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Influence of moisture content on shearing strength of unsaturated undisturbed quaternary system middle pleistocene

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Abstract: The unsaturated undisturbed quaternary system middle pleistocene loess, a typical unsaturated soil, often occurs in the implementation of western development strategy. To obtain the shearing strength characteristics of this unsaturated undisturbed loess, based on the analysis of mineral composition, the triaxial shear test of undisturbed quaternary system middle pleistocene loess under different moisture contents is conducted with the specialized triaxial instrument for unsaturated soil. The test results show that the mainly mineral composition of undisturbed quaternary system middle pleistocene loess is quartz and albite. Under the same confining pressure, the matric suction increases with the decrease of moisture content. The smaller the moisture content, the larger the matric suction; the higher the moisture content, the lower the matric suction. Under the same moisture content, the matric suction increases with the confining pressure and reaches a maximum when the confining pressure is 100 kPa, and then decreases with the increase of confining pressure. This phenomenon is closely related to the grain contact tightness of soil mass under high confining pressure. According to the triaxial test of loess, the sample of loess experiences 4 stages from loading to failure: 1) compaction stage; 2) compression stage; 3) microcrack developing stage; 4) shear failure stage. The test sample is of brittle failure (weak softening) under low moisture content and confining pressure. With the decrease of matric suction and the increase of consolidated confining pressure, the stress−strain curve changes from softening type to ideal plastic type. In the shearing strength parameters of unsaturated undisturbed loess, the influence of moisture content on internal friction angle is small, but that on cohesive force is obvious. Therefore, the shearing strength of unsaturated undisturbed loess is higher than that of saturated undisturbed loess and varies with the moisture content.

Key words: unsaturated undisturbed loess; matric suction; test; shearing strength

1 Introduction

Loess, a kind of special soil, mainly distributes in the northwest of China. With the implementation of western development strategy in recent years, the construction of foundation projects often involves loess works. Loess is a typical unsaturated soil and has always been regarded as an important object in the mechanics research on unsaturated soil [1−4]. CHEN [5] researched the deformation, strength, yielding and moisture change characteristics of remolded loess by unsaturated soil test. ZHANG et al [6] analyzed the stress−strain relationship of lime-fly ash loess under different confining pressures, based on the triaxial consolidation drained shear tests. GAO et al [7] analyzed microstructure and collapsibility behavior of unsaturated loess by conventional odometer, chemical measurements of the contents of solvable salts and dissolvable salts as well as ISIS X spectrum. MALYSHEV and PUSTOGACHEV [8] analyzed deformability of loess soils by odometer and triaxial tests. YING el at [9] obtained the shear strength characteristics of unsaturated loess and relevant relationship curve under different matric suction through the consolidated drained shear tests with suction control, based on the double-stress-state variable theory. The shearing strength characteristic of unsaturated undisturbed loess was discussed by unsaturated soil test [10−13]. HARDCASTLE and SHARMA [14] analyzed shear modulus and damping of unsaturated loess through and

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dynamic torsional shear tests. YAN et al [15] discussed the basic characteristics of contribution of matric suction to the shearing strength of unsaturated remolded loess by indoor test. HAN et al [16] analyzed stress−strain relationship curves and strength characteristics of loess through a series of consolidated undrained triaxial tests (CU test) and consolidated drained triaxial tests (CD test) of normal consolidation and over consolidation loess specimens.

The previous researches mainly take the undisturbed sample or remolded sample of quaternary system upper pleistocene series loess, lower pleistocene series loess and holocene series loess as the object and mainly use controlled suction method. According to the investigation and statistics [17−18], most of the loess works pass through the stratum of quaternary system middle pleistocene series loess and the suction of undisturbed loess in the actual work is variable. An experimental research on the suction, deformation and strength characteristics of unsaturated undisturbed Quaternary System Middle Pleistocene Series loess occurring in the loess works for recent years is conducted in this work by using specialized unsaturated triaxial instrument, to provide references for the construction of loess projects.

