level of anchors L_1、L_2、L_3 and anchor inclination α. Besides, five levels are specified in Table 1 and the range analysis result is given in Table 2.

Table 1 Affecting factors and levels of reinforcement with anchors

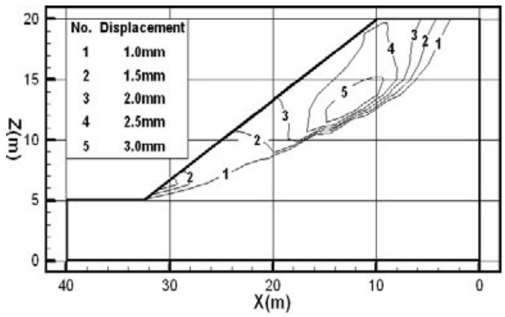
Level	H/m	D/m	L_1/m	L_2/m	L_3/m	α /°
1	10	1.88	2	2	2	15
2	11.25	2.50	4	4	4	16
3	12.5	3.13	6	6	6	17
4	13.75	3.75	8	8	8	18
5	15	4.37	10	10	10	19

Table 2 Range analysis

Items	H/m	D/m	L_1/m	L_2/m	L_3/m	α /°
M_{1j}	1.436	1.418	1.326	1.370	1.330	1.436
M_{2j}	1.458	1.458	1.450	1.334	1.356	1.362
M_{3j}	1.478	1.474	1.386	1.356	1.446	1.498
M_{4j}	1.462	1.480	1.530	1.524	1.540	1.436
M_{5j}	1.362	1.366	1.504	1.612	1.524	1.464
R_j	0.116	0.114	0.204	0.278	0.210	0.084
Sensitivity	$L_2 > L_3 > L_1 > H > D > \alpha$					
Optimum	H=12.5m, D=3.75m, L_1=8m, L_2=10m, L_3=8m, α =17°					

In Table 2, M_{ij} (i=1,2,3,4,5; j=1,2,3,4,5,6) presents the average value of safety factors with test level i of influencing factor j, R_j is the variation range. It can be seen that the sensitivity rank of parameters, ordered from significant to marginal, should be: $L_2>L_3>L_1>H>D>\alpha$. Generally speaking, length of anchors is the most important factor, especially length of the middle level. Subsequently, distribution and density of anchors on cross-section are also important. It seems that inclination of anchors, within the suggested range of 《Code》, is an "insignificant" factor. In fact, while arranging orthogonal tests, levels of factors should be specified according to engineering reality, otherwise, sensitivity acquired would be distorted. For this research, variation range of inclination of anchors is set to be relatively narrow for the convenience of installation.

Safety factor will reach the peak when the following circumstance happens: H=12.5m, D=3.75m, L_1=8m, L_2=10m, L_3=8m, α =17°. It indicates that anchors should be installed evenly to achieve maximum effectiveness; meanwhile, different level of anchors possesses different sensitivity. Safety factor obtained from optimal program is 1.82. Displacement contour (y=5) is shown in Figure 4, which indicates that displacement mainly occurs in mid-upper part of the slope, above the interface of red clay-limestone. It can be seen from Figure 5 that after reinforced by anchors, shear strain increment reduces dramatically and slope gets strengthened.



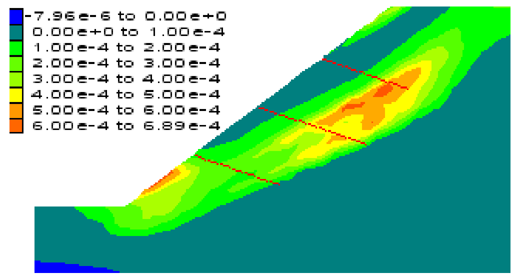
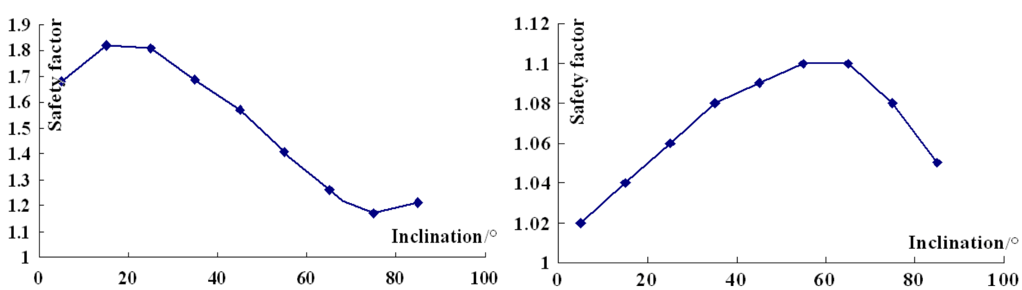


