Permeabilities of Cement-Treated Geomaterials Subjected to Varying Water-Cement Ratios

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ABSTRACT: The effect of cement-grouting plays an important role in the engineering property of cement-treated sands. To investigate the effect of different water-cement (*w/c*) ratios on sand cementation, one dimensional seepage test was conducted with different particle size in this study. The permeability coefficient and uniaxial compressive (UC) strength of treated samples were studied respectively. Test results indicated that with the increase of *w/c* ratio, the increase of permeability coefficient of sands with particle size 1.25-2.50 mm is larger than that of sands with particle size 2.50- 5.00 mm after 7 days curing time. The UC strength of treated samples decreases with the increase of *w/c* ratio. The larger the particle size, the smaller the reduction of UC strength. These phenomena are closely related to the formed bond strength between sand particles.

KEYWORDS: One-dimensional seepage test, Water-cement ratio, Permeability coefficient, Porosity, Uniaxial compressive strength.

1. INTRODUCTION

Cement is widely used in soil improvement as the strong stability, good fluidity and high consolidation strength of formed cement slurry (Fam and Santamarina, 1996; Bhuria and Sachan, 2014; Meepon et al., 2016; Pan et al., 2018; Zhang et al., 2018; Chen et al., 2019; Kou et al., 2020). In the process of cement grouting, the grout filled the pores between sand particles to improve the strength and reduce the permeability of cemented sand.

A series of experimental studies have been conducted to explore the diffusion process of cement slurry in grouting. Some field tests were also carried out to investigate the influence of static and dynamic water pressure on grouting (Kamruzzaman et al., 2000; Yang, 2006; Nikbakhtan and Osanloo, 2009; Vipulanandan et al., 2016; Raof et al., 2018). Dupla et al (2004) studied the monodirectional grout injection process in sand matrices using model tests. For a given level in the column, a strong increase in pressure with respect to normalized time is observed. The distribution of fluid pressure along the column after initial grout filling up in not linear. Bouchelaghem (2011) obtained the effective permeability of fine sands by the periodic homogenization approach during cement suspension flow. The influence of cement location was also investigated for several geometries. However, the effects of water-cement ratio and particle size were not considered. Jehan (2017) studied the engineering properties of medium and coarse sands treated by 2%, 4% and 6% cement grout. The shear strength of the grouted sand increases with the increase in cement quantity. 4% cement grout is effective as compared to 2% and 6% of grout. Although many studies were conducted on the characteristics of cement-treated sands, there are still some deficiencies, especially for the influence of sand particle size and water-cement (*w/c*) ratio on grouting effect.

In this paper, the properties of cement-treated sands with different *w/c* ratios are studied based on one-dimensional seepage test. The permeability coefficient and uniaxial compressive strength of treated samples are also discussed in detail.

2. METHOD AND MATERIALS

Figure 1 shows the diagram of grouting system used in this study. This system consists of pressure supply equipment, slurry chamber and sand container. An air compressor was used to provide the required air pressure and could be controlled constant by a pressure gauge. A slurry chamber was specially manufactured for cement slurry storage in this test. It has good air tightness and can be used to place cement slurry. An acrylic tube with inner diameter of 50.0 mm and wall thickness of 5.0 mm was used as sand container in the system. The slurry is injected from the top of sand container and flowed out from the lower port.

The cement used in this study was 42.5 Ordinary Portland cement. Four different water-cement ratios of 1:1, 4:3, 2:1 and 4:1 were adopted respectively. For each treated sample, the amount of slurry injected was 500 ml. In order to study the slurry diffusion law in sands with different particle size, two single-sized siliceous sands with particle size of 1.25-2.50 and 2.50-5.00 mm were used in this test as the cement slurry with higher water-cement ratios cannot be injected into smaller particle sizes.