2 Mineral composition analysis

The mineral composition of undisturbed quaternary system middle pleistocene series loess is tested by D8ADVANCE X-ray diffraction (XRD) produced by Germany BEVKER-axs. Test conditions are as follows: scanned area of 5°−95°, scanning speed of 0.02(°)/step, tube voltage of 40 kV and tube current: 40 mA. Grind the test sample into fine powder with a size of about 10 μm, fill in the groove on the sample platform of diffraction and then flatten it with glass plate. After test, the data processing system will output the distribution curve of X-ray diffraction and the corresponding interplanar crystal spacing and count number of each diffracted ray automatically (Fig. 1).

In Table 1, the semi-quantitative test results of undisturbed quaternary system middle pleistocene Series loess show that its mineral composition is mainly quartz accounting for 31.63%, calcite accounting for 5.35%, albite accounting for 36.80%, clinochlore accounting for 4.39%, muscovite accounting for 10.15% and plagioclase accounting for 11.70%. It can be seen that the mineral composition of undisturbed quaternary system middle pleistocene series loess is mainly quartz and albite, accounting for 68.41 % of the fresh mother rock.

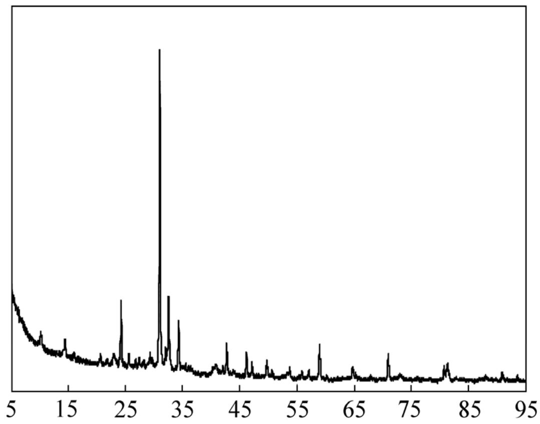

Fig. 1 X-ray diffraction pattern of soil sample

3 Experimental research

3.1 Selection and preparation of test sample

The soil sample was taken from the middle up step with a buried depth of 25 m in the Yaojiashan Tunnel of Lin−Li Expressway in Shanxi Province, China. This soil mass was the quaternary system middle pleistocene Series Lishi Group loess. The surrounding rock here was of good stability, no underground water and Level IV. To reduce the disturbance on soil sample as far as possible, the test sample with dimensions of 200 mm×200 mm ×200 mm should be marked with direction up and down, wrapped with plastic paper and adhesive tape and placed into an iron box. The cap of the iron box should be sealed with transparent adhesive tape and the iron box should be delivered to the laboratory with some damping measures. After getting the soil sample, the plastic paper and adhesive tape were stripped. The soil sample structure should be checked to see whether there was any disturbance or whether the soil sample quality met the

Table 1 Mineral composition of soil sample

Compound	Chemical formula	Mineral	Semi quantitative/%
Silicon dioxide	SiO_2	Quartz	31.61
Calcite	$CaCO_3$	Calcite	5.35
Sodium tecto-alumotrisilicate	$Na(AlSi_3O_8)$	Albite low	36.80
Clinochlore	$(Mg,Fe)_6(Si,Al)_4O_{10}(OH)_8$	Clinochlore	4.39
Muscovite	$KAl_2Si_3AlO_{10}(OH)_2$	Muscovite	10.15
Potassium sodium alumotrisilicate	$(K_{0.95}Na_{0.05})AlSi_3O_8$	Microcline	11.70

test requirements. In the case of good condition of the soil sample, the soil sample should be cut into a cylindrical test sample with a height of 80 mm and diameter of 39.1 mm with specialized soil cutting machine according to the requirements of geotechnical test rules. To reduce the influence brought by the dry density difference of loess, the dry density difference value of test sample should not be more than 0.03 g/cm^3 and the moisture content difference value of test samples in the same group should not be more than 2.0 %. It can be seen that there was tiny fine sand and quartz granule in the loess and also calcareous concretion layer in partial loess during indoor sample preparation.

