Overall volume change, water volume change, and yield associated with an unsaturated compacted loess

Zheng-Han Chen, D.G. Fredlund, and Julian K.-M. Gan

Abstract: This paper presents the overall volume change, water volume change, and yield associated with an unsaturated, compacted, low-plasticity loess from China. Two types of tests were conducted using a modified triaxial apparatus, namely isotropic compression tests with controlled suction (ICT), and triaxial shrinkage tests (TST). In the triaxial shrinkage tests, the net cell pressure is controlled and suction is allowed to increase. The results show that the stress path has a significant effect on overall volume change and the water volume change. The soil parameters related to overall volume change and the water volume change for the isotropic compression tests vary significantly in the low suction range, whereas the same soil parameters related to the triaxial shrinkage tests exhibit gradual changes. The yield net mean stress for the loading-collapse yield curve increases with suction. The yield suction is not equal to the maximum suction experienced by the soil specimen for the suction increase yield locus. Based on the test data obtained from the low-plasticity loess, a modified criterion for yield associated with suction increase is proposed. The proposed modified yield criterion should be valid for loess and silts of similar densities and plasticities.

Key words: stress path, triaxial shrinkage test, volume change, water drainage, yield, loess, unsaturated soil, matric suction.

Résumé : Cet article présente les changements de volume total, de volume occupé par l'eau et les propriétés de rupture pour un lœss non saturé compacté de faible plasticité provenant de Chine. Deux types d'essais ont été faits en utilisant un équipement triaxial modifié, à savoir des essais de compression isotrope à succion contrôlée (ICT) et des essais triaxiaux de retrait (TST). Dans ces derniers, on contrôle la pression nette dans la cellule et on permet à la succion d'augmenter. Les résultats montrent que le chemin des contraintes a un effet important sur les changements de volume total et de volume occupé par l'eau. Pour les essais de compression isotrope, les paramètres de sol reliés aux changements de volume total et de volume d'eau varient considérablement pour les succions faibles, alors que les mêmes paramètres pris dans les essais triaxiaux de retrait présentent des changements graduels. La contrainte nette moyenne d'écoulement sur la ligne chargement-effondrement augmente avec la succion. La succion à l'effondrement n'est pas égale à la succion maximale supportée par le sol le long de l'enveloppe des augmentations de succion à l'effondrement. A partir des résultats d'essais sur le lœss de faible plasticité, on propose un critère d'écoulement modifié associé à l'augmentation de succion. Ce critère devrait être valide pour des lœss et des silts de densité et de plasticité comparables.

Mots clés : chemin de contrainte, essai triaxial de retrait, changement de volume, drainage, écoulement, lœss, sol non saturé, succion matricielle.

[Traduit par la Rédaction]

Introduction

Compacted soils are widely used in the construction of earth structures. Several studies have been conducted on the volume change and water content variations of compacted unsaturated soils. Matyas and Radhakrishna (1968) found that the void ratio and degree of saturation state surfaces were unique provided the stress path did not induce appreciable desaturation and swelling. Barden et al. (1969) studied the effect of various stress paths during K_0 loading. The results indicated that the overall volume change of the specimen was stress path dependent, and was a function of whether the soil was going towards saturation or desaturation.

Fredlund (1973) and Fredlund and Morgenstern (1977) used independent stress state variables (i.e., $(\sigma - u_a)$ and $(u_a - u_w)$) for the study of the volume change behavior of unsaturated soils. The stress state variables and deformation state variables were used to formulate constitutive relations for the soil structure, the air phase, and the water phase. Only two of the three constitutive relations are required for a complete description of the phase volume changes. The constitutive relations can be expressed in an elasticity form, a compressibility form, or a traditional soil mechanics form (Fredlund 1979, 1985; Fredlund and Rahardjo 1993). Fredlund and Morgenstern (1976) experimentally tested the

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constitutive surfaces of unsaturated soils for uniqueness by inducing small monotonic changes in the stress state variables. Ho and Fredlund (1989), Rahardjo (1990), and Ho et al. (1992) measured the volume change indices associated with matric suction changes by using pressure plates tests and a shrinkage test. The soil-water characteristic curves and the shrinkage curves were combined to obtain the soil structure and water volumetric change curves and the corresponding indices.

