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Quantitative analysis of the relationship between permeability and microstructure of solidified dredger fill

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The dredger fill of Shanghai Hengsha Island Dongtan is solidified by self-made curing agent, and the permeability of Solidified dredger fill is measured by the indoor penetration test. The microstructure of the solidified dredger fill and unsolidified dredger fill is observed by using Scanning Electron Microscope (SEM). The microscopic image of dredger fill is processed and analysed by using IPP, and the microstructure parameter was calculated that include mean equivalent particle diameter Dp, mean equivalent pore diameter Db, plane porosity n. The Quantitative analysis of the relationship between permeability and microstructure of Solidified dredger fill is done. The research results show that the permeability of solidified dredger filled creases with the increase of mean equivalent particle diameter Dp and the decrease of mean equivalent pore diameter Db and plane porosity n; Under the same age, the permeability coefficient K has a good linear relationship with mean equivalent particle diameter Dp, mean equivalent pore diameter Db and plane porosity n; The effect of plane porosity on the permeability of solidified dredger fill is larger than the mean equivalent particle diameter and mean equivalent pore diameter.

Key words: Solidified dredger fill, curing agent, permeability coefficient, microstructure SEM.

INTRODUCTION

The rapid development of China's coastal economy promotes the construction of port and waterway dredging, which produced a lot of dredger fill. 2010 to 2015, in process of the Yangtze River waterway dredging, 80 million cubic meters of dredger fill is produced each year; In the Pearl River Delta region, the amount of dredger fill is about 80 million cubic meters [5]. In 2013, the amount of dredger fill is 1 billion 600 million in china. In 2016, it will be 3 billion cubic meters in china. The water content of the dredger fill is very high, and the engineering quality is very poor. The water content and the engineering properties can be improved by adding the curing agent to the dredger fill. The permeability of solidified soil is an important index of its mechanical properties, and the permeability coefficient is one of the decisive factors in the selection of static and dynamic drainage consolidation method and the determination of its technological parameters[6].At present, the research on the permeability of soil is mostly focused on the structure of soil, the consolidation stress and the influence of saturation on the permeability[2,7,8].Many scholars have discussed the relationship between the permeability and microstructure of bentonite, contaminated soil and so on[9,12]. The micro aspect of the soil is the research process of the material from the internal mechanism to the external performance, which can reflect the real situation of the soil.

EXPERIMENTAL

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 minor components mainly include lignin sulfonate, acrylamide and so on.

Test method

In this experiment, the water content of the soil is 56%, the amount of curing agent is0%, 4%, 8%, 12%. The high of cutting ring is 40mm, the diameter of cutting ring is 61.8mm. Curing temperature is 20±2℃, Curing humidity is 90%. Permeability test and scanning electron microscope test were carried out for 7 days, 14 days, 21 days and 28 days respectively.

Permeability test is done by South TST - 55 type osmometer, the test procedure and calculation method is in accordance with《Standard For Soil Test Methods》[3], specific operating procedures in this won't repeat them.

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Table. 1. Physical properties of the soil specimens.

Specific gravity	Gravity kN/m^3	Water content(%)	Liquid limit	Plastic limit	Internal friction angle	Cohesion (kPa)
2.75	18.3	45	30.43	27.91	35.64	0.917

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. Dehydration and drying method for samples is oven drying method. The dried sample is cut into small pieces with a knife slowly. The size of small pieces is 6*6*20mm. The small pieces is broken carefully and the plane of break is used for scanning electron microscope test. Image-Pro Plus

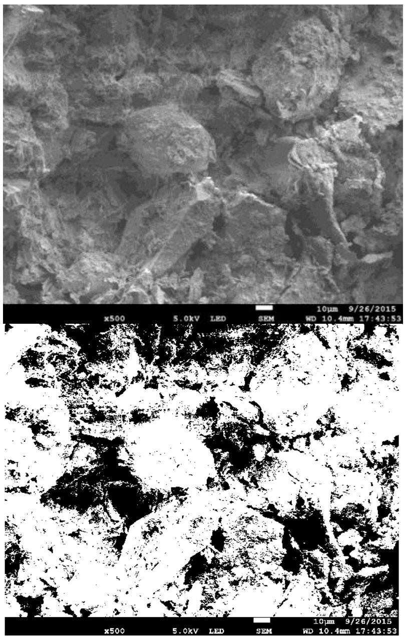

Fig. 1. Microscopic image and binary image of dredger fill

The micro image of solidified dredger fill is processed and analysed by using the Image-Pro Plus. 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. Huang li [4], zhang jiru [13], zheng zhiheng [14], cui yongtao [1], xuriqing [10,11] have done a detailed introduction, not tired in words here.The microscopic imageand binary image of dredger fill is showed in Fig.1. The Microscopic image and binary image of solidified dredger fill is showed in Fig.2.