3.2 Physical property test

Physical tests were conducted for the undisturbed quaternary system middle pleistocene series loess taken from the Yaojiashan Tunnel [19], mainly including test of moisture content, density, specific gravity of soil grain and moisture content limit (liquid limit and plastic limit). Each test was conducted three times and the mean measured value of three times was taken as the final value. Table 2 lists the physical parameters of undisturbed quaternary system middle pleistocene series loess.

Table 2 Physical parameters of undisturbed quaternary system middle pleistocene series loess

Natural moisture content, w/%	Natural density, ρ/(kg·m^{-3})	Relative density, G_s	Liquid limit, w_L	Plastic limit, w_P	Porosity, n
17.09	1980	2.422	34.2	16.70	0.367

3.3 Mechanics test of undisturbed loess

1) Test instrument

The triaxial test system of unsaturated soil (Fig. 2), transformed by the University of Logistics Engineering, was adopted as the test instruments and the screw jack driven by electric motor and gearbox can directly impose the load on the piston rod of top cover running through the pressure chamber through the reverse action of fixed cross beam on the instrument rack and then on the test sample. The volume change was measured with the volume change tube comprising dial gauge and needle tube. The pressure was measured with the steel proving ring, pressure sensor. The pore water pressure and pore air pressure were measured with corresponding sensor respectively. The range and sensitivity of all instruments should meet the test requirements.

Fig. 2 Triaxial test system of unsaturated soil

2) Test program

Four groups of test samples of undisturbed loess with a number of 16 in total were prepared in this test and the control condition was the confining pressure and moisture content. To reflect the influence of consolidated confining pressure on structural property of loess, the confining pressures were 50, 100, 200 and 300 kPa, respectively, and the moisture contents were 12.00%, 17.09% (natural moisture content), 19.00% and 21.58% (saturated moisture content), respectively, during test.

The test sample of unsaturated undisturbed loess was of consolidated undrained shear test (CU) and that of the saturated undisturbed loess was of consolidated drained shear test (CD) with a consolidation time of 24 h. The test instrument was installed with the pore water pressure and pore air pressure sensor to test the u_a and u_w in the test sample. The matric suction was $s=u_a-u_w$ and the shear rate in test was 0.015 mm/min. The reading of dial gauge of proving ring, volume change tube, axial deformation dial gauge and pore air pressure and pore water pressure should be recorded during test. The shear in test should be up to 15.00% with axial strain or the instrument should be shut down in the case of complete damage of test sample.

4 Influence on matric suction

4.1 Influence of moisture content on matric suction

The moisture content can affect the saturation of soil and the change in the saturation of soil is directly close to the matric suction of soil. According to the test results, the matric suction of unsaturated undisturbed quaternary system middle pleistocene series loess under different confining pressures (50, 100, 200, 300 kPa) varies with the moisture content shown in Fig. 3.

It can be seen from Fig. 3 that 1) under the same confining pressure, the matric suction of undisturbed Quaternary System Middle Pleistocene Series loess increases with the decrease of moisture content; the smaller the moisture content, the larger the matric suction; the larger the moisture content, the smaller the moisture content. When the moisture content is saturated, the matric suction is almost 0. 2) In the nature, the changes in moisture content of soil (drying or wetting) are continuous; therefore, the change in matric suction is also continuous and there is matric suction in the unsaturated soil under any moisture content.

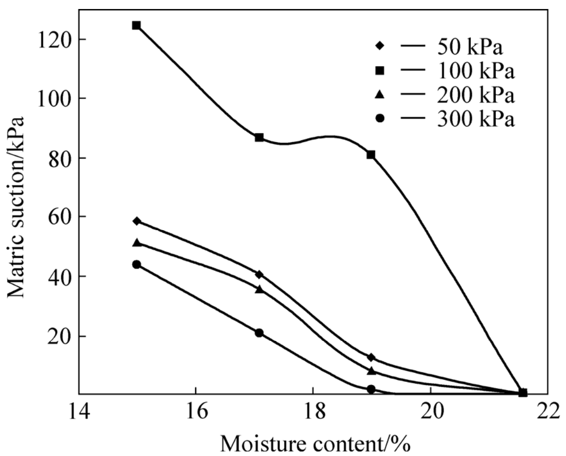

Fig. 3 Matric suction varying with moisture content under different confining pressures

4.2 Influence of confining pressure on matric suction

According to the test data, the matric suction of quaternary system middle pleistocene series loess under different moisture content (15.00% and 17.09% (natural moisture content), 19.00% and 21.58% (saturated moisture content)) varies with the moisture content shown as Fig. 4.

