Influence of curing conditions on mechanical properties of chemically grouted sands and its micromechanism

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Abstract

This paper presents an investigation of the influence of different curing conditions on the mechanical properties of chemically grouted sands by using laboratory experiment and microscopic techniques. The orthogonal experiment shows that slurry concentration has more influence on unconfined compressive strength of chemically grouted sands. Curing period is main effect on the permeability. Slurry concentration has a greater impact on cohesion and temperature has more impact on the internal friction angle. The results of mercury porosimetry show that the porosity decreases with increasing chemical grout slurry concentration. The porosity of most chemically grouted sands substantially equals to or greater than that of the samples before the compression test. The porosity of different chemically grouted sands is different due to the different concentration of grout, which has important influence on the permeability.

Keywords: chemically grouted sands; curing conditions; mechanical properties; mercury porosimetry

1. Introduction

Chemical grouting has been successfully and intensively used in engineering practice, including seepage prevention for dam safety, ground improvement in mining, renovation of ruptured shafts in mines. Under complex geological conditions, the mechanical properties of chemical grouted sands are the main factors in the consideration of choosing grouts (Sui, et al., 2008; Ge, 2006). Moreover, curing conditions, including curing temperature and curing time directly affect the performance of chemical grouts (Xia, et al., 2001). The influence of curing conditions on the chemical grouted sands has attracted interests of many researchers. The curing conditions they considered are usually limited to single condition, such as curing time and mixture ratio of slurry (Dash et al., 2003). Therefore, the influence of multi-factors on the properties of grouted sand is worth further studying. Grout concentration, curing time, temperature are selected as the main factors. As well, the microstructure of grouted sand has been analyzed in this paper.

2. Materials and methods

2.1 Testing materials

Chemical grouted sands are composed by sands and chemical grouts.

A coarse sand (C.S) (particle size lager than 0.5 mm accounted for over 50% weights) according to classification standard of soil (GBJ145-90), was selected, and its particle size distribution is shown in Table 1.

Table 1 Particle size distribution of a coarse sand

Particle size (mm)			d_{10} (mm)	Cu	Cc
2-0.5	0.5-0.25	0.25-0.075			
55%	25%	20%	0.16	4.7	1.1

Chemical grout slurry used in this study were made of urea-formaldehyde resin (Component A) and acidic curing agent (Component B). Component A was composed by urea-formaldehyde resin and 4% additive, the concentration of acidic curing agent is 2%, A: B = 10: 3 by volume.

2.2 Sample preparation

(1) Dry coarse sands were prepared according to Table 1 and stirred well in a bowl, then chemical grout

slurry were prepared according to planed proportion. The concentrations of grouts are 10%, 30%, 50%, 70%, respectively.

(2) Sample molds were made using PVC pipes with different diameters and heights, which employed to do unconfined compressive strength test, direct shearing test and conventional permeability test.

(3) 10% water were added into the well mixed sand, then chemical grout slurry with different concentrations were added into the sand respectively and stirred well with coarse sand. The mixed coarse sands were filled to different sample molds.

(4) Prepared samples were put into the thermotank, and cured according to the test plane.

2.3 Orthogonal test design

Orthogonal test is a useful technique to reduce the number of test cases, which can be used to optimize experiment of multi-factor multi-index (Wu, 1997), and the optimum test scheme can be formulated based on tests results. Three factors, including grout concentration, curing temperature and curing period, were considered and each of them has 4 values.

The concentrations of chemical slurry are 10%, 30%, 50%, 70%, respectively. Curing period used in this experiment are 7, 14, 30, and 60 days. The curing temperature are 20 ℃ , 30 ℃, 40 ℃ and 50 ℃. 16 tests were designed according to L16 orthogonal tables. Table 2 shows the results.