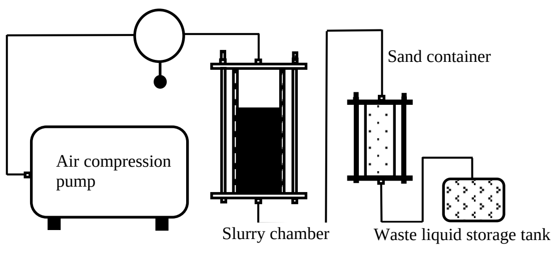


Figure 1 Diagram of grouting system in this study

3. TEST PROCESS

The acrylic tube was firstly filled with the sand at a certain compaction. After that, the sand container was connected to the slurry chamber (Figure 1). The grouting pressure was kept at 50.0 kPa using pressure gauge. The volume of grout injected into each sample was all 500 ml. During the grouting process, the flow of cement slurry was recorded, as shown in Figure 2. It should be noted that the cement slurry during grouting was kept homogeneous to avoid sedimentation. Then the cement-treated samples were cured in the laboratory for 7 days. The permeability coefficient and uniaxial compressive (UC) strength of treated samples were measured, respectively.

Figure 2 Cement grouting in laboratory

4. RESULTS AND DISCUSSION

4.1 Permeability Coefficient

The permeability coefficient of treated samples was measured using a triaxial cell according to ASTM D2434-68 (ASTM 2006) in this study. An effective confining pressure of 50.0 kPa was applied to all samples. A back pressure of 30.0 kPa was then applied to the lower base of samples while the upper drainage system was left open. That is, the used hydraulic gradient i in the permeability test is 3.0/0.1=30. The permeability coefficient of treated samples can be calculated from the volume change following the Darcy's low (Bordier et al., 2000)

$$k=(Q\cdot H)/(60A\cdot 102\cdot \Delta P\cdot \Delta t) \quad (1)$$

where k is the permeability coefficient of treated sands, cm/s; Q is the total flow volume, cm^3; H is the height of samples, cm; A is the average flowing section, cm^2; ΔP is the pressure difference of flowing water, kPa; Δt is the flow duration, s.

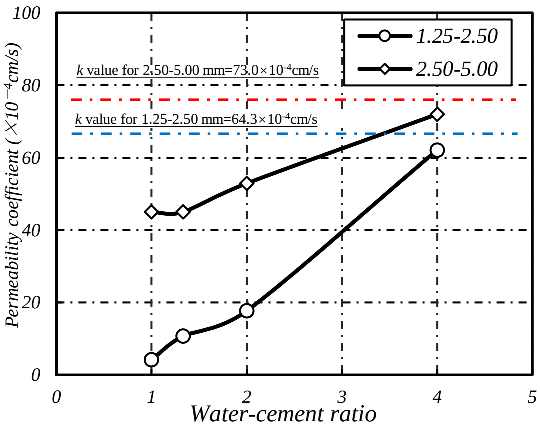
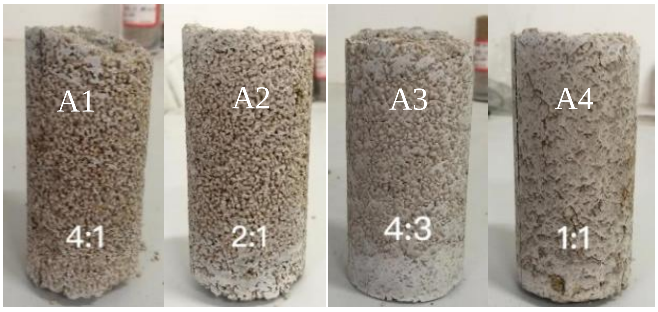
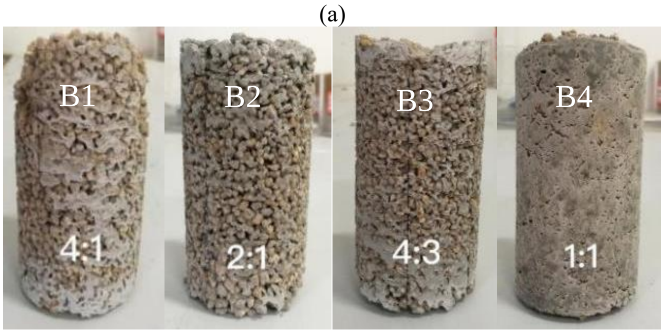


