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QUANTITATIVE ANALYSIS OF THE RELATIONSHIP BETWEEN SHEAR STRENGTH AND FRACTAL DIMENSION OF SOLIDIFIED DREDGER FILL WITH DIFFERENT FLY ASH CONTENT UNDER MONOTONIC SHEAR

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ABSTRACT

The dredger fill of Shanghai Hengsha Island Dongtan is solidified by curing agents with different fly ash content, and the shear strength index of solidified dredger fill is measured by the direct shear test. The microscopic images of solidified dredger fill are obtained by using SEM. The microscopic images are processed and analyzed by using IPP, and the fractal dimension including particle size fractal dimension D_{ps}, aperture fractal dimension D_{bs} and particle surface fractal dimension D_{pr} is calculated by fractal theory. The quantitative analysis of the relationship between shear strength index and fractal dimension of solidified dredger fill is done. The research results show that the internal friction angle and the cohesion are closely related to the fly ash content λ and the curing period T, and the addition of fly ash can improve the effect of curing agent; There is no obvious linear relationship between the internal friction angle and the three fractal dimensions; The smaller particle surface fractal dimension D_{pr} and particle size fractal dimension D_{ps}, the larger aperture fractal dimension D_{bs}, the greater the cohesion, and the cohesion has a good linear relationship with three fractal dimensions, and the correlation coefficient R^2 is above 0.91.

Keywords: curing agent, fly ash, shear strength, fractal dimension, SEM

INTRODUCTION

The rapid development of China's coastal economy has promoted port construction and channel dredging, resulting in a lot of dredger fill. Due to the high water content of dredger fill, the engineering properties are very poor. Mixing the curing agent in dredger fill can improve the engineering performance in a short time. The addition of fly ash can effectively improve the effect of the curing agent and reduce the cost of the curing agent, and can alleviate the pollution of the fly ash to the environment, and play the role of waste utilization. In engineering application, the shear strength of soil is an important index. Many scholars have done a lot of research on the shear strength of solidified soil [2,3,5], and many valuable theoretical and application conclusions have been drawn. The microstructure of soil has certain self-similarity. The microstructure of solidified soil is analyzed by fractal theory [12]. Many scholars have made a lot of research on the microstructure of soil [1,4,6], including micro image processing, the extraction of microstructure parameters and the calculation method of fractal dimension, and so on.

TEST MATERIALS AND TEST METHODS

TEST MATERIALS

The dredger fill is from Hengsha Island of Shanghai. The physical indexes of the dredger fill are tested by the laboratory test and the data are shown in Tab.1. The curing agent used in the experiment is a mixture of various materials, which accounts for the main components of the material for cement and lime. The grade of fly ash used in the experiment is grade two, and its main components are shown in Tab.2.

Tab. 1. Physical indexes of the dredger fill

specific gravity	2.69
gravity kN/m^3	16.01
water content（%）	24
liquid limit	37
plastic limit	26
internal friction angle	7
cohesion (kPa)	0.826

Tab. 2. Main components of fly ash

component	content(%)
SiO_2	90.7
Al_2O_3	28.9
Fe_2O_3	6.42
CaO	1.93
MgO	1.73
SO_3	0.45
K_2O	0.59
Na_2O	0.48

TEST METHOD

In this experiment, the water content of the soil is 40%, and the sample is divided into five groups. One of the curing agent content is 4%, the other four groups of curing agent are 3%, and 0%, 2%, 4% and 8% fly ash respectively. The scheme of the proportioning in the test is shown in Tab.3. The high of cutting ring is 20 mm, the diameter of cutting ring is 61.8mm. Direct shear test and scanning electron microscope test were carried out for 14 days, 28 days, 42 days and 90 days respectively.

Tab. 3. The scheme of the proportioning in the test

test number	water content	curing agent	*fly ash*
1	40%	4%	0%
2	40%	3%	0%
3	40%	3%	2%
4	40%	3%	4%
5	40%	3%	8%

Scanning electron microscope test is done by field emission scanning electron microscope (ER-SEM) that made in Japan in the Analysis and Testing Center of Shanghai Jiao Tong University. The sample is dehydrated and dried by oven drying method, and then the sample is slowly cut out with a knife of 10 * 10 *20 mm, and the sample is carefully broken to reveal the fresh surface for observation.