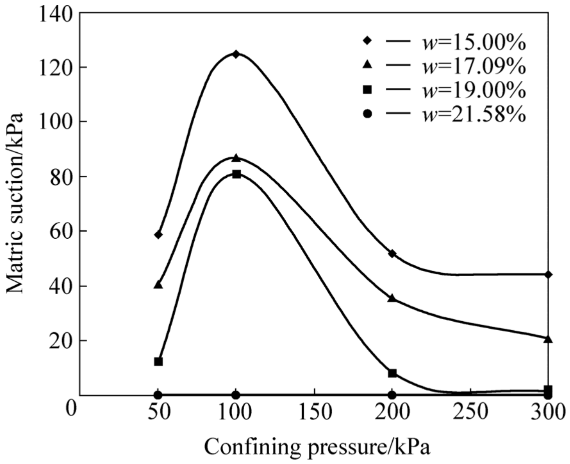

Fig. 4 Matric suction under different moisture contents varying with confining pressure

It can be seen from Fig. 4 that under the same moisture content, the matric suction of undisturbed quaternary system middle pleistocene series loess increases with the confining pressure and be maximum when the confining pressure is up to 100 kPa and then decreases with the increase of confining pressure. This phenomenon is closely related to the grain contact tightness of soil mass. And when the moisture content is saturated, the matric suction of soil will not change with the confining pressure and is approximate to 0.

5 Shearing strength characteristics

5.1 Stress−strain relations under different moisture contents

According to the test results, the stress−strain relation curves of undisturbed quaternary system middle pleistocene series loess under different moisture content are shown in Fig. 5.

It can be seen from Fig. 5, due to the influence of structural property of undisturbed quaternary system middle pleistocene series loess, the stress−strain relation curves under different confining pressure conditions have the crossover phenomenon (Figs. 5(a), (b), (c) are obvious). Under the same shearing strain value, the shearing strain value under high confining pressure is less than that under low confining pressure and this crossover phenomenon is somewhat changed when the shearing strain under high confining pressure is approximate to the yield stress. The undisturbed quaternary system middle pleistocene series loess is of brittle failure (weak softening) under low moisture content and confining pressure with the high peak stress and lower failure strain. The shear stress−strain relation curve is approximate to linear relation curve before peak and then is of strength softening after peak. With the decrease of matric suction (increase of moisture content) and the increase of consolidated confining pressure, the stress−strain curve of undisturbed loess changes from softening type to ideal plastic type gradually.

In addition, it also can be seen from Fig. 5 that the test sample of unsaturated undisturbed loess of triaxial shear test under various confining conditions experiences the following stages from loading to failure.

1) Compaction stage. As the undisturbed quaternary system middle pleistocene series loess is the structured soil and of columnar jointing. Under load effect, the pore between grains is compressed, the soil mass is compacted and the volume of test sample reduces and the stress−strain curve is concave upward in the initial stage.

2) Compression stage. After compaction of the test sample and under load effect, the soil grain is compressed; the volume of test sample reduces and the stress−strain curve is a straight line of elastic deformation and then is a curve of nonlinear deformation.

3) Microcrack developing stage. When the axial strain reaches a certain level, the stress of test sample reaches yielding and there are microcracks seen from the outside of pressure chamber.

4) Shear failure stage. As the axial strain increases further, the cracks become more and larger and partial cracks connect to each other and then the shear failure surface of test sample forms until failure of test sample.