Fig.4 Displacement contour **Fig.5 Shear strain increment contour**

DISCUSSION ON EFFECTS OF SPATIAL PARAMETERS OF ANCHOR

Influence of Inclination

Neglecting the construction process, variation range of inclination is widened for further research on the given slope. Safety factors with inclinations of 5°, 15°, 25°, …85° are calculated respectively and the relationship curve between safety factor and anchor inclination is plotted in Figure 6a. As a contrast, reinforcing effect of homogeneous slope with anchors is also studied, as shown in Figure 6b. It can be seen that as to slope without bedrock, safety factor becomes the largest when inclination is about 60°, near perpendicular to slope surface; on the other hand, safety factor rises to the peak with an inclination of about 20° for given slope, which coincides with the angle needed for convenient grouting, consequently inclination of anchors is suggested to be 17°.



a. Bedding slope **b. Homogeneous slope**

Fig.6 Influence of anchor inclination

Influence of Length

Uniform length for all levels of anchors is usually adopted for construction convenience. Different lengths of anchors l=2m, 4m, 6m, 8m,10m, 12m are specified in numerical simulation. Installation states of anchors are listed in Table 3 and relationship curve between anchor length and safety factor is plotted in Figure 7.

Figure 7 shows that when uniform length of anchors increases from 2m to 4m, safety factor will rise slowly. When anchor length increases from 4m to 8m, safety factor increases by 42%, i.e. from 1.13 to 1.61. After that, increasing rate slows down again. Middle section of safety factor curve with fast growth corresponds to the status changing from "all anchors are not embedded in bedrock" to "middle and lower levels are embedded in bedrock", which indicates that middle and lower anchors are quite important in slope reinforcement. Additionally, it is not suitable to adopt too long anchors for strengthening because of negligible increment of slope stability and multiplied cost (Gurung, 2001; He, 2006). As comprehensive consideration, 8m of uniform length is regarded to be reasonable for anchors.

Table 3 Installation state of anchors

Uniform length	Installation state of anchors (Embedded in limestone?)		
	Upper level	Mid-level	Lower level
2m	No	No	No
4m	No	No	No
6m	No	No	Yes
8m	No	Yes	Yes
10m	No	Yes	Yes
12m	Yes	Yes	Yes

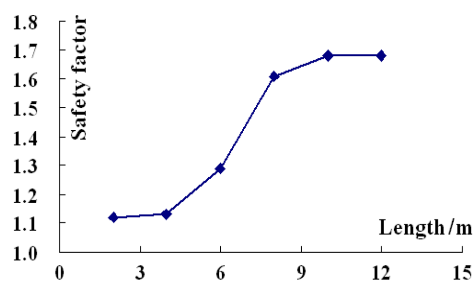


Fig.7 Influence of anchor length

Influence of Longitudinal Spacing between Anchors

People usually simplify slope engineering problem as a two dimension one with an infinitely long side along the longitudinal direction though it is often improper for many cases because of neglecting spatial effects. As a result, slope stability is studied with different longitudinal spacing and the result is shown in Figure 8. The relationship curve between longitudinal spacing and safety factor is similar to downward parabola and safety factor reaches the peak when longitudinal spacing is 3m. It proves again that anchors should be installed neither too dense nor too dispersed to get the best effectiveness. This principle is

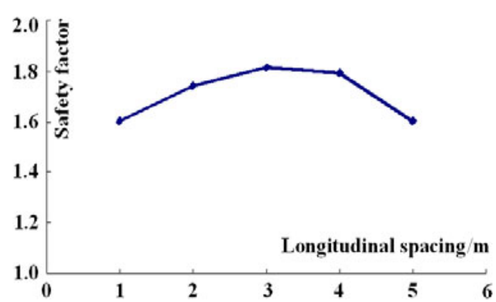
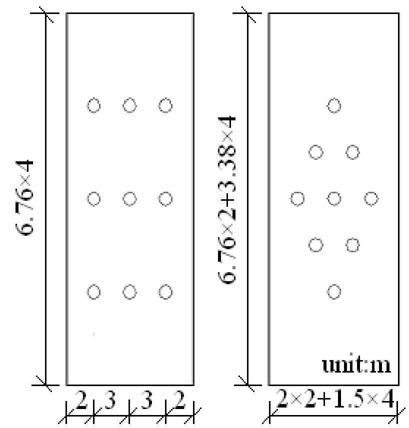


Fig.8 Influence of horizontal spacing

consistent for distribution on either cross-section or longitudinal slope surface. Each anchor has its effect radius; it is better to install anchors without overlap of effecting area, as well as large unreinforced area.

