IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

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IOP Conf. Series: Earth and Environmental Science **242** (2019) 062017 doi:10.1088/1755-1315/242/6/062017

Characteristics of volume and suction of undisturbed unsaturated loess under triaxial compression

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Abstract. The compression of unsaturated loess was explored with triaxial instrument for unsaturated soils. The test covered 3 different water contents of unsaturated loess and the saturated loess at initial confining pressures of 100 kPa, 200kPa and 400 kPa. The matric suction and volume change were obtained during virgin compression. Test results showed unsaturated loess have similar compression properties on the compression curve of saturated soil on the semi-logarithmic plane of average net stress, with yield points, which can be expressed by straight lines before and after yielding. With an increase of degree of saturation, compressibility gradually increases. The matric suction of unsaturated loess gradually decreases, and the variation is similar to that of volume. The parameters for the Modified Cambridge model were obtained to describe the compression of unsaturated soils.

1. Introduction

Collapsibility is the main feature of loess, and is the focus in researches concerning loess. Liu introduced the understanding of the basic physical and mechanical properties of loess in northwest China, and pointed out that loess is mainly composed of silt particles, easily eroded and lost by wind and rain, with large porosity and good permeability, which is the main reason for strong collapsibility exposed to water[1]. Sun first linked the moisture content of loess with collapsibility, and proposed that collapsibility is a continuous function of pressure and moisture content[2]. The former Northwest Institute of Water Conservancy Science has studied 8 groups of soil specimens with different initial moisture contents through compression tests, believed that the initial density, moisture content and pressure are the main factors determining collapsibility and have a unique relationship. Liu and Zhang proposed to calculate the collapsibility of loess with deformation modulus, eliminate test errors and considered the collapsibility of loess deformation[3]. Liu *et al* also studied the stress-strain relationship of loess first, summarized the deformation characteristics of loess, and reiterated the necessity of using stress-strain relationship to calculate collapsibility [4,5].

According to the experimental study of loess collapsibility deformation with conventional consolidation instruments, the collapsibility of loess was related to moisture content, pressure and structure, and its compression curve showed different characteristics with the change of moisture content[3,6-9]. Zhang has studied the deformation and strength characteristics of loess under humidification and dehumidification with conventional consolidation instrument and conventional triaxial apparatus, analyzed the similarities, and concluded that the compression curve of unsaturated soil is related to the initial moisture content, and the specimen with large moisture content has greater compressibility, and proposed the simulation method of collapsibility deformation[10]. The change of matric suction is not measured in the above-mentioned researches, and the test results are usually related to the moisture content. This method of using moisture content to explain loess collapsibility is simple and direct in description of the relationship formula between collapsibility and moisture content for field judgment and analysis, but the suction was ignored which is one of the stress variables of current unsaturated soil mechanics.

In this study, the triaxial apparatus of unsaturated soil was used to study the characteristics of volumetric deformation, axial deformation and matric suction during virgin compression of undisturbed loess to understand the mechanical properties of unsaturated soil upon water in different stress levels.

2. Test program

2.1. Physical properties of loess

The advanced triaxial apparatus for unsaturated soils (made by GDS Ltd.) was used to study the unsaturated compression properties of undisturbed loess taken from Xianjiang Uygur Autonomous Region of China. The sample was taken at depth of 13.5 m to 14.0 m and then enveloped with plastic film and sealed with wax. The specific gravity was 2.70, the liquid limit 29.8, and plastic limit 19.8.

The soil specimen was made by the following procedures. First, cut the undisturbed soil blocks into a soil sample in a diameter larger than 40 mm, then prepare the soil sample to the target water content by the water film transfer method; bury the soil sample in loose loess with the target moisture content, and let it stand for 7 to 10 days; finally, cut the soil sample to a specimen with a diameter of about 39.1 mm and a height of about 79 mm.

2.2. Test method

Virgin compression tests were conducted under six-level stress of 12.5 kPa, 25 kPa, 50 kPa, 100 kPa, 200 kPa and 400 kPa to obtain the volume change, axial deformation and matric suction change (for unsaturated soils) of undisturbed loess with four initial saturations. The tests were conducted under drainage condition and subjected to unloading and reloading procedures under 200kPa pressure. The tests were carried out with reference to SL237-1999 *Geotechnical Test Regulations* published by Ministry of Water Resources of the Peoples' Republic of China. Four moisture contents were about 6.5%, 10%, 16% and saturated moisture contents respectively, corresponding to degrees of saturation of 15.12%, 28.51%, 46.51%, and 100%, respectively.