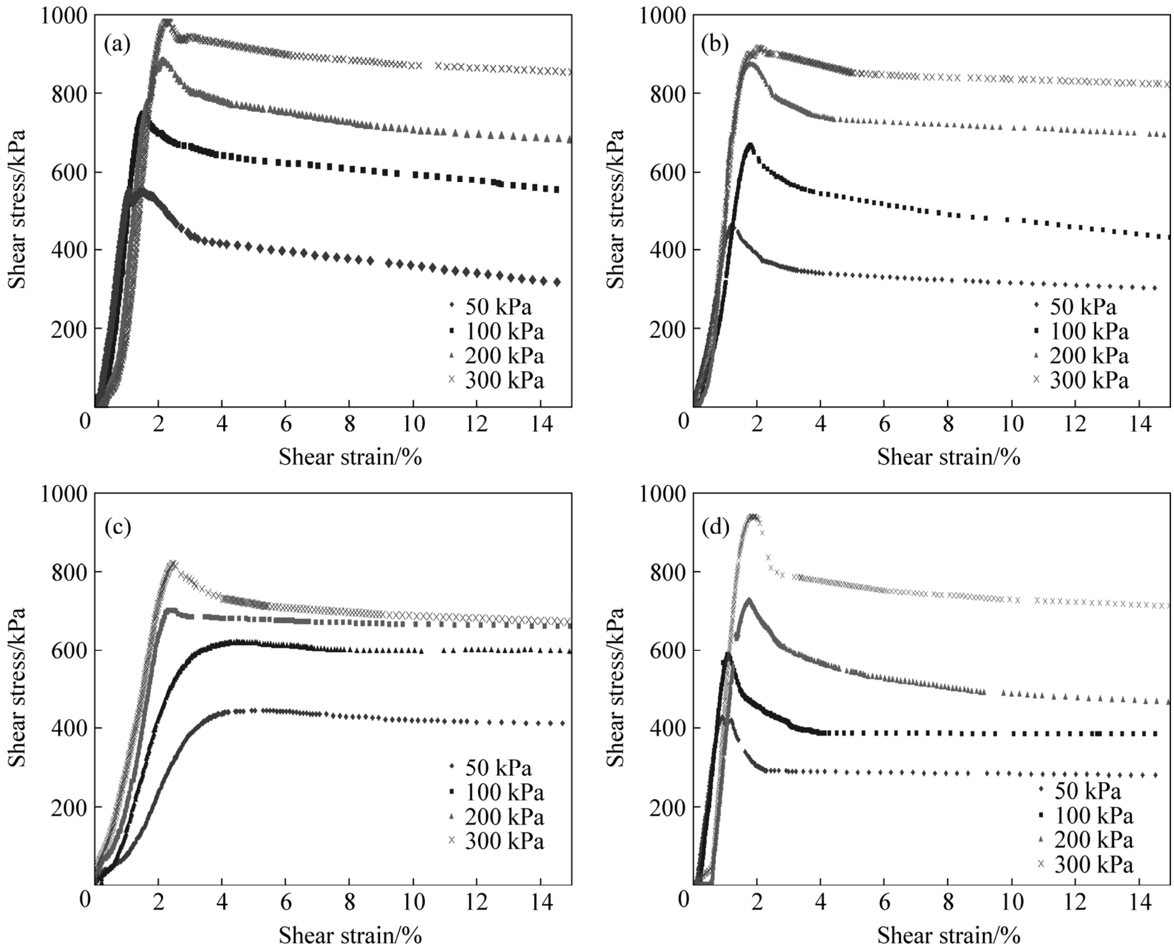

Fig. 5 Stress−strain relations under different moisture contents: (a) Under 15.00% moisture content; (b) Under 17.09% moisture content; (c) Under 19.00% moisture content; (d) Under 21.58% moisture content

5.2 Failure envelope and shearing strength parameters

According to the test results, the derived Mohr−Coulomb failure enveloping surface diagram of unsaturated undisturbed loess under different moisture contents is drawn as shown in Fig. 6.

According to the above failure enveloping surface diagram, the calculation results of engineering characteristics of unsaturated undisturbed loess are listed as Table 3.