Figure 3 Permeability coefficient versus water-cement ratios after 7 days curing time

The permeability coefficients of treated samples with different water-cement ratios after 7 days curing time are shown in Figure 3. The permeability coefficients of untreated sands are also presented in the figure for comparison. It can be seen that with the increase of *w/c* ratio, the increase of permeability coefficient of treated samples with particle size 1.25-2.50 mm is smaller than that of samples with particle size 2.50-5.00 mm. The permeability coefficients of treated samples have a great difference when the *w/c* ratio is less than 2:1, while the difference is not obvious when the *w/c* ratio is larger than 2:1. This is because the pores of sands with smaller size are easier to be filled in grouting. However, the permeability coefficients of treated samples are always smaller than that of untreated, which are 64.3$\times$10^{-4} cm/s and 73.0$\times$10^{-4} cm/s, respectively. Furthermore, the smaller the water-cement ratio is, the less easy for slurry to flow between sand pores. This phenomenon can be intuitively reflected from the physical appearance of treated samples after 7 days, as shown in Figure 4. When the *w/c* ratio is less than 2:1, the cement effect for sand samples is more obvious. Therefore, the *w/c* ratio of 1:1 is preferred in engineering practice.



(a)



(b)

Figure 4 Cement-treated samples after 7 days curing: (a) 1.25-2.50 mm; (b) 2.50-5.00 mm

For porous media, the porosity n can be calculated using the relationship between porosity and permeability coefficient proposed by Carman (1956)

$$k=\frac{n^3}{5(1-n)^2}\left(\frac{D_{eff}}{6}\right)^2 \quad (2)$$

where k is the permeability coefficient of treated sands, cm/s; n is the porosity after treated; D_{eff} is the mean effective particle size of used sands, cm.

Table 1 shows the permeability coefficient and porosity of test samples before and after treatment. It should be noted that the permeability variation before and after treatment was irrelevant with grouting pressure. The reduction of permeability coefficient of sands before and after treatment gradually increases with the decrease of *w/c* ratios. The reduction of permeability coefficient with *w/c* ratio of 1:1 is about 27.5 times of that with the *w/c* ratio of 4:1. For 1.25-2.50 mm and 2.50-5.00 mm sands, the initial porosity before treatment are 68.7 % and 56.3 %, respectively. The porosity reduction before and after treatment also increases with the decrease of *w/c* ratio. The porosity reduction with *w/c* ratio of 1:1 for particle size 1.25-2.50 mm sand is about 78.4 times of that with the *w/c* ratio of 4:1. For particle size 2.50-5.00 mm, the porosity reduction with *w/c* ratio of 1:1 is about 29.0 times of that with the *w/c* ratio of 4:1. The smaller the particle size, the larger the porosity reduction. This can be explained from the perspective of cementation effect. The smaller the particle size, the better the cementation effect resulting in bigger porosity reduction.

Figure 5 shows the relationship between permeability coefficient and porosity of sand samples. The corresponding values before treatment are also illustrated in the figure for comparison. It is obvious that the permeability coefficient of sands after treatment has a positive relationship with porosity. However, these values are smaller than that of untreated sands. For the same permeability of test sands, the larger the particle size is, the larger the porosity after treatment.

Table 1 Permeability coefficient and porosity values before and after treatment

Specimens	A1	A2	A3	A4	B1	B2	B3	B4
Grain size (mm)		1.25-2.50				2.50-5.00		
w/c	4:1	2:1	4:3	1:1	4:1	2:1	4:3	1:1
k values before treatment ($\times 10^{-3}$ cm/s)	6.43	6.43	6.43	6.43	7.3	7.3	7.3	7.3
k values after treatment ($\times 10^{-3}$ cm/s)	6.21	1.77	1.07	0.42	7.2	5.29	4.5	4.5
Permeability coefficient reduction (%)	3.4	72.5	83.4	93.5	1.4	27.5	38.4	38.4
Porosity values before treatment (%)	68.7	68.7	68.7	68.7	56.3	56.3	56.3	56.3
Porosity values after treatment (%)	68.3	56.0	50.9	41.8	56.2	53.1	51.4	51.4
Porosity reduction (%)	0.5	18.4	25.8	39.2	0.3	5.8	8.7	8.7