The air intake value of the ceramics plates embedded in the pedestal is 800kPa. After installing the specimen, according to the axial translation method, pore gas pressures ranging from 100 kPa to 300 kPa were applied according to the moisture content of the specimen. In order to prevent the rubber membrane from bulging, the confining pressure was always kept 5kPa higher than the gas pressure. After the volumetric changes and the matric suction stabilized, the stress was applied in levels. The loading rate was 30 min to 200 min for each stress level. The stress did not apply until the deformation (volumetric change) at the previous stress level came to stabilize. The stability standard was less than 10mm^3 per 60 min, and the stability time was not less than 1 d. Usually it took 1 to 3 days for each level of load to stabilize.

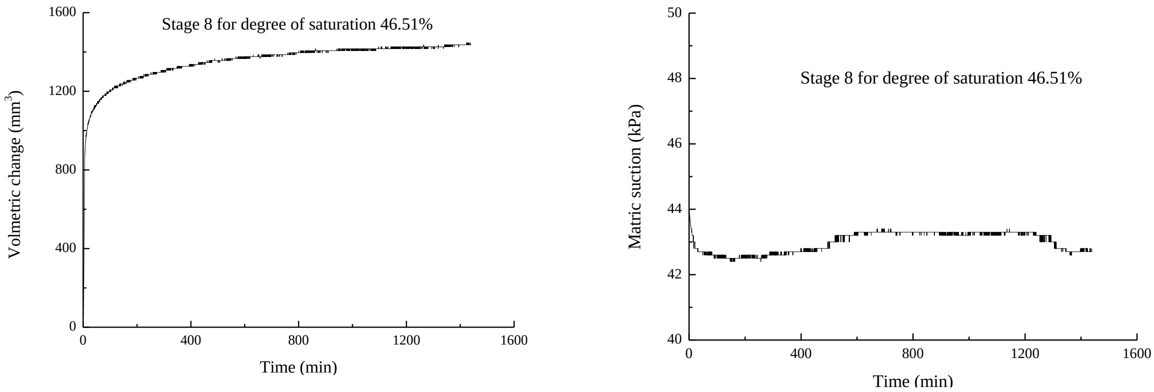
The saturated specimen was tested with GDS dynamic triaxial apparatus. The specimen was first subjected to back pressure saturation and then graded loading. The back pressure was increased to 400 kPa with a saturation criterion in which the pore water pressure coefficient B reached 0.95 and did not decrease for 8 h.

3. Test results

3.1. Compression stability

Figures 1 shows the volume and matric suction of the sample with initial saturation of 46.51% during virgin loading from stress 100 kPa to 200 kPa, respectively. It can be seen that the volume change stabilized within about one day and the matric suction remained basically unchanged during this process, decreasing only from 44 kPa to 42.7 kPa.

For saturated loess specimen, the volume change was plotted in the coordinate plane versus square root of time to determine the theoretical consolidation time t_{100}.The primary consolidation finished within about 700 min.



(a) **(b)**

Figure 1. Compression of saturated loess: (a) Volumetric change; (b) Matric suction.

3.2. Compression deformation

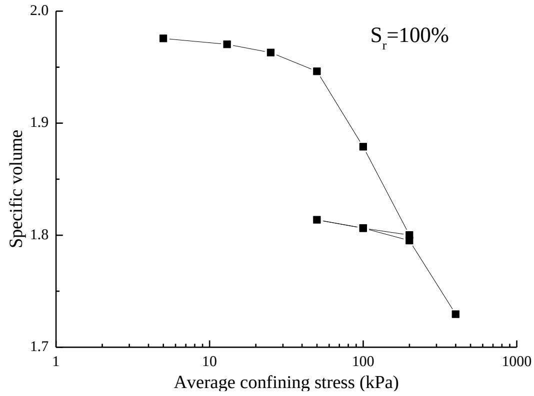
For saturated soil, the compression curve is drawn on the effective confining pressure versus specific volume. For unsaturated soils, test curves were drawn on net confining pressure versus specific volume and net confining pressure versus matrix suction.