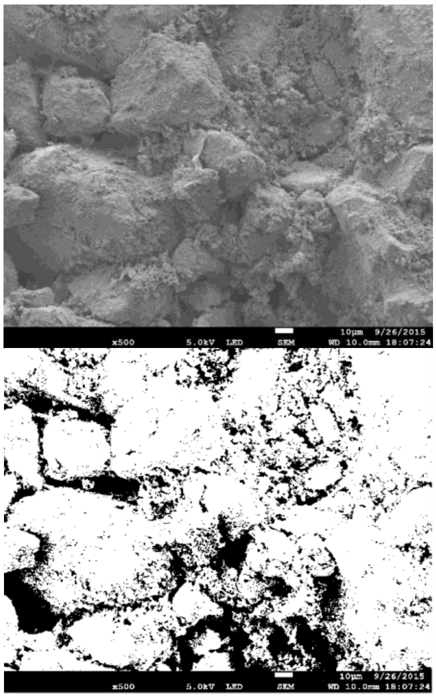

Fig. 2. Microscopic imageand binary image of solidified dredger fill

TEST RESULT

Permeabilitytest result

The permeability coefficient of solidified dredger fill under different age and different curing agent content is showed in Tab.2. The relationship between the permeability coefficient and curing period is showed in Fig.3.The relationship between the permeability coefficient and curing agent content is showed in Fig.4.

Table. 2. The permeability coefficient of Solidified dredger fill.

curing period T(d)	curing agent content λ/% 0	4	8	12
0	7.319	7.315	7.308	7.299
7	7.331	4.867	3.546	1.903
14	7.208	2.782	1.859	0.611
21	7.351	2.091	0.813	0.416
28	7.119	1.325	0.575	0.201

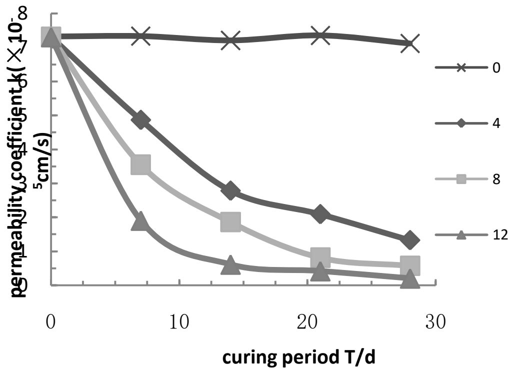

Fig. 3. Relationship between the permeability coefficient and curing period.

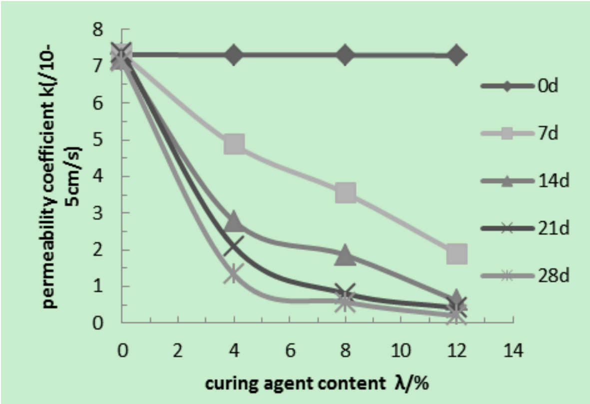

Fig. 4. Relationship between the permeability coefficient and curing agent content.

Fig. 3 shows that along with the curing period growth, the permeability coefficient of solidified dredger fill is getting smaller; The permeability coefficient decreased very significantly before 14 days, and the permeability coefficient tended to be stable after 14 days; the permeability coefficient of solidified dredger fill that curing agent content is 8%, 12% and curing period is 28 days is close to, which indicates that the curing agent for the improvement of permeability of dredger fill has been fully played when the curing agent content is 8%.