The micro image of solidified dredger fill is processed and analyzed by using the image processing software. Main operating procedures include Image segmentation, image morphological processing, the calibration of the measuring unit, the selection of measurement parameters and data analysis and finishing. Cui Yongtao[1],Hang Li[4], Xu Riqing[10,11], Zhen Zhiheng[15] have done a detailed introduction, not tired in words here. The Microscopic image and binary image of solidified dredger fill is showed in Fig. 1.

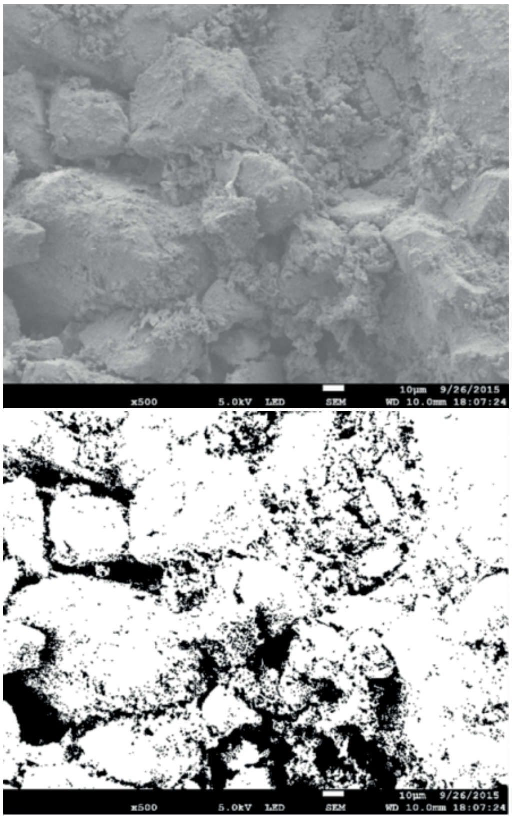

Fig. 1. Microscopic image and binary image of solidified dredger fill

FRACTAL THEORY

At present, fractal theory is applied to many parameters of soil microstructure, and different parameters reflect different structural characteristics. In view of the macroscopic mechanical properties of solidified dredger fill, three fractal dimensions are selected: particle surface fractal dimension D_{pr}, particle size fractal dimension D_{ps} and aperture fractal dimension D_{bs}.

PARTICLE SURFACE FRACTAL DIMENSION D_{PR}

Measuring the particle contour line of solidified dredger fill with length measuring ruler of ε, the number of required measuring ruler is N(ε). By changing ε, the different N(ε) can be obtained. A series of ε and N(ε) as points are depicted on the double logarithmic coordinate diagram, and the negative value of the slope of the straight line fitting through these points is the particle surface fractal dimension.

$$D_{pr} = -\lim_{\varepsilon \to 0} \frac{\ln N(\varepsilon)}{\ln \varepsilon} \tag{2}$$

Where:
D_{pr} – particle surface fractal dimension
ε – length of measuring ruler measuring the particle contour line of solidified dredger fill
$N(\varepsilon)$ – number of measuring ruler

APERTURE FRACTAL DIMENSION D_{BS} AND PARTICLE SIZE FRACTAL DIMENSION D_{PS}

The number of aperture which is larger than r is N (≥r), r values will be changed, and a series of N (≥r) will be obtained. N (≥r) and r are depicted on the double logarithmic coordinate diagram. The negative value of the slope of the straight line fitting through these points is the aperture fractal dimension.

$$D_{bs} = \frac{-\ln N(\geq r)}{r} \tag{3}$$

Where:
D_{bs} – aperture fractal dimension
r – aperture
N – aperture number

Particle size fractal dimension D_{ps} is similar to the calculation principle and method of aperture fractal dimension.

TEST RESULT

DIRECT SHEAR TEST RESULT

The internal friction angle of solidified dredger fill under different curing periods and different curing agents is shown in Tab.4. The relationship between the internal friction angle and curing period is showed in Fig.2. The relationship between the internal friction angle and the type of curing agent is showed in Fig.3.

