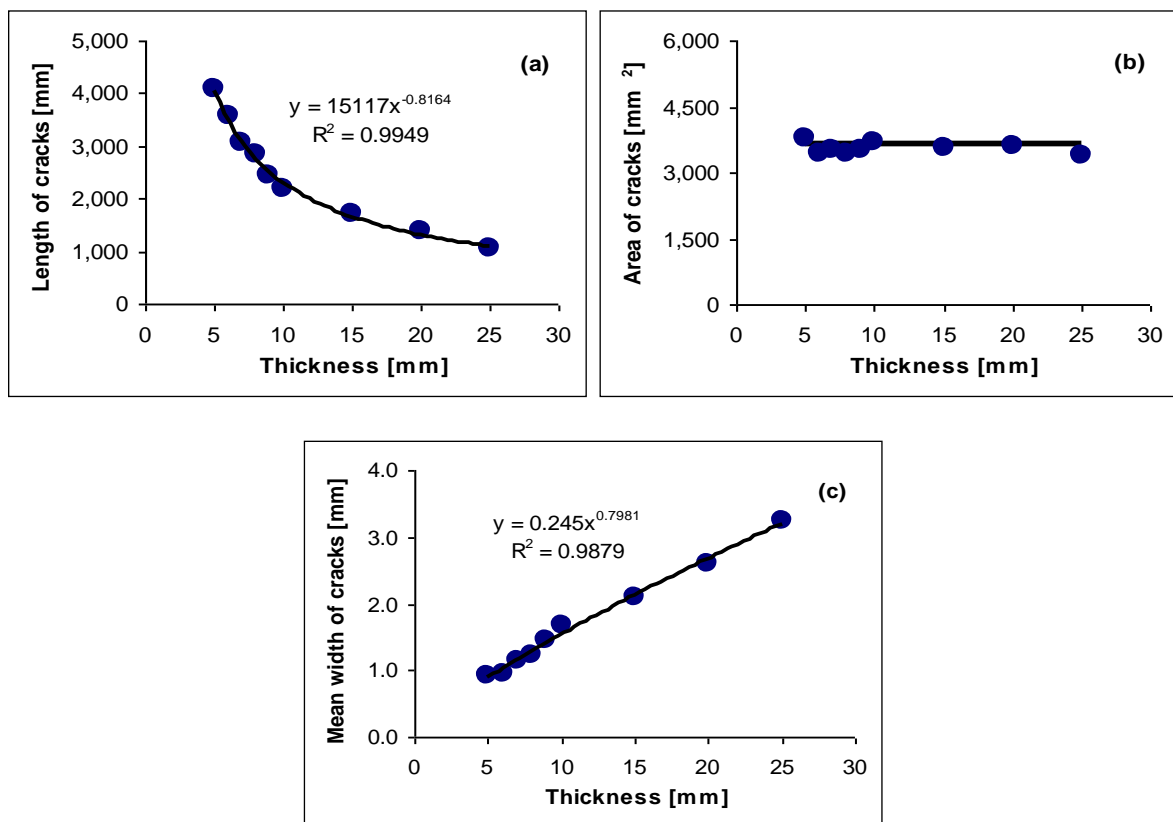
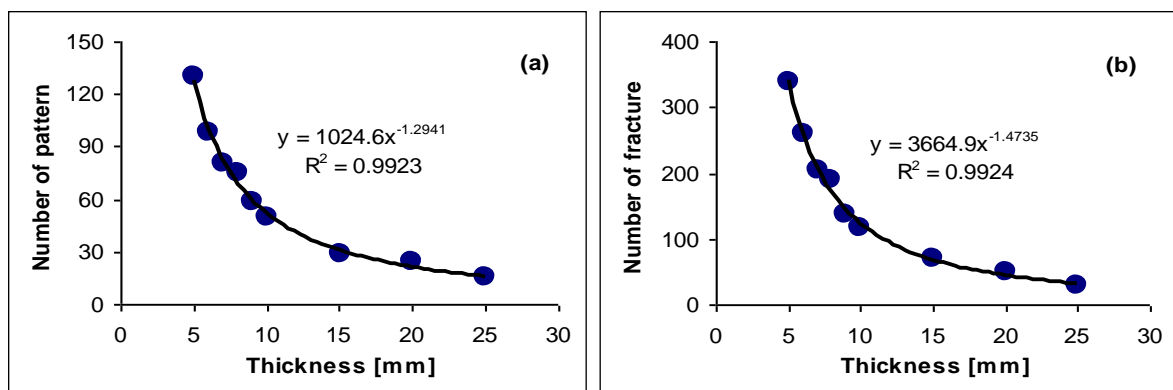