Fig.4shows that along with the curing agent content growth, the permeability coefficient of solidified dredger fill is getting smaller under the same curing period; The difference of the permeability coefficient of solidified dredger fill is very big when the curing period is 7 days and it is not big when the curing period is 14 days, 21 days and 28 days

Image analysis results

The micro image of solidified dredger fill is processed and analyzed by using the Image-Pro Plus. Data extracted from the image is analyzed. mean equivalent particle diameter Dp , mean equivalent pore diameter Db and plane porosity n are quantitatively analyzed.

Mean equivalent particle diameter Dp is the mean value of the equivalent diameter of all the particles in the analyzed area, that is the size of particles from the statistical significance. Mean equivalent particle diameter Dp is equal to the diameter of the equivalent circle that is equal to the area of the particles unit, which can approximately represent the size of a single particle.

$$D_p = \sum \frac{d_i}{n} \quad (1)$$

Error! Reference source not found. (2)

Where:**Error! Reference source not found.Error! Reference source not found.**—the diameter of the equivalent circle that is equal to the area of the particleunit

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The mean equivalent particle diameter of Solidified dredger fill under different age and different curing agent content is showed in Tab.3.The relationship between the mean equivalent particle diameter and curing period is showed in Fig.5. The relationship between the mean equivalent particle diameter and curing agent content is showed in Fig.6.

Table. 3. the mean equivalent particle diameter of solidified dredger fill

Curing period T(d)	Curing agent content λ/%			
	0	4	8	12
7	1.83	2.11	2.61	2.71
14	1.83	2.35	2.88	2.94
28	1.83	2.69	2.94	3.25

Fig. 5 shows that along with the curing period growth, the mean equivalent particle diameter increases linearly under different curing agent content and the linear correlation coefficients are above 0.95. Fig. 6 shows that along with the curing agent content growth, the mean equivalent particle diameter increases linearly under different curing period and the linear correlation coefficients are above 0.91. It is proved that the mean equivalent particle diameter increases gradually during the solidification process.

Mean equivalent pore diameter Db is the mean value of the equivalent diameter of all the pores in the analyzed area, that is the size of pores from the statistical significance. Mean equivalent pore diameter Db is equal to the diameter of the equivalent circle that is equal to the area of the structural unit, which can approximately represent the size of a single pore.

$$D_b = \sum \frac{d_i}{N} (1)$$

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Where:**Error! Reference source not found.Error! Reference source not found.**—the diameter of the equivalent circle that is equal to the area of the pore unit

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The mean equivalent pore diameter of Solidified dredger fill under different age and different curing agent content is showed in Tab.4.The relationship between the mean equivalent pore diameter and curing period is showed in Fig.7. The relationship between the mean equivalent pore diameter and curing agent content is showed in Fig.8.

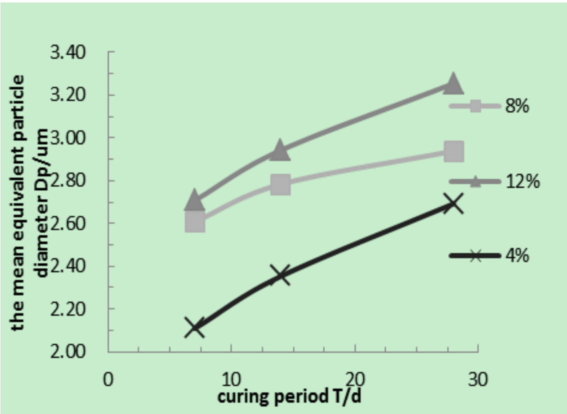

Fig. 5. Relationship between the mean equivalent particle diameter and curing period.