Tab. 4. The internal friction angle of solidified dredger fill

test number	curing period T/d			
	14	28	42	90
1	24.5	37.7	38.1	38.2
2	22.2	35.4	35.6	35.6
3	23	35.9	37.5	37.6
4	21.8	35.4	39	40.2
5	20	34.4	38.5	41.2

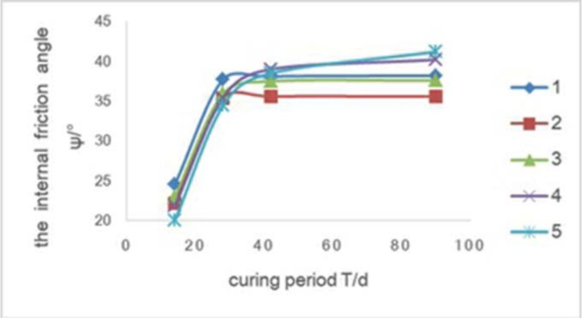

Fig. 2. Relationship between the internal friction angle and curing period

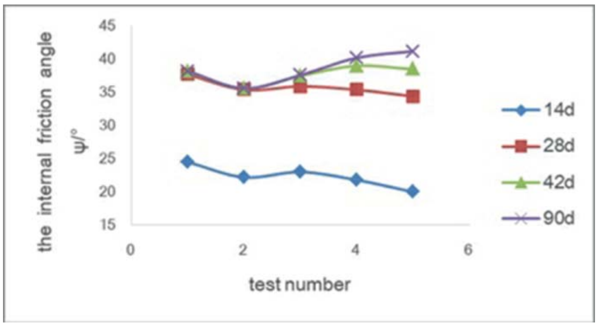

Fig. 3. Relationship between the internal friction angle and the type of curing agent

Fig. 2 shows that under the same type of curing agent, along with the curing period growth, the internal friction angle of solidified soil increases first and then tends to be stable. The internal friction angle of test 4 and test 5 had exceeded the internal friction angle of test 1 at the time of 42 days; Moreover, it can be seen that the internal friction angle between test 4 and test 5 is relatively close on the 90 day, which indicates that increasing the fly ash content will not increase the internal friction angle.

In Fig. 3, compared with 2, 3, 4 and 5 of the test, it can be seen that along with the fly ash content growth , the internal friction angle will increase first and then decrease before 42 days, and the internal friction angle will increase along with the fly ash content growth after 42 days.

The cohesion of solidified dredger fill under different curing periods and different curing agents is shown in Tab.5. The relationship between the cohesion and curing period is showed in Fig.4. The relationship between the cohesion and the type of curing agent is showed in Fig. 5.

Tab. 5. The cohesion of solidified dredger fill

test number	curing period T/d			
	14	28	42	90
1	42.4	64.4	72.4	74.7

test number	curing period T/d			
	14	28	42	90
2	31.1	51.3	59.8	59.8
3	33.1	52	77.6	77.7
4	29.5	50.4	84.5	86.5
5	20	35.6	77.2	96.9

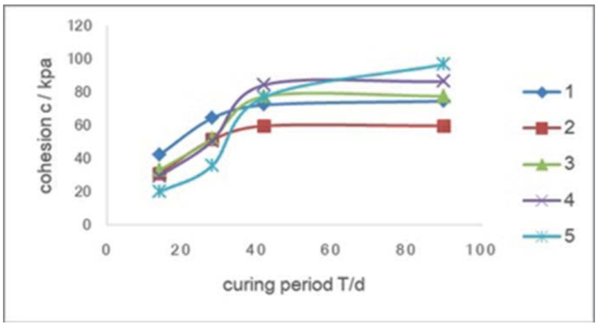

Fig. 4. Relationship between the cohesion and curing period

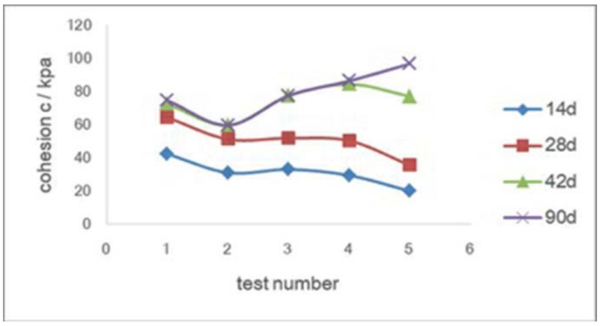

Fig. 5. Relationship between the cohesion and the type of curing agent

Fig. 4 shows that under the same type of curing agent, along with the curing period growth, the cohesion of solidified soil increases first and then tends to be stable. The cohesion of test 4 and test 5 had exceeded the cohesion of test 1 at the time of 42 days.