Figure 2(a) is the compression curve for the saturated specimen. The specimen volume after saturation was calculated according to the dried mass, moisture content and drained water volume during consolidation. As can be seen, the compression curve of saturated loess specimen is divided into two straight lines on the semi-logarithmic coordinate, with an obvious yield point, which is called the normal consolidation line after the yield point.

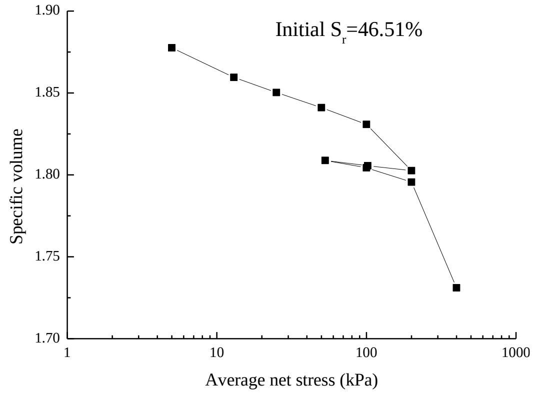
Figures 2(b), 2(c) and 2(d) are compression curves of specimens with initial degrees of saturation of 46.51%, 28.51%, and 15.12%, respectively. These curves start with the initial volumes of unsaturated soil specimens and give a pressure of 1 kPa on logarithmic coordinates as the starting point.

It can be seen that these three groups of unsaturated soil compression curves with different initial degrees of saturation have similar consolidation curves in semi-logarithmic coordinate plane. The relationship of volume change versus average net stress is linear before and after yielding and the rebound curves is basically straight.

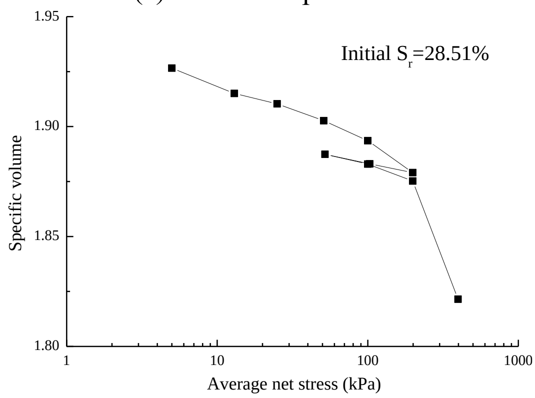
The initial yield stresses were determined by Casagrande method. For the saturated soil, the yield stress was 46 kPa, 152 kPa for the specimen with initial degree of saturation of 46.51%, 161 kPa for the specimen with initial degree of saturation of 28.51%, and 175 kPa for the specimen with initial degree of saturation of 15.12%. Obvious the yield stress decreased with an increase of degree of saturation.