It can be seen from the derived Mohr−Coulomb failure enveloping surface diagram of unsaturated undisturbed loess under different moisture contents (see Fig. 6) and its engineering characteristics (see Table 3).

1) The shearing strength of unsaturated undisturbed loess is higher than that of saturated undisturbed loess and varies with the moisture content. The lower the moisture content, the higher the shearing strength; the higher the moisture content, the lower the shearing strength. When the moisture content approaches saturated moisture content, the shearing strength is close to that of saturated undisturbed loess gradually.

2) The influence of moisture content on internal friction angle is small and the internal friction angle between unsaturated undisturbed loess and saturated undisturbed loess is of small difference; but the influence of moisture content on total cohesive force is great and the cohesive force of unsaturated undisturbed loess is obviously higher than that of saturated undisturbed loess.

3) According to the relevant strength indexes c', φ' and ϕ_b of saturated and unsaturated undisturbed loess obtained and combining with the shearing strength formula of unsaturated soil $\tau_{ff}=c'+(\sigma_f-u_a)_f\cdot\tan\varphi'+(u_a-u_w)_f\tan\varphi_b$ put forward by FREDLUND et al [20], the shearing strength value of unsaturated undisturbed loess under a certain matric suction can be obtained where c' is the intercept of extension of Mohr−Coulomb failure envelope and shearing stress axis and the normal failure stress and matrix suction at the shearing stress axis are zero, that is to say, c' is the effective cohesive force; $(\sigma_f-u_a)_f$ is the normal static stress state on the failure surface upon failure; φ' is the internal friction angle related to normal static stress state variable $(\sigma_f-u_a)_f$; $(u_a-u_w)_f$ is the matric suction on the failure surface upon failure; and ϕ_b is the increase rate of shearing strength with the matric suction $(\sigma_f-u_a)_f$).