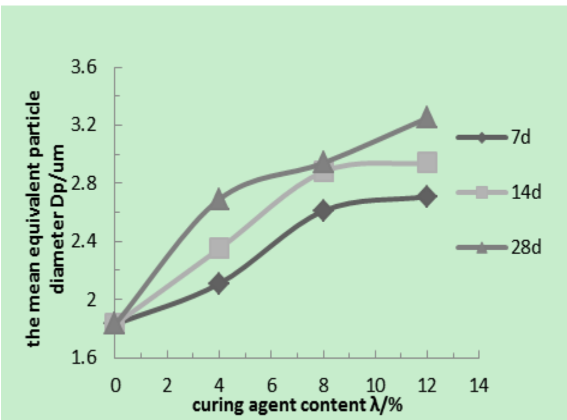

Fig. 6. Relationship between the mean equivalent particle diameter and curing agent content.

Table 4. The mean equivalent pore diameter of Solidified dredger fill.

Curing period T(d)	Curing agent content λ/%			
	0	4	8	12
7	4.44	2.03	1.52	1.26
14	4.44	1.56	1.15	1.09
28	4.44	1.48	1.06	0.98

Fig. 7 and Fig.8 show that along with the curing period and curing agent content growth, the mean equivalent pore diameter gradually decrease. Compared with the mean equivalent particle diameter, the rate of decrease of the mean equivalent pore diameter is faster than the rate of increase of the mean equivalent particle diameter, which indicates that due to the presence of grain resistance (friction, cohesion, etc.), the size, shape and position of soil particles will change when the cementing effect of the curing agent is fully played and overcome grain resistance.

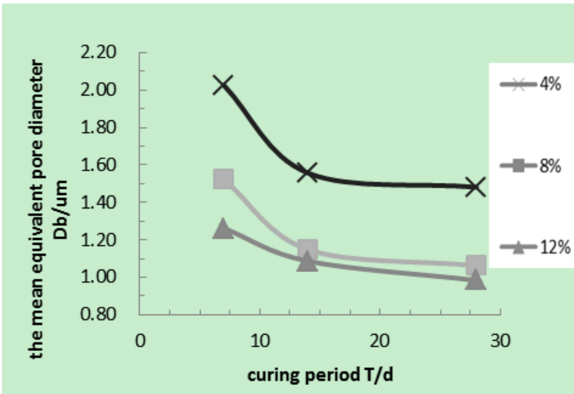

Fig. 7. Relationship between the mean equivalent pore diameter and curing period.

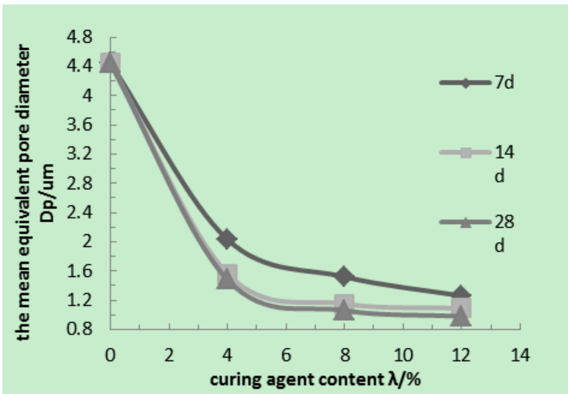

Fig. 8. Relationship between the mean equivalent pore diameter and curing agent content.

Fig. 7 shows that the difference of the mean equivalent pore diameter is not obvious when the curing agent content is 8% and 12%, and both are smaller than the mean equivalent pore diameter that curing agent content is 4%. This analysis is similar to the analysis of Fig. 3, which indicates that the permeability of solidified dredger fill is closely related to the mean equivalent pore diameter.

Plane porosity n is the pore area percentage of the whole analyzed area. The calculation formula is as follows:

$$n = \frac{S_b}{S} \times 100\% \quad (5)$$

Where: n—Plane porosity

Error! Reference source not found.—pore area in the analyzed area

S—the whole analyzed area.

The plane porosity of solidified dredger fill under different age and different curing agent content is showed in Table. 5. The relationship between the plane porosity and curing period is showed in Fig. 7. The relationship between the plane porosity and curing agent content is showed in Fig. 8.

Table. 5. the plane porosity of Solidified dredger fill.