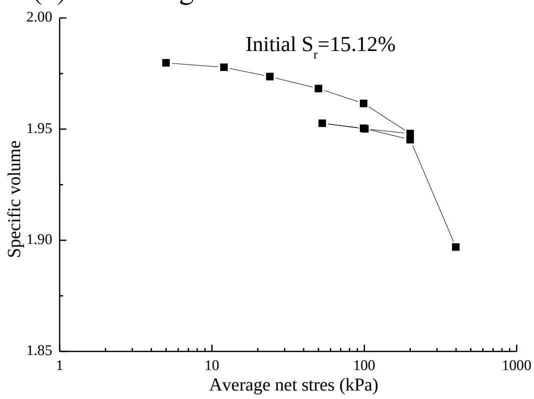
(a) Saturated specimen



(b) Initial degree of saturated of 46.51%



(c) Initial degree of saturated of 28.51%

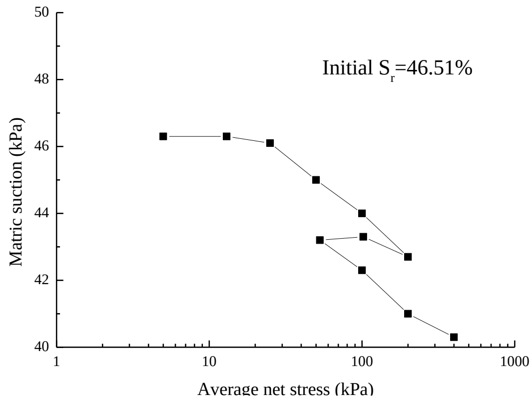


(d) Initial degree of saturated of 15.12%

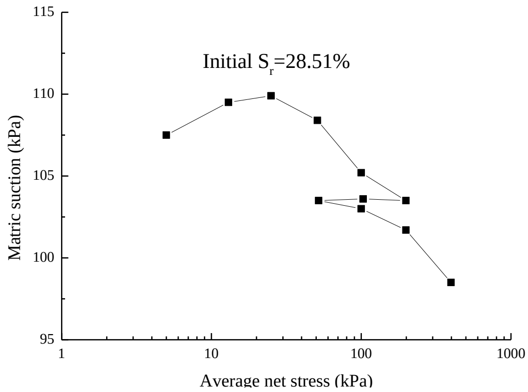
Figure 2. Compression of undisturbed loess specimens with different initial degrees of saturation.

3.3. Variation of matric suction

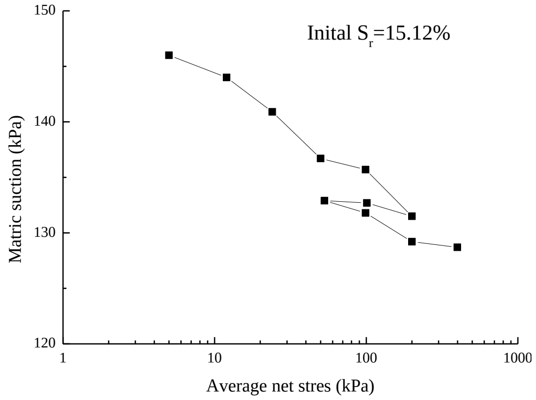
The matric suction was also measured in the virgin compression test for unsaturated soils. Figure 3 shows the development of matric suction versus pressure plotted in semi-logarithmic coordinates. It can be seen that although the experimental data are somewhat discrete, and also the matric suction gradually decreases with the increase of pressure and the variation law of matric suction is similar to that of specific volume.



(a) Initial degree of saturated of 46.51%



(b) Initial degree of saturated of 28.51%



(c) Initial degree of saturated of 15.12%

Figure 3. Matric suction variation of unsaturated loess.

3.4. Compression model

In Modified Cambridge model, the relationship between specific volume and effective stress during virgin consolidation is as follows

$$v = N - \lambda \ln(\frac{p'}{p_0})$$

where p_0 is reference stress, N is the specific volume when $p'/p_0 = 1$ and λ is the slope of the compression curve on the semi-logarithmic plane. On the rebound curve, λ is replaced by κ.

For unsaturated soil, the effective stress in the formula can be replaced by net stress. Therefore the compression parameters of specimens with different initial degrees of saturation were obtained as shown in Table 1. It can be seen that with the increase of degree of saturation, λ and κ gradually increase, indicating that compressibility also gradually increases due to the existence of matrix suction enhancing the compression ability of soil.

Table 1. Compression parameters for modified Cambridge model.

Water content (%)	Degree of saturation (%)	N	λ	κ
36.14	100	2.36	0.11	0.01
15.34	46.51	2.32	0.1	0.01
10.12	28.51	2.3	0.08	0.08
6.50	15.12	2.33	0.07	0.01

4. Conclusions

The compression of undisturbed unsaturated and saturated loess was explored via triaxial test apparatus with the virgin stress applied in several levels to 400 kPa. The following conclusions were drawn:

(1) The unsaturated loess have similar compression properties on the compression curve of saturated soil on the semi-logarithmic plane of average net stress, with yield points, which can be expressed by straight lines before and after yielding. With an increase of degree of saturation, compressibility gradually increases.

(2) The yield stresses of loess is 46 kPa for saturated soil, 152 kPa for specimens with degree of saturation of 46.51%, 161 kPa for specimens with degree of saturation of 28.51%, and 175 kPa for specimens with degree of saturation of 15.12%. The yield stress decreases with the increase of saturation.

(3) In the process of compression, the matric suction of unsaturated loess gradually decreases, and the variation is similar to that of volume.

(4) The Modified Cambridge model can be used to describe the compression of unsaturated soils.

Acknowledgements

This research was supported by a grant (Grants 2018 YFC1508502) National Key Research and Development Program of China, and a grant (No.51379220) from National Natural Science Foundation of China.

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