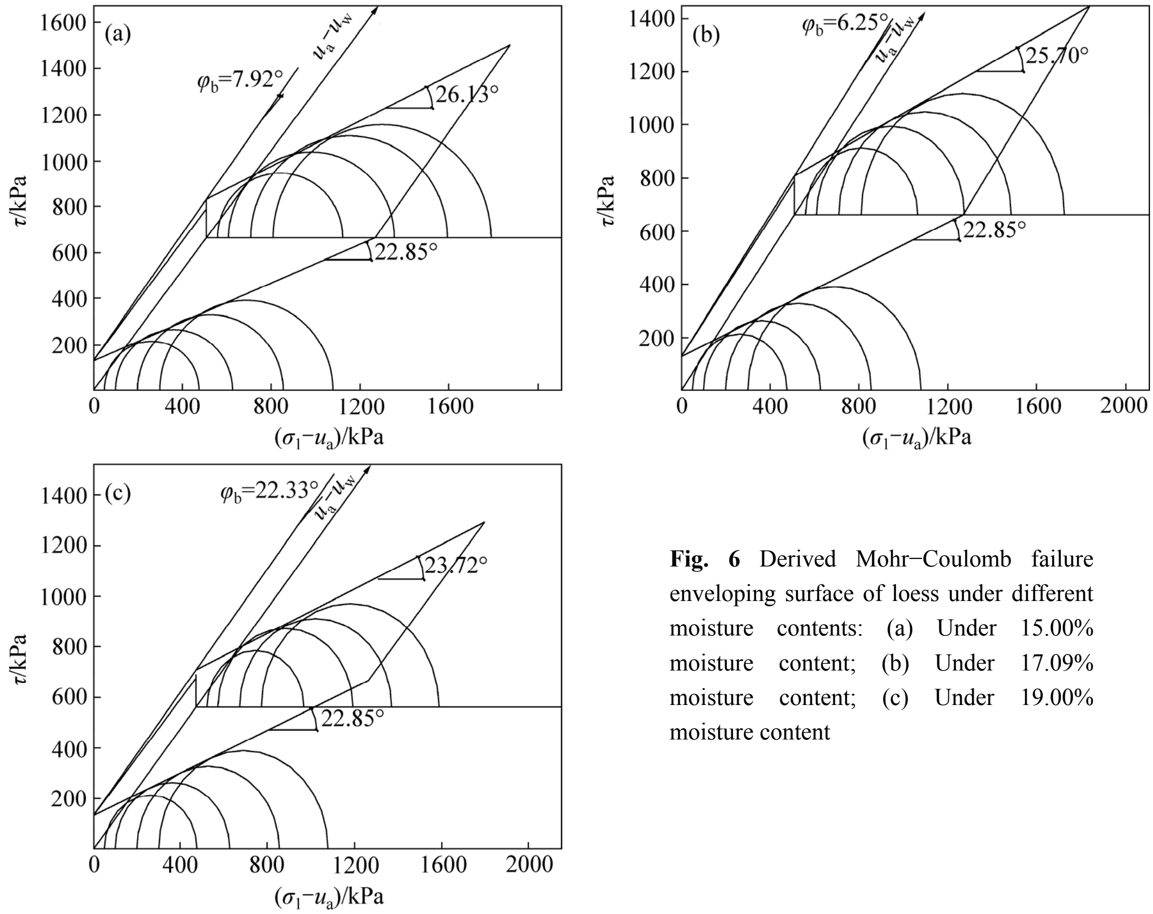

Fig. 6 Derived Mohr−Coulomb failure enveloping surface of loess under different moisture contents: (a) Under 15.00% moisture content; (b) Under 17.09% moisture content; (c) Under 19.00% moisture content

Table 3 Engineering characteristics of unsaturated undisturbed loess

Moisture content, w/%	Saturation, S_r/%	Matric suction, s/kPa	Cohesive force, c'/kPa	Internal friction angle, φ'/(°)	φ_b/(°)
15.00	70	106.40	167.773	26.133	7.92
17.09	79	62.65	146.450	25.698	6.25
19.00	88	37.75	139.424	23.722	22.33
21.58	100	0.00	127.332	22.849	—

6 Conclusions

1) According to the test with XRD, the mineral composition of undisturbed quaternary system middle pleistocene series loess is mainly quartz accounting for 31.63%, calcite accounting for 5.35%, albite accounting for 36.80%, clinochlore accounting for 4.39%, muscovite accounting for 10.15% and plagioclase accounting for 11.70%, in which the quartz and albite account for 68.41% of the fresh mother rock.

2) Under the same confining pressure, the matric suction of undisturbed quaternary system middle pleistocene series loess increases with the decrease of moisture content. The smaller the moisture content, the larger the matric suction; the higher the moisture content, the lower the matric suction. When the moisture content is saturated, the matric suction is almost 0.

3) Under the same moisture content, the matric suction of undisturbed quaternary system middle pleistocene series loess increases with the confining pressure and reaches a maximum when the confining pressure is 100 kPa, and then decreases with the increase of confining pressure. This phenomenon is closely related to the grain contact tightness of soil mass under high confining pressure.

4) It can be seen from the triaxial shear test curve of undisturbed quaternary system middle pleistocene series loess that the test sample experiences 4 stages from loading to failure, namely compaction stage, compression stage, microcrack developing stage, and shear failure stage, and is of brittle failure (weak softening) under low moisture content and confining pressure. The higher the failure peak, the lower the failure stress. The deviatoric stress-deviatoric strain relation curve is approximate to linear relation curve before peak and then is of strength softening after peak. With the decrease of matric suction (increase of moisture content) and the increase of consolidated confining pressure, the stress−strain curve of undisturbed loess changes from softening type to ideal plastic type gradually.

5) The shearing strength of unsaturated undisturbed loess is higher than that of saturated undisturbed loess and varies with the moisture content. The lower the moisture content, the higher the shearing strength. Among the shearing strength parameters of unsaturated undisturbed loess, the influence of moisture content on internal friction angle is small, but that on cohesive force is obvious. The higher the moisture content is the lower the matric suction is, the smaller the total cohesive force and the matric suction are and total cohesive force is of positive correlation.

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