Curing period T(d)	Curing agent content λ/%			
	0	4	8	12
7	33.37	23.09	18.30	17.86
14	33.37	18.51	17.71	13.77
28	33.37	14.50	13.75	13.36

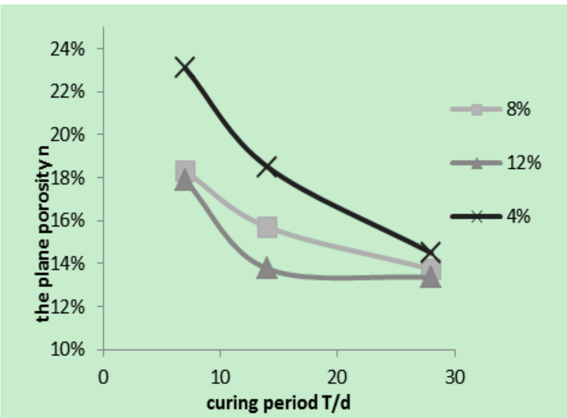

Fig. 9. Relationship between the plane porosity and curing period.

Fig. 9 and Fig. 10 show that along with the curing period and curing agent content growth, the plane porosity gradually decrease. Compared with the mean equivalent pore diameter Db, the variation law of the two is very similar, which indicates that the permeability of solidified dredger fill is closely related to the plane porosity.

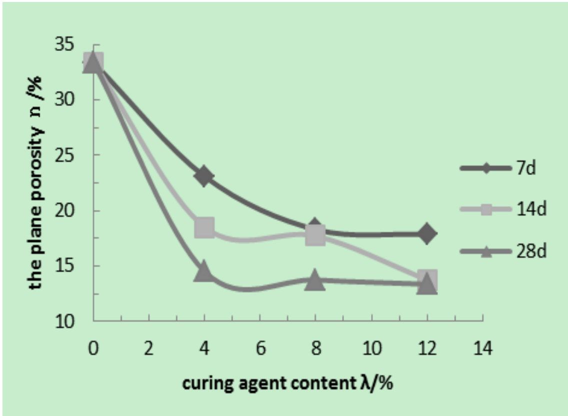

Fig. 10. Relationship between the plane porosity and curing agent content.

Quantitative analysis of relationship between permeability coefficient and microstructure

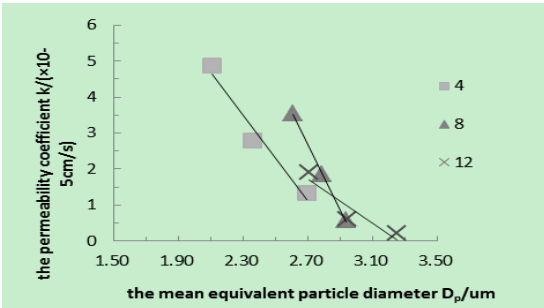

Fig. 11. Relationship between the permeability coefficient and mean equivalent particle diameter.

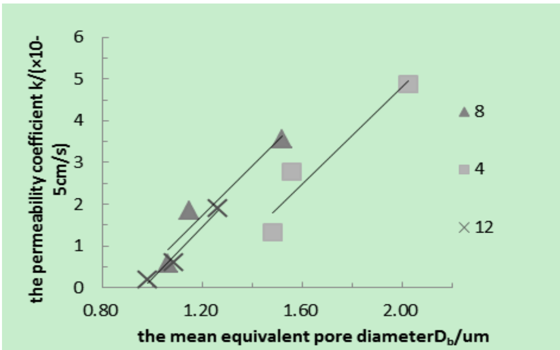

Fig. 12. Relationship between the permeability coefficient and mean equivalent pore diameter

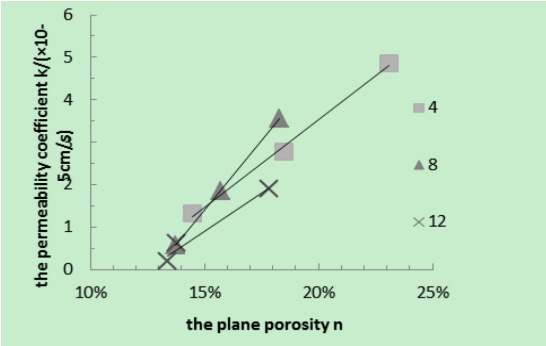

Fig. 13. Relationship between the permeability coefficient and plane porosity.