Fig. 8. The effects of thickness on crack parameters: (a) length, (b) mean width, and (c) area of cracks



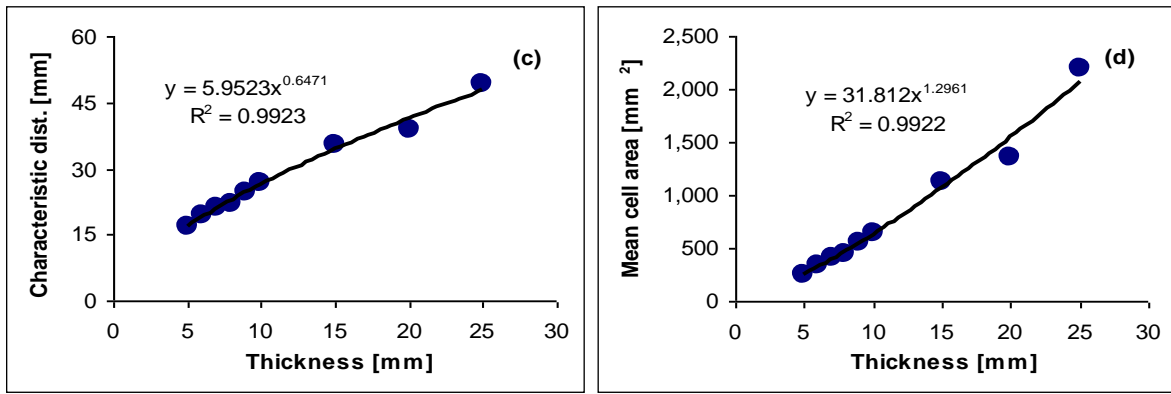


Fig. 9. The effects of thickness on crack parameters: (a) number of patterns, (b) number of fractures, (c) characteristic distance, and (d) mean cell area.

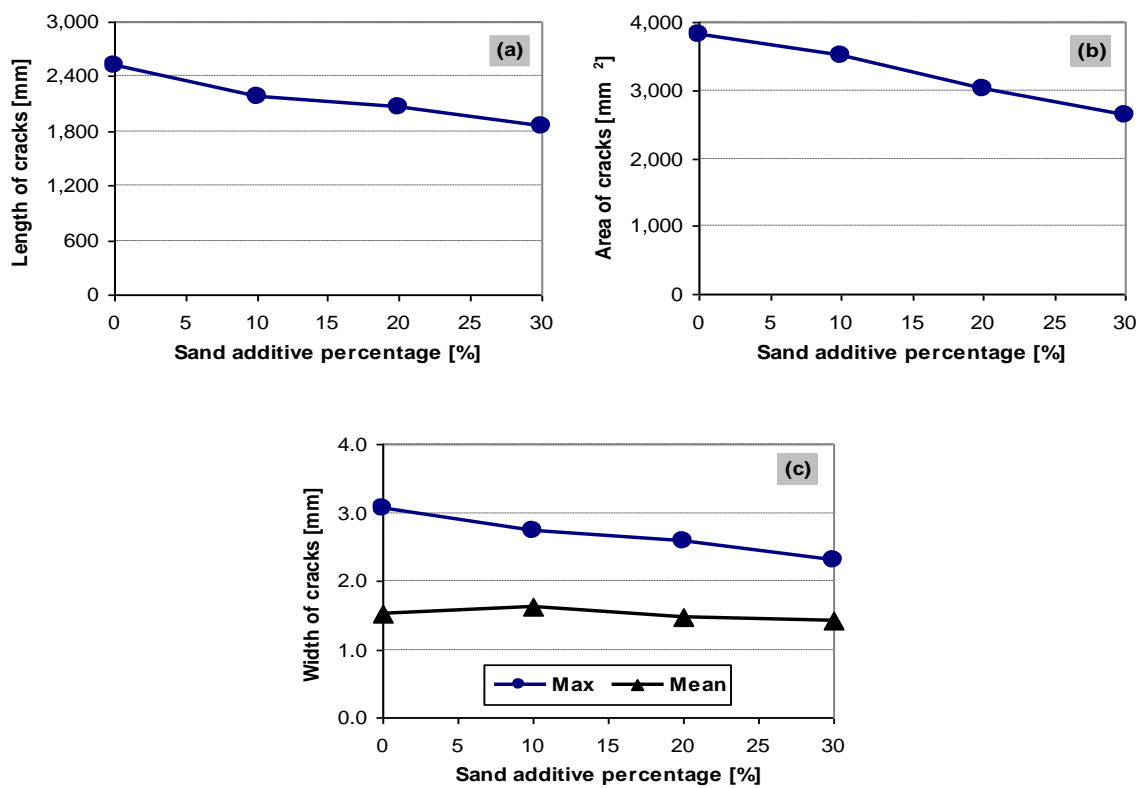
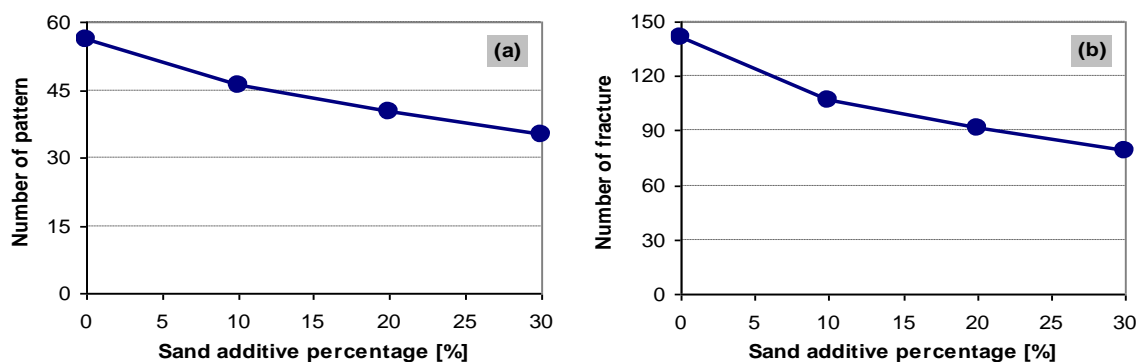