Comparison of Different Layouts

Based on previous discussion, reinforcing effects of two anchor layouts are compared. Mainly adopted layouts are rectangular layout and diamond-shaped layout respectively, as shown in Figure 9. Reinforcing effects are given in Table 4. Safety factor of rectangular layout is smaller than that of diamond-shaped layout with the same other parameters, on the other hand, maximum displacement in slope and maximum tensile stress of anchors are larger. It indicates that stress distribution is more reasonable and possesses lager rising capacity when anchors are installed as diamond-shaped. As a conclusion, diamond-shaped layout provides better reinforcing effect.



a. Rectangular b. Diamond-shaped

Fig.9 Layouts comparison

Table 4 Reinforcement effects under different layouts

Layout	**Safety factor**	**Max. displacement of slope**	**Max. tensile stress of anchor**
Rectangular	1.82	3.69 mm	54.6 MPa
Diamond-shaped	1.96	3.48 mm	49.6 MPa

CONCLUSIONS

Orthogonal tests indicates that length of anchors is the most important factor affecting reinforcing effects; subsequently, distribution and density of anchors on cross-section are also important. Without bedrock, safety factor reaches the peak when inclination of anchors is about 60°; on the other hand, the inclination is suggested to be 17° for the given slope. A uniform length of 8m is suggested for anchors, as well as a longitudinal spacing of 3m. Anchors should be distributed evenly to get the best reinforcing effect. Unreinforced soil mass should be divided into small blocks by adjusting spacing between anchors. Research also shows that the reinforcing effect of diamond-shaped anchors is better than that of rectangular layout.

REFERENCES

Cai, Y., Jiang, Y., Tetsuro, E. (2003). "Coupling model of bolt reinforcement system and application." *Chinese Journal of Rock Mechanics and Engineering*, Vol. **22** (6): 1024-1028.

Gurung, N. (2001). "1 D analytical solution for extensible and in extensible soil/rock reinforcement in pull-out test." *Geotextiles and Geomembranes*, Vol. **19** (2): 195-212.

He, R., Zhang, P. (2006). "Working mechanism of fully grouted bolt in pullout working state." *Journal of Central South University*, Vol. **37** (2): 402-407.

Itasca Consulting Group, Inc. (2005). "Flac^{3D} User Manuals." USA: Itasca Consulting Group Inc, pp. 339-344.

Jiang, Z. (2001). "A Gauss curve model o n shear stress along anchoring section of anchoring rope of extensional force type." *Chinese Journal of Geotechnical Engineering*, Vol. **23** (6): 697-699.

Lin, H. (2007). "The application of strength reduction method in Hoek-Brown criterion." *Journal of Central South University*, Vol. **38** (6): 1219-1224.

Liu, D., Cheng, Y. (2004). "Applied Statistics." Chemical Industry Press, Beijing.

Lu, M., Wei, M. S. (2006). "Simulation tests on pit foundation reinforced by full length bonding pre-stressed anchors." *Chinese Journal of Geotechnical Engineering*, Vol. **28** (1): 92-96.

Peng, W., Zhao, M. (2006). "Parameters analysis of grouted bolts by Lagrangian difference method." *Journal of Central South University*, Vol. **37** (5): 1002-1007.

The second survey & design institute of railway ministry. (2006). "Code for design of railway subgrade and retaining structure." China Railway Publishing House, Beijing.

Wang, G.. (2006). "Choice and optimization of landslide control plan." *Chinese Journal of Rock Mechanics and Engineering*, Vol. **25** (2): 3867-3873.

Yang, J. (2003). "Construction technique and quality control of prestressed anchors for stabilizing cutting slopes of expressway." *Chinese Journal of Rock Mechanics and Engineering*, Vol. **22** (2): 2759-2764.