The relationship between the permeability coefficient and the mean equivalent particle diameter is showed in Fig. 11. Fig. 11 shows that along with the mean equivalent particle diameter increases, the permeability coefficient gradually decrease. In the solidification process of the dredger fill, the micro aspect is the increase of the mean equivalent particle diameter, the macroscopic aspect is the decrease of the permeability coefficient. The change of macroscopic and microscopic show that in the solidification process of the dredger fill, small particles gradually gather large particles due to the cementation of hydration products, the contact force between particles is enhanced, the soil structure become denser, integrity is improved, and permeability is improved.

The relationship between the permeability coefficient and the mean equivalent pore diameter is showed in Fig. 12. Fig. 12 shows that along with the mean equivalent pore diameter decrease, the permeability coefficient gradually decrease. In the solidification process of the dredger fill, the micro aspect is the decrease of the mean equivalent pore diameter, the macroscopic aspect is the decrease of the permeability coefficient. The change of macroscopic and microscopic show that in the solidification process of the dredger fill, the smaller the mean equivalent pore diameter, the greater the flow resistance is., and the lower the permeability coefficient is.

The relationship between the permeability coefficient and the plane porosity is showed in Fig. 13. Fig. 13 shows that along with the plane porosity decrease, the permeability coefficient gradually decrease. The change of macroscopic and microscopic show that in the solidification process of the dredger fill, the lower the plane porosity, the More compact structure is., and the lower the permeability coefficient is.

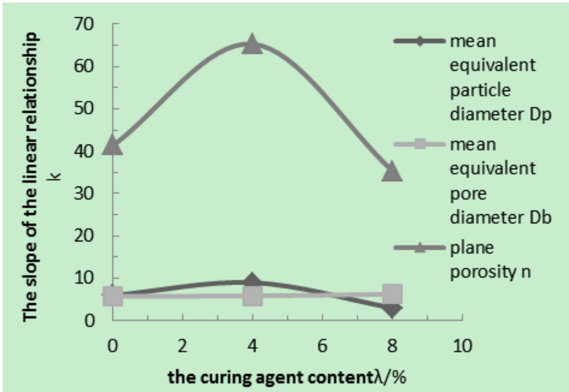

Fig. 14. The slope of the linear relationship of microstructure parameters and permeability coefficient under different content of curing agent.

Table. 6. Linear relationship between permeability coefficient and microstructure of Solidified dredger fill.

Microscopic parameter	Curing agent content λ/%	The linear relationship between permeability coefficient k and microstructure	R^2	Slope K
mean equivalent particle diameter D_p	4	$k= -5.9631D_p+ 17.215$	0.9624	5.9631
	8	$k= -8.9982D_p + 26.979$	0.9981	8.9982
	12	$k= -3.0179D_p+ 9.8619$	0.8681	3.0179
mean equivalent pore diameter D_b	4	$k= 5.7832D_b- 6.7695$	0.9166	5.7832
	8	$k= 5.8814D_b - 5.3245$	0.9295	5.8814
	12	$k= 6.2588D_b - 6.0475$	0.9801	6.2588
plane porosity n	4	$k = 41.342x - 4.7395$	0.9960	41.342

8	k= 65.284x - 8.3987	0.9991	65.284
12	k= 35.309x - 4.3905	0.9772	35.309

The linear relationship between permeability coefficient and microstructure of Solidified dredger fill is showed in Table. 6. It can be seen from the table 6 that there is an excellent linear relationship between the permeability coefficient and the three micro structure parameters, which indicates that the permeability coefficient K is strongly correlated with the mean equivalent particle diameter Dp, mean equivalent pore diameter Db and plane porosity n.

The slope of the linear relationship of microstructure parameters and permeability coefficient under different content of curing agent is showed in Fig. 14. It can be seen from the figure 14 that the slope of the linear relationship between the permeability coefficient and the mean equivalent particle diameter Dp and the mean equivalent pore diameter Db is very small, which is below 10, and the slope of the linear relationship between the permeability coefficient and the plane porosity n is above 35, which is 8-10 times of the former under the same conditions. So compared with the mean equivalent particle diameter Dp and the mean equivalent pore diameter Db, The effect of the plane porosity on permeability of solidified soil is greater.