Fig. 10. The effects of coarse-grained sand additive on (a) length, (b) mean width, and (c) area of cracks



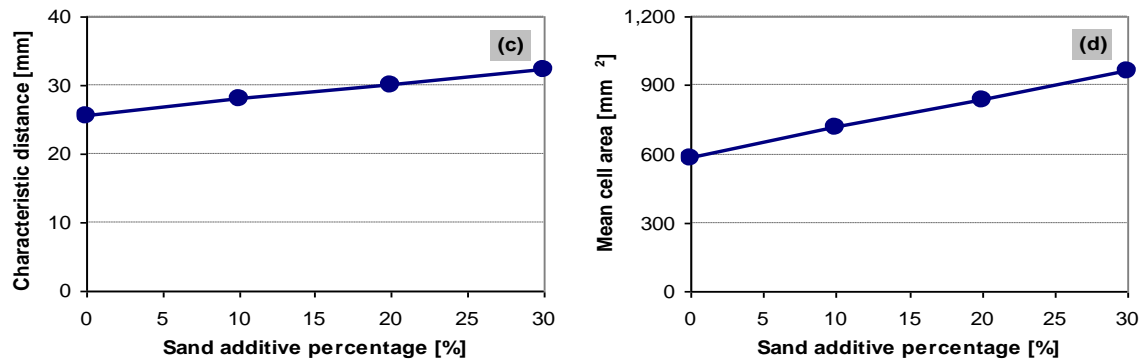


Fig. 11. The effects of coarse-grained sand additive percentage on crack parameters: (a) number of patterns, (b) number of fractures, (c) characteristic distance, and (d) mean cell area.

Acknowledgements

We acknowledge Ho Chi Minh University of Technology (HCMUT), VNU-HCM for supporting this study. Thanks are also directed to anonymous reviewers, who help to improve the submission.