Zhang, F., Liu, H. (2000). "Design practice of reinforcing rock slope with prestressed anchors." *Rock and Soil Mechanics*, Vol. **21**(2): 177-179.

Zou, J., Li, L. (2007). "Study on the ultimate pullout force of pre-stressed anchor based on nonlinear Mohr-Coulomb failure criterion." *Chinese Journal of Geotechnical Engineering*, Vol. **29** (1): 107-111.

Study on Strength Parameter Selection for Slope Stability Analysis of Red Clay (in Chenzhou) under Dry-wet Cycling

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ABSTRACT: To select proper strength parameters for slope stability analysis of red clay, study on the influence of dry-wet cycling and water content variation was performed based on direct shear tests. It is found that: (1) shear strength parameters are greatly affected by water content instead of cycling; (2) with the decrease of water content, shear strength increases, especially, relationship curve between cohesion and water content is concluded to be logarithmic; (3) under the same experimental conditions, cohesion and friction angle of hard plastic clay are generally larger than those of soft plastic clay. Dry-wet cycling leads to cracks which are harmful to slope integrity. Slope failure of red clay under dry-wet cycling, appearing to be shallow sliding, is resulted from cracks and water infiltration. Consequently, it can be analyzed with (c_u, φ_u) or (c_{cu}, φ_{cu}) of saturated upper layer, as well as taking cracks on potential sliding surfaces into consideration.

INTRODUCTION

Red clay is a kind of special soil which forms mainly in tropical and subtropical areas with humid climate. It contains montmorillonite and other hydrophilic minerals, resulting in its sensitivity to water. There are many cutting slopes of red clay along Wuhan-Guangzhou passenger line. Shallow failure occurs frequently under heavy rainfall, because cracks in superficial layers are highly developed. Rain infiltrates downward easily and shear strength might decrease; on the other hand, soil becomes heavier and seepage force drags the soil skeleton downhill. Once sliding force becomes larger than resistance, shallow failure occurs. This process does not take a long time, failure generally occurs in several days, even in several hours.

Strength parameters' selection is a key problem for slope stability analysis. As to above failure model of red clay slope, what extent of influences will it be for dry-wet cycling and water content changes? What kind of strength parameters should be adopted for stability analysis under dry-wet cycling? Studies on influences of dry-wet cycling have been performed by some former researchers, which are mainly about expansive soil (Liu, 1992; Yang, 2006). As special clay with significant shrinkage and slight expansion, similar researches on red clay are necessary. Direct shear tests were conducted on original red clay samples, then relationship between water content/dry-wet cycling and shear strength parameters were studied, which provide references to parameters' selection in stability analysis.

TEST GOAL AND PROGRAMME

Samples were obtained near Chenjiawan bridge (DK1821+254.5m), Chenzhou and the main properties are listed in Table 1. Based on different water content ratio ranges (a_w), which is defined as the ratio of water content and liquid limit, 144 samples were classified into three series: hard plastic ($0.55 < a_w \leq 0.7$), moderately plastic ($0.7 < a_w \leq 0.85$) and soft plastic ($0.85 < a_w \leq 1.00$). To make sure that samples were of uniform properties, sampling sites and depths was concentrated in a small area for each status of red clay.

Table 1 Main characteristics of red clay (average)

Sampling depth	W	ρ	s_r	e	W_l	W_p	I_p	I_L	a_w	E_s
m	%	g/cm^3	%	—	%	%	%	—	—	MPa
5.3~8.6	32.70	1.91	97.65	0.92	56.15	31.23	24.93	0.06	0.58	9.50
8.6~10.2	35.60	1.89	98.15	1.01	48.65	26.20	22.45	0.40	0.73	8.65
10.2~13.4	41.85	1.82	98.85	1.18	48.10	21.50	26.60	0.77	0.87	5.64