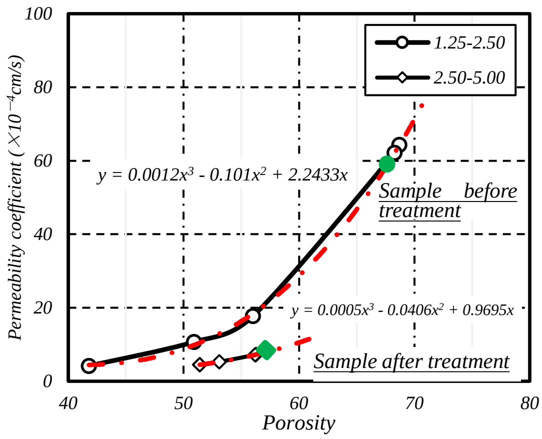


Figure 5 Relationship between permeability coefficient and porosity of test sands

4.2 UC strength of treated samples

The uniaxial compressive (UC) strength of treated samples were determined using uniaxial compressive test. Figure 6 shows the UC strength of treated sands with different *w/c* ratios. It can be seen from the figure that when the *w/c* ratios is 4:1 and 2:1, the UC strength of treated sands with both particle size are almost same. When the *w/c* ratios are 4:3 and 1:1, the UC strengths of treated sands with particle size 1.25-2.50 mm particle size are about 1.42 and 1.67 times than that of sands with particle size 2.50-5.00 mm. The smaller the *w/c* ratio, the larger the UC strength. It is also indicated that the *w/c* ratio of 1:1 or smaller should be used regardless of particle size in practice.

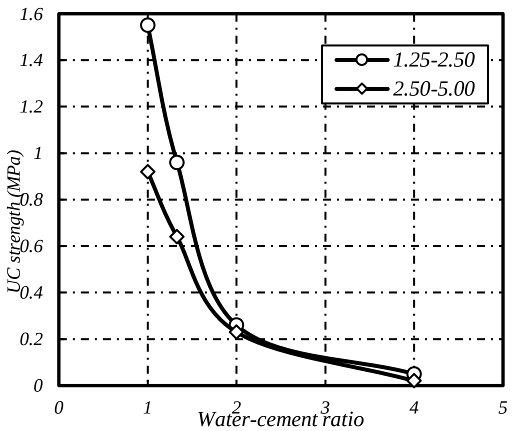


Figure 6 Uniaxial compressive strength with different water-cement ratios after 7 days curing time

These phenomena mentioned above can be explained by the formed physical bond between sand particles. When the *w/c* ratios are greater than 2:1, the formed physical bond between sands are relatively weak. Once a small external force is applied, the physical bond would be easily broken. This will result in smaller UC strength of treated sands. When the *w/c* ratios are less than 2:1, the sand pores are fully filled with cement slurry and the formed physical bond is stronger, which can withstand some external forces.

5. CONCLUSIONS

This paper studied the properties of cement-treated sands with two different particle sizes. The main conclusions could be obtained as follows:

(1) The difference in permeability coefficient with different particle sizes became smaller with the increase of *w/c* ratios. With the increase of *w/c* ratios, the porosity reduction of treated sands increases with the decrease of *w/c* ratios.

(2) The study shows that the uniaxial compressive strength of treated sands decreases with the increase of *w/c* ratios. When the *w/c* ratios is 1:1, the smaller the particle size, the greater the reduction of uniaxial compressive strength. The *w/c* ratio of 1:1 or smaller should be used regardless of particle size in practice. These phenomena are closely related to the formed physical bond between particles.

6. ACKNOWLEDGMENTS

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