Literature - References

1. Kwan, A.K.H., Mora, C.F. and Chan, H.C. (1999), "Particle Shape Analysis of Coarse Aggregate Using Digital Image Processing", *Cement and Concrete Research*, Vol.29, Issue.9, pp.1403-1410.
2. Mora, C.F. and Kwan, A.K.H. (2000), "Sphericity, Shape Factor, and Convexity Measurement of Coarse Aggregate for Concrete Using Digital Image Processing", *Cement and Concrete Research*, Vol.30, Issue.3, pp.351-358.
3. Rechenmacher, A.L. and Saab, N.A. (2002), "Digital Image Correlation (DIC) to Evaluate Progression and Uniformity of Shear Bands in Dilative Sands", 15th ASCE Engineering Mechanics Conference, June.2-5, Columbia University, New York, NY, pp.1-8.
4. Sharma, R.S., Mohamed, M.H.A. and Lewis, B.A. (2002), "Prediction of Degree of Saturation in Unsaturated Soils Using Image Analysis Technique", *Unsaturated Soils*, Swets & Zeitling, Lisse, ISBN 90 5809 371 9, pp.369-373.
5. Alshibli, K.A. and Sture, S. (1999), "Sand Shear Band Thickness Measurements by Digital Image Techniques", *Journal of Computing in Civil Engineering*, Vol.13, No.2, pp.103-109.
6. Aydilek, A.H. and Edil, T.B. (2004), "Evaluation of Woven Geotextile Pore Structure Parameters Using Image Analysis", *Geotechnical Testing Journal*, Vol.27, No.1, pp.1-12.
7. Konrad, J.-M. and Ayad, R. (1997), "Desiccation of a Sensitive Clay: Field Experimental Observations", *Canadian Geotechnical Journal*, Vol.34, pp.929-942.
8. Wijeyesekera, D. C. and Papadopoulou, M. C. (2001), "Cracking in Clays with an Image Analysis Perspective", *Clay Science for Engineering*, Adachi & Fukue (eds) Balkema, Rotterdam, ISBN 90 5809 175 9, pp.437-482.
9. Waller, P. M., Wallender, W. W. (1993), "Changes in Cracking, Water Content, and Bulk Density of Salinized Swelling Clay Field Soils", *Soil Science*, Vol.156, No.6, pp.414-423.
10. Velde, B. (1999), "Structure of Surface Cracks in Soil and Muds", *Geoderma*, Vol.93, Issues.1-2, pp.101-124.
11. Velde, B. (2001), "Surface Cracking and Aggregate Formation Observed in a Rendzina Soil, La Touche (Vienne) France", *Geoderma*, Vol.99, Issues.3-4, pp.261-276.
12. Peng, X., Horn, R., Peth, S. and Smucker, A. (2006), "Quantification of Soil Shrinkage in 2D by Digital Image Processing of Soil Surface", *Soil & Tillage Research*, Vol.91, Issues.1-2, pp.173-180.

13. Morris, P. H., Graham, J. and Williams, D. J. (1993), "Cracking in Drying Soils", *International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts*, Vol.30, No.2, pp.263-277.
14. Hu, L. B., Peron, H., Hueckel, T. and Laloui, L. (2006), "Numerical and Phenomenological Study of Desiccation of Soil", *Unsaturated Soil, Seepage, and Environmental Geotechnics*, pp.166-173.
15. Yesiller, N., Miller, C. J., Inci, G. and Yaldo, K. (2000), "Desiccation and Cracking Behavior of Three Compacted Landfill Liner Soils", *Engineering Geology*, Vol.57, Issues.1-2, pp.105-121.
16. Preston, S., Wirth, S., Ritz, K., Griffiths, B. S. and Young, I. M. (2001), "The Role Played by Microorganisms in The Biogenesis of Soil Cracks: Importance of Substrate Quantity and Quality", *Soil Biology and Biochemistry*, Vol.33, Issues.12-13, pp.1851-1858.
17. Kodikara, J. K., Barbour, S. L. and Fredlund, D. G. (2000), "Desiccation Cracking of Soil Layers", *Unsaturated Soils for Asia*, Rahardjo, Toll & Leong (eds). Balkema, Rotterdam, ISBN 90 5809 139 2, pp.693-698.
18. Albrecht, B. A. and Benson, C. H. (2001), "Effect of Desiccation on Compacted Natural Clays", *Journal of Geotechnical and Geoenvironmental Engineering*, Vol.127, No.1, pp.67-75.
19. Indrawan, I.G.B., Rahardjo, H. and Leong, E.C. (2006), "Effects of Coarse-Grained Materials on Properties of Residual Soil", *Engineering Geology*, Vol.82, Issue.3,5, pp.154-164.
20. Vallejo, L.E. and Mawby, R. (2000), "Porosity Influence on The Shear Strength of Granular Material–Clay Mixtures", *Engineering Geology*, Vol.58, Issue.2, pp.125-136.