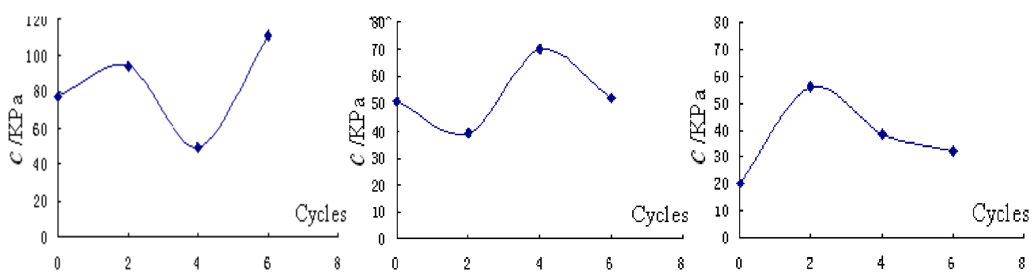
Process consisting of saturation-baking-saturation would be regarded as a loop of dry-wet cycling in this study. Firstly, put samples into overlapping saturator to maintain constant volume during saturation, then vacuum pumping method was adopted to saturate samples. Secondly, saturated samples were emplaced in oven for 6 hours, and the temperature was set to be 40 according to actual climate. Thirdly, dried samples were saturated again.

For each status: (1) saturated samples under four different dry-wet cycles (0, 2, 4, 6 cycles) and four different vertical load levels (100, 200, 300, 400KPa) were tested to establish the relationship between strength parameters and dry-wet cycles; (2) in order to investigate the influence of water content on strength parameters, for given cycles, baking time was controlled to get different water contents. Additionally, samples experienced 0 and 4 cycles were baked for 0, 2, 4, 6 hours respectively and then kept in maintainers for more than 24 hours to achieve water balance. After shear tests under 4 load levels, water content of every sample was measured.

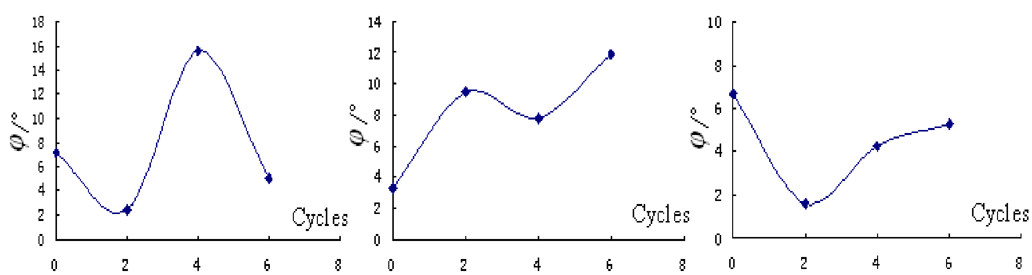
TEST RESULT AND ANALYSIS

Relationship between Strength Parameters and Dry-wet Cycles

Figure 1 shows the test results of strength parameters under dry-wet cycles. From hard plastic status to soft plastic status, the variation ranges of cohesion are (49.4KPa, 111.1KPa), (38.8KPa, 70.1KPa) and (20.1KPa, 56.0KPa) while the variation ranges of friction angle are (2.39°, 15.54°), (3.29°, 11.87°) and (1.59°, 6.66°). Average values of strength parameters under three status are (82.8KPa, 7.62°), (53.0KPa, 8.11°) and (36.7KPa, 4.43°), respectively. It shows that for any status of red clay, relationship curves between dry-wet cycling and strength parameters vary irregularly.



(1) Hard plastic (2) Moderately plastic (3) Soft plastic



(1) Hard plastic (2) Moderately plastic (3) Soft plastic

Figure 1 Relationship between shear strength parameters and dry-wet cycling

Relationship between Strength Parameters and Status

Table 2 gives the comparison of strength parameters of saturated samples within different status after different cycles. It can be seen that under the same test conditions, cohesion and friction angle of hard plastic samples are generally larger than those of soft plastic samples. For common soils, lower layers are more compact after consolidation process and thus own higher strength. From Jiang (1991) and Liao (2006), we know that consolidation of red clay, which contains physical and chemical consolidation, is a strengthening process of structural and mechanical properties. Especially, during formation process of red clay, Fe_2O_3, Al_2O_3.and other free oxides cement loose soil particles together and finally stable aggregated particles are formed. Because of the affecting depth of climate, the further to the slope surface, the less free oxides exist. With the decrease of free oxides' content, the integrity of mass becomes weaker and strength of red clay reduces.