In Fig. 5, compared with 2, 3, 4 and 5 of the test, it can be seen that along with the fly ash content growth , the cohesion increased first and then decreased before 42 days, and the cohesion will increase along with the fly ash content growth after 42 days.

Fig. 2 and Fig.4 show that under the same type of curing agent, with the curing period growth, the hydration products with cementation increase after hydration of the curing agent, which makes the internal friction angle and the cohesion increase. When the curing agent is fully hydrated, the internal friction angle and the cohesion tend to be stable.

Fig. 3 and Fig. 5 show that fly ash played a role in filling and hindering the hydration of curing agent before 42 days, along with the fly ash content growth, the filling effect offly ash is firstly greater than the hindrance effect, and then is less than the hindrance, which make the shear strength index increase first and then reduce; After 42 days, the fly ash will accelerate the hydration reaction, which makes the shear strength index increase with the fly ash content growth.

The test results of the internal friction angle and the cohesion of solidified dredger fill show that the internal friction angle and the cohesion of test 4 and test 5 are much higher than those of test 1 after 42 days, which indicates that adding fly ash can enhance the effect of curing agent.

FRACTAL DIMENSION COMPUTING RESULT

According to the calculation method of fractal dimension of soil, the specific value of particle surface fractal dimension D_{pr}, particle size fractal dimension D_{ps} and aperture fractal dimension D_{bs} is obtained by applying the method to the solidified dredger fill with different content of fly ash.

Tab. 6 is the result of surface fractal dimension of solidified dredger fill at different curing periods and different fly ash content.

Tab. 6. The surface fractal dimension of solidified dredger fill

curing period T（d）	fly ash content λ/%			
	0	2	4	8
14	1.142	1.143	1.144	1.143
28	1.125	1.129	1.132	1.135
42	1.123	1.12	1.12	1.122
92	1.122	1.119	1.112	1.111

Tab. 7 is the result of particle size fractal dimension of solidified dredger fill at different curing periods and different fly ash content.

Tab. 7. The particle size fractal dimension of solidified dredger fill

curing period T（d）	fly ash content λ/%			
	0	2	4	8
14	1.436	1.462	1.458	1.457
28	1.293	1.368	1.407	1.416
42	1.288	1.295	1.325	1.335
92	1.292	1.269	1.259	1.254

Tab. 8 is the result of aperture fractal dimension of solidified dredger fill at different curing periods and different fly ash content.

Tab. 8. The aperture fractal dimension of solidified dredger fill

curing period T（d）	fly ash content λ/%			
	0	2	4	8
14	1.483	1.478	1.504	1.489
28	1.604	1.586	1.534	1.538
42	1.613	1.633	1.648	1.638
92	1.611	1.642	1.659	1.667

QUANTITATIVE ANALYSIS OF RELATIONSHIP BETWEEN FRACTAL PARAMETERS AND MECHANICAL PARAMETERS OF SOLIDIFIED DREDGER FILL WITH DIFFERENT AMOUNTS OF FLY ASH

SURFACE FRACTAL DIMENSION D_{PR}

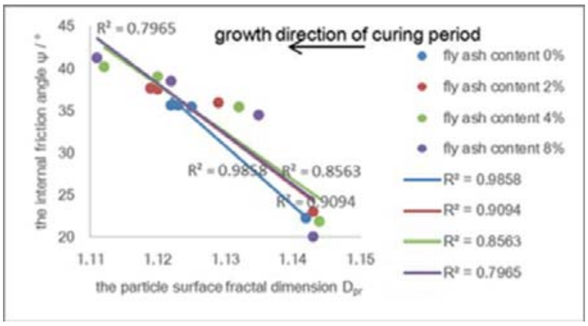

Fig. 6. Relationship between the internal friction angle and particle surface fractal dimension

The relationship between the internal friction angle and the particle surface fractal dimension is showed in Fig. 6. Fig. 6 shows that there is no obvious linear relationship between the two factors. Moreover, the point distribution in the figure is inhomogeneous, and the internal friction angle is between 35 and 40 degrees, indicating that the change between the particle fractal dimension and the internal friction angle is not obvious.