Table 2 Results of orthogonal test

Trial No.	Symbol	factors			Tests results			
		A Concentration (%)	*B* Curing period (day)	*C* Curing temperature (℃)	q_u (kPa)	*K* (10^{-5}cm/s)	Shear strength	
							C(kPa)	ϕ (°)
1	$A_1B_1C_2$	10	7	30	20.00	1.07	28.76	33.4
2	$A_1B_2C_1$	10	14	20	24.67	2.17	44.26	19.3
3	$A_1B_3C_3$	10	30	40	50.00	9.57	50.12	28.0
4	$A_1B_4C_4$	10	60	50	63.9	3.83	54.80	33.8
5	$A_2B_1C_1$	30	7	20	422.65	0.80	87.75	31.8
6	$A_2B_2C_2$	30	14	30	279.44	1.11	56.65	33.8
7	$A_2B_3C_4$	30	30	50	440.66	8.30	26.66	37.2
8	$A_2B_4C_3$	30	60	40	244.94	2.11	94.05	20.3
9	$A_3B_1C_3$	50	7	40	676.59	0.40	133.29	33.4
10	$A_3B_2C_4$	50	14	50	600.24	0.80	151.07	24.2
11	$A_3B_3C_2$	50	30	30	739.94	6.58	89.61	27.0
12	$A_3B_4C_1$	50	60	20	466.18	1.32	144.64	10.8
13	$A_4B_1C_4$	70	7	50	933.56	0.30	130.00	38.7
14	$A_4B_2C_3$	70	14	40	1148.39	0.64	148.10	38.0
15	$A_4B_3C_1$	70	30	20	1199.9	4.81	265.84	20.3
16	$A_4B_4C_2$	70	60	30	635.94	1.18	179.94	26.6

3. Experimental results and analysis

Unconfined compressive strength (ASTM D2166), hydraulic conductivity (ASTM D5084-03), shear strength (ASTM D3080) of grouted sand samples were respectively obtained from uniaxial compression strength test, falling head permeability test, direct shear tests. In order to reduce the error of test, parallel tests were conducted in those 16 test groups shown in Table 2. Unconfined compressive strength test includes 3 samples in each group, permeability test includes 2 samples, shear strength test contains 4 samples, and the final value of parameter can be computed by averaging all samples in each group.

3.1 The factors analysis of unconfined compressive strength

The results show that there are differences among the unconfined compressive strength of each group. The minimum value is 20 kPa, while the maximum is 1199.9 kPa. This shows that different curing conditions have obvious effects on the unconfined compressive strength of the chemically grouted sands. The result of unconfined compressive strength was shown in Table 4.

Where, $\bar{K}_i$（i= 1, 2, 3, 4）is the average value of corresponding columns at i value for each factor, R is the difference between the minimum and maximum value of $\bar{K}_i$. In this process the data are described using one of two possible descriptions: 'the larger the better', 'the smaller the better'. In this study, the value of $\bar{K}_i$ and R are related to the form 'the larger the better' following its characteristic.

Table 3 shows the most important factor for unconfined compressive strength is the slurry concentration, followed by curing period, finally is the curing temperature. The best ratio is $A_4B_3C_3$, that slurry concentration is 70%, curing period is 30 days and the curing temperature is 40□.

Table 3 Orthogonal analysis of unconfined compressive strength factors

	Factors			q_u（kPa）
	A (%)	B (d)	C (℃)	
$\bar{K}_1$	39.64	513.2	418.83	
$\bar{K}_2$	346.923	513.185	528.350	
$\bar{K}_3$	620.737	607.625	529.980	$A>B>C$
$\bar{K}_4$	979.447	352.740	509.590	
R	939.805	254.885	111.150	
Recommended ratio	A_4	B_3	C_3	$A_4B_3C_3$

3.2 The factors analysis of shear strength

As can be seen from Table 2, cohesion ranges from 26.66 kPa to 265.84 kPa, internal friction angle ranges from 10.8° to 38.7°. Compared with Test No.1-8, cohesion of Tests No.9-16 are relatively large. Orthogonal analysis results of shear strength factors are shown in Table 4.