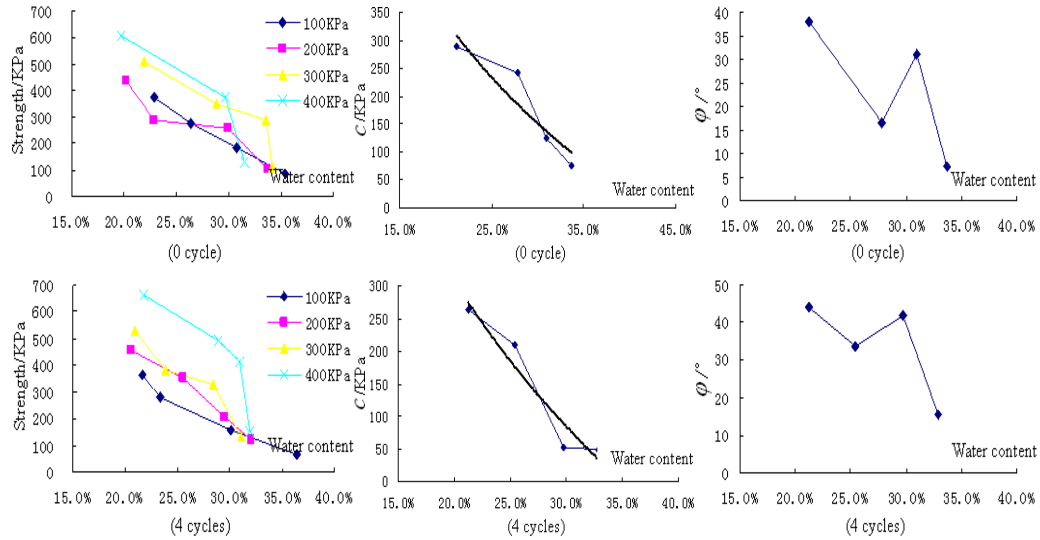
Researches indicate that the difference between hard plastic clay and soft plastic clay is not merely the content of water; the more important thing is that the structural properties are quite different because of combination effect of external causes such as warm-humid environment and internal reasons such as mineral composition and form. These differences are difficult to be evaluated in lab tests for remolded samples; this is a reason to use undisturbed samples at different depth within different status as experiment objects.

Table 2 Comparison between saturated hard plastic and saturated soft plastic samples

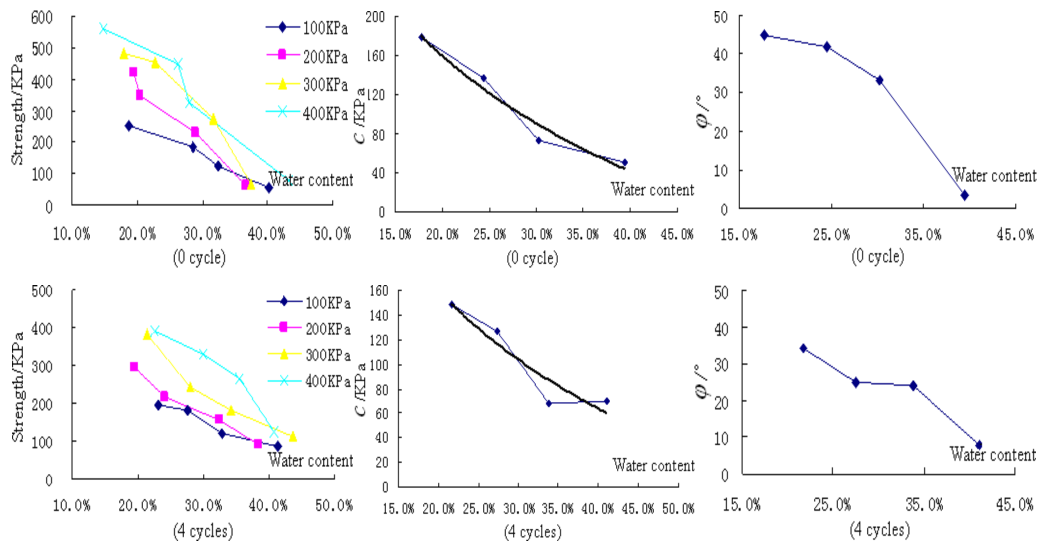
Status	Cycles	Cohesion/KPa	Friction angle/°
Hard plastic	0	77.14	7.14
	2	93.59	2.39
	4	49.36	15.54
	6	111.12	5.41
Soft plastic	0	20.06	6.66
	2	55.99	1.59
	4	38.28	4.24
	6	32.41	5.24

Relationship between Strength Parameters and Water Content

After 0 and 4 dry-wet cycles respectively, samples were baked for different time and relationship between shear strength parameters and water content were studied, as shown in Figure 2.



(1) Hard plastic



(2) Moderately plastic