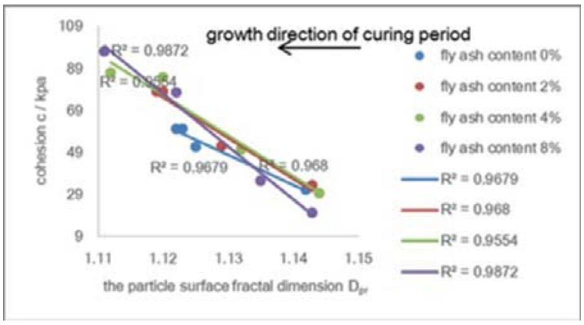

Fig. 7. Relationship between the cohesion and particle surface fractal dimension

The relationship between the cohesion and the particle surface fractal dimension is showed in Fig. 7. Fig.7 shows that along with the decrease of particle surface fractal dimension, the cohesion increases under different fly ash content, and there is a linear correlation between the two, the correlation coefficient is above 0.95.

It can also be seen that along with fly ash content growth, the inclination of fitting line increases, indicating that along with fly ash content growth, the cohesion of dredger soil is more sensitive to the particle surface fractal dimension, the influence of the degree of particle surface fluctuation on the cohesion is enhanced.

PARTICLE SIZE FRACTAL DIMENSION D_{PS}

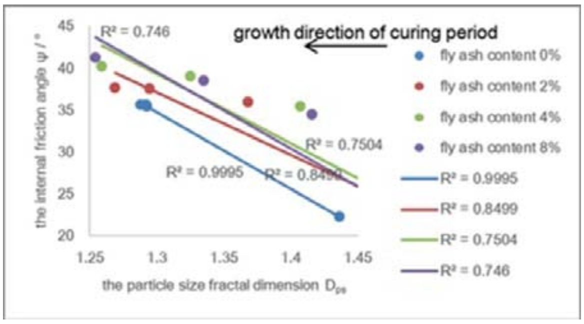

Fig. 8. Relationship between the internal friction angle and particle size fractal dimension

The relationship between the internal friction angle and the particle size fractal dimension is showed in Fig. 8. Fig. 8 shows that there is no obvious linear relationship between the two factors. Moreover, the point distribution in the figure is concentrated, and the internal friction angle is between 35 and 40 degrees, indicating that the change between the particle size fractal dimension and the internal friction angle is not obvious.

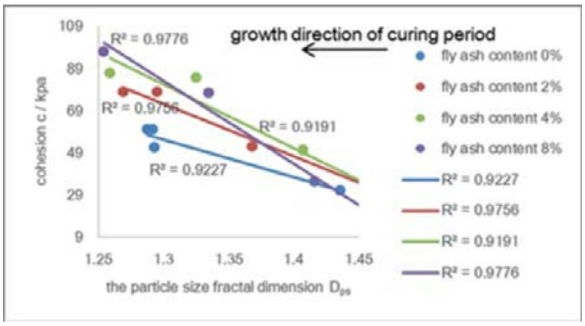

Fig. 9. Relationship between the cohesion and particle size fractal dimension

The relationship between the cohesion and the particle size fractal dimension is showed in Fig. 9. Fig. 9 shows that along with the decrease of particle size fractal dimension, the cohesion increases under different fly ash content, and there is a linear correlation between the two, the correlation coefficient is above 0.91. The particle gradation and the particle homogenization degree of solidified dredger fill will affect the cohesion.

It can also be seen that along with fly ash content growth, the inclination of fitting line increases, indicating that along with fly ash content growth, the influence of particle size fractal dimension on the cohesion of dredger fill increases, and the influence of particle homogenization degree on cohesion is enhanced.