The results indicate that the main factors on cohesion are slurry concentration, curing temperature and curing period. The best ratio is $A_4B_4C_2$, that slurry concentration is 70%, curing period is 60 days, curing temperature is 20□.

Curing temperature has remarkable effect internal friction angle, and the followed is curing period and slurry concentration. The best ratio is $A_4B_1C_4$, slurry concentration is 70%, curing period is 7 days, curing temperature is 50□.

Table 4 Orthogonal analysis of shear strength factors

	Factors			c (kPa)
	A (%)	B (d)	C (℃)	
$\bar{K}_1$	44.455	94.950	135.623	
$\bar{K}_2$	66.278	100.020	88.740	
$\bar{K}_3$	129.653	108.027	106.360	$A>C>B$
$\bar{K}_4$	180.970	118.358	90.632	
R	136.515	23.408	46.883	
Recommended ratio	A_4	B_4	C_1	$A_4B_4C_1$

3.3 The factors analysis of hydraulic conductivity

Table 5 shows hydraulic conductivity of chemically grouted sands range from 0.3×10^{-5} ~ 9.57×10^{-5} cm/s. The lower of hydraulic conductivity, the higher seepage resistance. Orthogonal analysis results are shown in Table 5.

Table 5 Orthogonal analysis of hydraulic conductivity factors

	Factors			K
	A(%)	B(d)	C(℃)	(10^{-5}cm/s)
$\bar{K}_1$	4.160	0.642	2.275	
$\bar{K}_2$	3.080	1.180	2.485	
$\bar{K}_3$	2.275	7.315	3.180	$B>A>C$
K_4	1.732	2.110	3.308	
R	2.428	6.673	1.033	
Recommended ratio	A_4	B_1	C_1	$A_4B_1C_1$

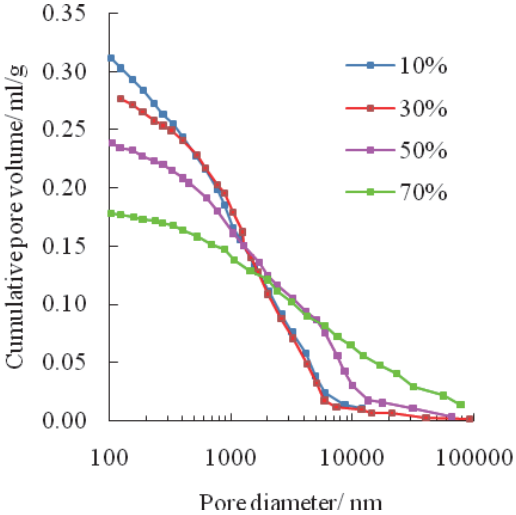
The most important factor for permeability is curing period, the followed is slurry concentration, curing period is the final one. The best ratio is $A_4B_1C_2$, which slurry concentration is 70%, curing period is 7 days, curing temperature is 20□.

4. The micro-structure change of chemically grouted sands in different curing condition

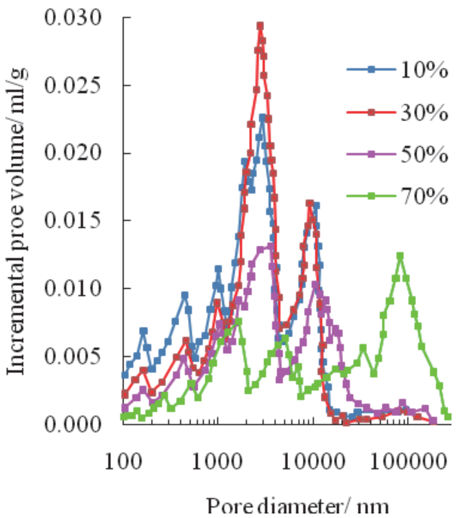
4.1 Micropores characteristics before unconfined compressive strength test

All the sand samples to be tested after 7 days, and grouting concentration are 10%, 30%, 50%, 70%. Figure 1 shows the micropores size distribution of chemical grouted sands in different grouting concentration before unconfined compressive strength test.