CONCLUSION

The permeability of solidified dredger fill is measured by the indoor penetration test. The microstructure of the solidified dredger fill and unsolidified dredger fill is observed by using Scanning Electron Microscope (SEM). The microscopic image of dredger fill is processed and analyzed by using IPP, and the microstructure parameter is calculated that include mean equivalent particle diameter Dp, mean equivalent pore diameter Db, plane porosity n. The Quantitative analysis of the relationship between permeability and microstructure of Solidified dredger fill is done. The research results show that:

1) Self-made curing agent can effectively reduce the permeability of dredger fill, the permeability coefficient decrease with the growth of the age and the increase of the content of curing agent.The permeability coefficient decreased very intense before 14 cured days, and the permeability coefficient tends to be stable after 14 days.So in order to improve the permeability of the dredger fill, it can be taken to increase the amount of curing agent.

2) The quantitative analysis of the particles of the solidified dredger fill shows that the mean equivalent particle diameter Dp has a linear correlation with the curing period T, and the correlation coefficient is above 0.95.

3) The quantitative analysis of the pores of the solidified dredger fill shows that the difference of the mean equivalent pore diameter is not obvious when the curing agent content is 8% and 12%, and both are smaller than the mean equivalent pore diameter that curing agent content is 4%. Compared with the mean equivalent particle diameter, the rate of decrease of the mean equivalent pore diameter is faster than the rate of increase of the mean equivalent particle diameter.

4) The quantitative analysis of the plane porosity of the solidified dredger fill shows that the plane porosity of original dredger fill is 66.63%. The plane porosity of solidified dredger fill decreases with the increase of the curing agent and the growth of the curing period. When the curing period is 28 days, the plane porosity of the solidified dredger under three different content of curing agent is little difference and tends to be stable.

5)The quantitative analysis of the relationship between permeability coefficient and microstructure of the solidified dredger fill shows that the larger the mean equivalent particle diameter Dp is, and the smaller the mean equivalent pore diameter Db and plane porosity n are, the lower the permeability coefficient is. The mean equivalent particle diameter Dp, mean equivalent pore diameter Db, plane porosity n have a good linear relationship with the permeability coefficient k, and the correlation coefficient K is above 0.9, compared with the mean equivalent particle diameter Dp and the mean equivalent pore diameter Db, The effect of the plane porosity on permeability of solidified soil is greater.

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REFERENCES

1. Y.T. Cui, W.B. Liu, B.Q. Xu, *Science Technology and Engineering*, **05**, 260 (2016).
2. Z.W. Gu, B.N. Sun. Dong Yining, *Chinese Journal of Rock Mechanics and Engineering*, **22**(3), 505 (2003).
3. GB/T 50123-1999 Standard For Soil Test Methods.
4. L. Huang, Quantitative Analysis of Micro-Porosity of Saturated Soft Clay and Its Fractal Description, Wuhan University of Technology, 2007.
5. B. Ji, X.M. Xiao, Z. Li, *Safety and Environmental Engineering*, **02**, 54 (2010).
6. M.C. Jia, L. Wang, J. Zhou, *Journal of Tong Ji University(natural science)*, **4**, 493 (2010).
7. Y.Y. Li, B.J. Liu, Y.L. Xie, *Journal of Rock Mechanics and Engineering*, **25**(S2), 3587 (2004).
8. K.H. Xie, Y.C. Zhuang, X.B. Li, *Journal of Geotechnical Engineering*, **27**(5), 591 (2005).
9. C. Xu, D. Li, L. Huang, *Journal of Tong Ji University(natural science)*, **06**, 819 (2011).
10. R. Q. Xu, W. W. Deng, B. Xu, J. P. Lai, X. Q. Zhan, L. Y. Xu, J. Y. Lu, *Journal of Earth Science and Environment*, **3**, 104 (2015).
11. R.Q. Xu, L.Y. Xu, W.W. Deng, Y. H. Zhu, *Journal of Zhejiang University(Engineering Science),* **8**, 1417 (2015).
12. Z.H. Zhang, H.Y. Li, Y.M. Shi, *China Civil Engineering Journal*, **47**(12), 122 (2014).
13. J.R. Zhang, J. Zhu, L. Huang, W.J. Huang, *Journal of Wuhan University of Technology*, **4**, 80 (2008).
14. Z.H. Zhen, J.W. Gao. *Transportation Science and Technology*, **8**, 124 (2015).