APERTURE FRACTAL DIMENSION D_{BS}

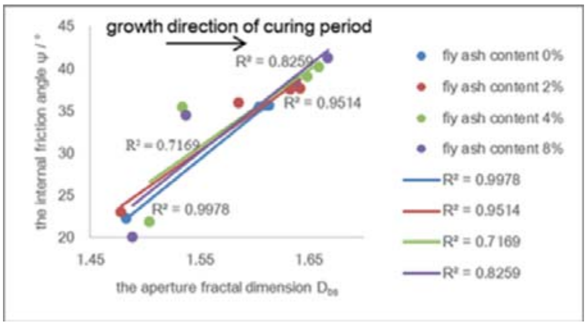

Fig. 10. Relationship between the internal friction angle and aperture fractal dimension

The relationship between the internal friction angle and the aperture fractal dimension is showed in Fig.10. Fig.10 shows that there is no obvious linear relationship between the two factors.

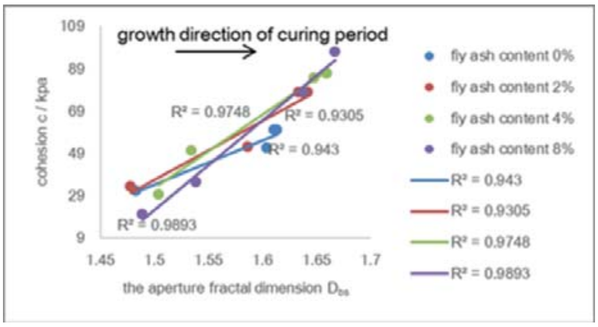

Fig. 11. Relationship between the cohesion and aperture fractal dimension

The relationship between the cohesion and the aperture fractal dimension is showed in Fig.11. Fig.11 shows that along with the aperture fractal dimension growth, the cohesion increases under different fly ash content, and there is a linear correlation between the two, the correlation coefficient is above 0.93.

It can also be seen that along with fly ash content growth, the inclination of fitting line increases, indicating that along with fly ash content growth, the influence of aperture fractal dimension on cohesion of dredger fill increases, and the influence of pore homogenization degree on cohesion is enhanced.

Fig.7, Fig.9 and Fig.11 show that with the increase of curing period, the smaller particle surface fractal dimension D_{pr} and particle size fractal dimension D_{ps}, the larger aperture fractal dimension D_{bs}, the greater the cohesion, which indicates that the change of the three fractal dimensions enhances the relationship between particles, which makes the contact area between particles increase, and the cohesion increases.

CONCLUSION

The shear strength index of solidified dredger fill is measured by the direct shear test. The microscopic images of solidified dredger fill are obtained by using Scanning Electron Microscope (SEM). The microscopic images of dredger fill are processed and analyzed by using IPP, and the fractal dimension including particle size fractal dimension D_{ps}, aperture fractal dimension D_{bs} and particle surface fractal dimension D_{pr} was calculated by fractal theory. The quantitative analysis of the relationship between shear strength index and fractal dimension of solidified dredger fill is done. The research results show that:

1) Under the same type of curing agent, along with the increase of curing period T, the shear strength index of solidified dredger fill increases first and then tends to be stable. This indicates that with the increase of curing period, the hydration products with cementation increase after hydration of the curing agent, which makes the internal friction angle and the cohesion increase. When the curing agent is fully hydrated, the internal friction angle and the cohesion tend to be stable.
2) Before 42 days of the curing period, the shear strength index increased first and then decreased with the increase of fly ash content λ, and increased with the increase of fly ash content in 42 days. This shows that, 42 days ago, fly ash plays a role in filling and hindering the hydration of the curing agent during the curing process. With the increase of fly ash, the filling effect is first greater than the hindrance effect, and then is less than the hindrance; after 42 days, fly ash plays a role in accelerating hydration.
3) After a period of time, fly ash will accelerate the hydration of curing agent, which indicates that adding fly ash can enhance the effect of curing agent.
4) The relationship between the internal friction angle of solidified dredger fill and the three fractal dimensions shows that there is no obvious linear relationship between them. Moreover, the change of fly ash content has little effect on the relationship between the internal friction angle and the three fractal dimensions.
5) The relationship between the cohesion of solidified dredger fill and the three fractal dimensions shows that the cohesion has a good linear relationship with the three fractal dimensions, and the correlation coefficient R^2 is above 0.91. Moreover, with the increase of curing period, the smaller particle surface fractal dimension D_{pr} and particle size fractal dimension D_{ps}, the larger aperture fractal dimension D_{bs}, the greater the cohesion, which indicates that the change of the three fractal dimensions enhances the relationship between particles, which makes the contact area between particles increase, and the cohesion increases.