Figure 1(a) shows cumulative pore volume decrease with the increase of grouting concentration. This means the pore volume of grouted sand decreases. When the value of pore diameter is 4 μm, incremental pore volume of grouted sand is the same in different grouting concentration. Cumulative pore volume increases with the increase of grouting concentration when the value of pore diameter is larger than 4 μm. However, incremental pore volume of grouted sand decrease with the increase of grouting concentration when the value of pore diameter is smaller than 4 μm. Therefore, 4 μm can be called the critical pore diameter.



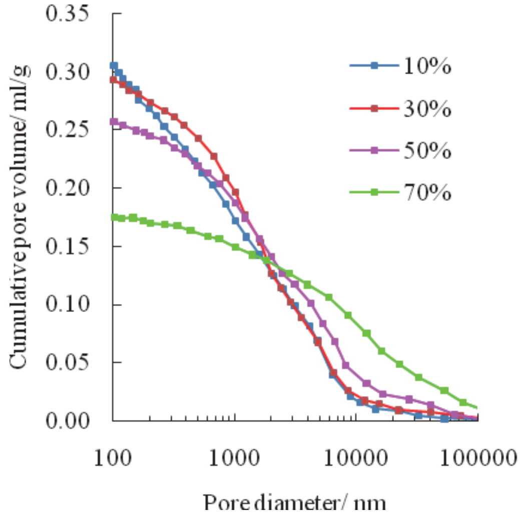
(a) Cumulative pore volume



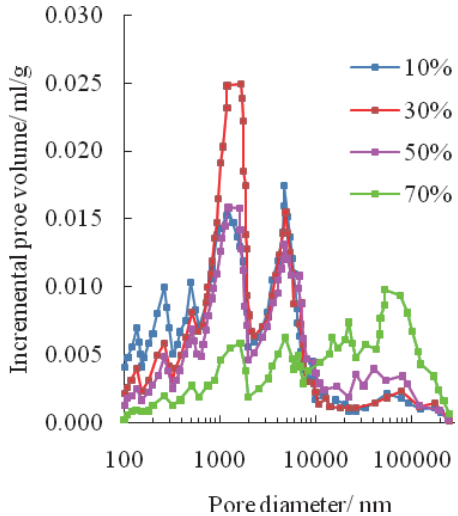
(b) Incremental pore volume

Fig. 1 Pore size distribution for chemically grouted sands before test

Figure 1(b) shows the relationship between incremental pore volume and pore diameter. When the pore diameter is 100μm, the value of incremental pore volume reaches the peak value no matter what the grout concentration is. However, there is an unusual curve pattern when the grout concentration is 70% and the pore diameter ranges from 500 to 1000 μm. The high concentration may contribute to this unusual pattern.



(a) Cumulative pore volume



(b) Incremental pore volume

Fig. 2 Proe size distribution for chemical grouted sand after test

4.2 Micropores characteristics after unconfined compressive strength

In comparison with Figure 1, it can be noted that the micro-structure of chemically grouted sands change a little before and after unconfined compressive strength test. Figure 2(a) shows the cumulative pore volume decreases with increasing grout concentration. Figure 2(b) shows that when the value of pore diameter is 6 μm, incremental pore volume reaches the peak value no matter what grouting concentration is. And before and after test, the relationship between incremental pore volume and pore before test is similar, only the pore volume relatively decreased.