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REFERENCE

1. Cui Yongtao, Liu Wenbai, Xu Bingqin: The study of compression modulus and changes in microstructure of dredged mud before and after solidification, Science Technology and Engineering, Vol.16, no.15, pp.260-267, 2016.

2. Ding Jianwen, Hong Zhenshun, Liu Songyu: Triaxial shear test of flow-solidified soil of dredged clays, Journal of Southeast University (Natural Science Edition), Vol.41, no.5, pp.1070-1074, 2011.

3. Fu Zhibin, Zhang Lihong, Zhang Jixing, Zhao Gang: Research on solidifying dredger fill of littoral facies with experiment, Geotechnical Investigation & Surveying, no.3, pp.7-11, 2012.

4. Huang Li: Quantitative Analysis of Micro-Porosity of Saturated Soft Clay and Its Fractal Description, Wuhan University of Technology, Wuhan, 2007.

5. Liu Xin, Fan Xiaoqiu, Hong Baoning: Experimental study of triaxial test of soils stabilized by cement mortar, Rock and Soil Mechanics, Vol.32, no.6, pp. 1676-1682, 2011.

6. Lu Peixia, Cao Ling, Xu Yongfu: Fractal Theory of Unsaturated Soil Mechanics, Chinese Journal of Underground Space and Engineering, Vol.11, no.2, pp. 375-381, 2015.

7. Shao Yufang, Xu Riqing, Liu Zeng-yong, Gong Xiaonan: Experimental study on new variety of cement-stabilized soil, Journal of Zhejiang University(Engineering Science), Vol.40,no.7,pp.1196-1200,2006.

8. Wang Dongxing, Xu Weiya: Research on strength and durability of sediments solidified with high volume fly ash, Rock and Soil Mechanics, Vol.33, no.12, pp.3659-3663, 2012.

9. Wu Yuanfeng, Yi Guiyun, Liu Quanrun, Li Fenghai, Zhao Liwei, Ma Mingjie: Current situation of comprehensive utilization of fly ash, Clean Coal Technology, Vol.19, no.6, pp.100-104, 2013.

10. Xu Riqing, Deng Weiwen, Xubo, Lai Jianping, Zhan Xuegui, Xu Liyang, Lu Jianyang: Quantitative Analysis of Soft Clay Three-dimensional Porsity Based On SEM Image Information, Journal of Earth Science and Enviroment, Vol.03, pp.104-110, 2015.

11. Xu Riqing, Xu Liyang, Deng Weiwen, Zhu Yihong: Experimental study on soft clay contact area based on SEM and IPP, Journal of Zhejiang University (Engineering Science), Vol.08, pp.1417-1425, 2015.

12. Zhang Zhihong, Li Hongyan, Shi yumin: Experimental Study on Permeability Properties and Microstructure of Clay Contaminated by Cu2+,China Civil Engineering Journal, Vol.47,no.12,pp.122-129,2014.

13. Zhang Jiru, Hu Yong, Yu Hongling, Tao Gaoliang: Predicting soil-water characteristic curve from multi-fractal particle-size distribution of clay, Journal of Hydraulic Engineering, Vol.46, no.6, pp. 650-657, 2015.

14. Zhao Minghua, Dai Jie, Zhang Ling, Yin Pingbao: Fractal Theory-based Study of the Permeability of Fly Ash, Journal of Hunan University(Natural Sciences), Vol.42,no.1,pp.75-80,2015.

15. Zhen Zhiheng, Gao Jianwei: The Microscopic Characteristic Analysis of Red Bed Mudstone Modified Soil Based on IPP, Transportation Science and Technology, Vol.08, pp.124-127, 2015.

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