4.3 The pore connectivity of chemically grouted sands

Figure 3 shows the relationship between pressure and pore volume for grouted sand with different slurry concentrations. The curves of mercury intrusion and extrusion volume changes obviously, which means the pore connectivity of grouted sand varies a lot. All curves plotted in Figure 3 shows that there are overlaps between the mercury intrusion pore volume curves and mercury extrusion pore volume curves, which indicate that there are a certain number of closed pores in the grouted sand. And there are also some differences between mercury intrusion volume and extrusion volume, which reflects the pore connectivity and hydraulic conductivity of grouted sands. A bigger volume differences mean a better pore connectivity and a higher hydraulic conductivity of grouted sands. Compare with grouted sands with 50% and 70% slurry concentrations, grouted sands with 10% and 30% slurry concentrations have a better pore connectivity and higher hydraulic conductivity. The volume difference of grouted sand with 70% slurry concentrations has the minimum value, which implies the worse pore connectivity and hydraulic conductivity, and more closed pores.

5. Conclusions

(1) The orthogonal tests show that, the most important factor for unconfined compressive strength is the slurry concentration. The main factors on cohesion are slurry concentration, curing temperature and curing period. Curing temperature has remarkable effect on the internal friction angle. The most important factor influencing the hydraulic conductivity is curing period.

(2) The results of mercury intrusion porosimetry show that the cumulative intrusion pore volumes decrease with increasing slurry concentration mixed in grouted sand. This implies that the porosity of grouted sand increases with decreasing slurry concentration.

(3) The morphology of the mercury intrusion and extrusion volume curve changes obviously, which means the pore connectivity of grouted sands vary tremendously. Porosity and pore connectivity would directly impact the hydraulic conductivity of grouted sand, it implies that lower porosity and worse pore connectivity will cause low hydraulic conductivity of grouted sands.

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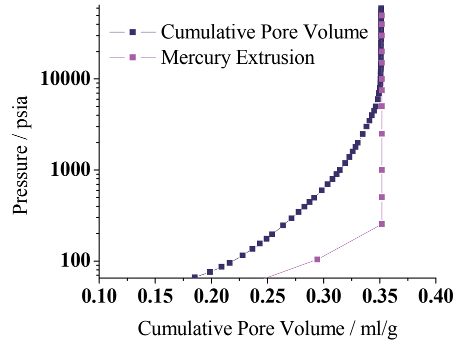
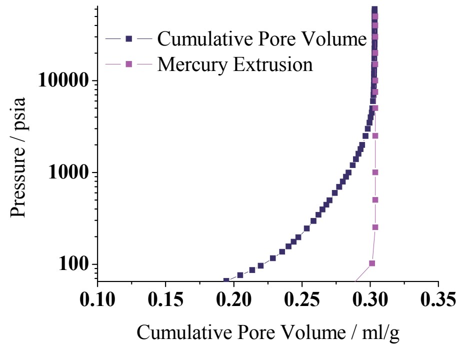
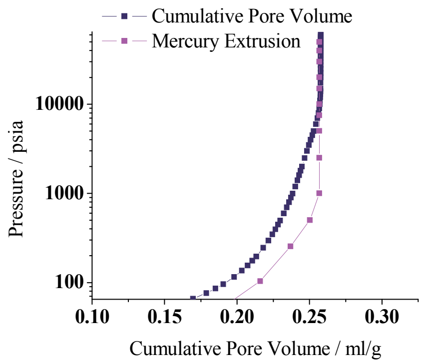


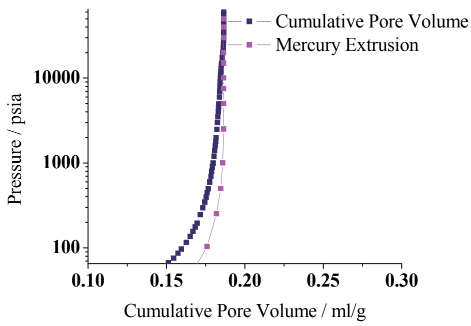
(a) Concentration 10%



(b) Concentration 30%



(c) Concentration 50%



(d) Concentration 70%

Fig. 3 The mercury intrusion and extrusion volume curves of grouted sand before test

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