Lloret and Alonso (1985) presented a number of linear and nonlinear functions for the constitutive surfaces of an unsaturated soil under K_0 and isotropic loading conditions. The constitutive surfaces for the soil structure and the water phase were expressed in terms of void ratio and degree of saturation. Test data were used to determine best-fit functions using a least squares method.

Several elastoplasticity models for unsaturated soils were recently proposed (Alonso et al. 1990; Wheeler and Sivakumar 1995; Cui and Delage 1996). Some new concepts such as the loading-collapse yield and suction-increase yield were introduced to account for the effect of suction change on the deformation of an unsaturated soil. However, experimental data to verify these new concepts are scarce.

In this paper, triaxial shrinkage tests and isotropic compression tests are performed to study the characteristics of overall volume change, water volume change, the effect of stress path, and the yield behavior of an unsaturated compacted loess.

Definition of stress and volume–mass variables

The following notations are used to denote the stress state variables for an unsaturated soil:

[1] $$p = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} - u_a$$

[2] $$s = u_a - u_w$$

where σ_1, σ_2, and σ_3 are the principal stresses; u_a and u_w are the pore-water pressure and the pore-air pressure, respectively; and p and s are the net mean stress and the matric suction, respectively. Volume change associated with the soil structure and the water phase is denoted using the variables, ε_v and ε_w, respectively.

[3] $$\varepsilon_v = -\frac{\Delta V}{\Delta V_0}$$

[4] $$\varepsilon_w = -\frac{\Delta V_w}{\Delta V_0}$$

where ΔV, ΔV_w, and V_0 are the total volume change, water volume change, and initial volume of the specimen, respectively. The variables ε_v and ε_w have been selected to define volume changes for the following reasons:

(1) ε_v and ε_w are the direct measures of the volume changes of the overall soil specimen and the water phase, respectively.

(2) It is convenient to use ε_v and ε_w in continuity equations for coupled problems involving water and air flow as well as the overall change of the soil structure. When the soil is saturated, ε_v is equal to ε_w.

(3) ε_v and ε_w are related to the specific volume v, gravimetric water content w, volumetric water content θ_w, and degree of saturation, S. These variables can be related using the following equations:

[5] $$v = (1 + e_0)\,(1 - \varepsilon_v) = v_0\,(1 - \varepsilon_v)$$

[6] $$\theta_w = \theta_{w0} - \varepsilon_w$$

[7] $$w = w_0 - \frac{1 + e_0}{G_s}\,\varepsilon_w$$

[8] $$S = \frac{G_s w}{e} = \frac{G_s w_0 - (1 + e_0)\,\varepsilon_w}{e_0 - (1 + e_0)\,\varepsilon_v}$$

where e is the void ratio; G_s is the specific gravity of soil particles; e_0, v_0, θ_{w0}, and w_0 are the initial void ratio, initial specific volume, initial volumetric water content, and initial gravimetric water content, respectively. The degree of saturation in eq. [8] is related to the volume changes associated with the soil structure and the water phase.

Laboratory testing equipment

The modified triaxial apparatus used in this study (Fig. 1) was developed at the Logistical Engineering University in Chongqing, China. A 1500 kPa high air entry ceramic disk was installed, using epoxy around the perimeter, into the base plate of the triaxial apparatus. A double-walled cell and a new volume change indicator were used to obtain accurate volume change measurements. The new volume change indicator consisted of a hypodermic syringe fixed inside the lucite cylinder. The piston of the syringe moves up or down depending on whether the specimen is dilating or contracting. The displacement of the piston was measured manually using a dial gauge. A displacement of 0.01 mm in the piston is equivalent to 0.006 cm^3 of overall volume change. For the measurement of water volume change, a small-bore polythene tube with a 4 mm inside diameter was attached to a stainless steel rule. A change in the water lever of 0.01 mm in the polythene tube is equivalent to 0.012 cm^3 of water volume change. Two layers of rubber membranes were used to enclose the soil specimen to reduce air diffusion.

Laboratory test procedure

The soil used in the study was a remolded loess from Shanxi Province, China. The specimens were prepared by static compaction with a stainless steel mold. Each specimen was compacted in five layers. The height of each layer was controlled using stainless steel rings attached to the piston of the mold. The specimens had a diameter of 39.1 mm and a height of 80 mm. The initial conditions of the compacted specimens are listed in Table 1.

A total of eight triaxial tests consisting of one saturated specimen and seven unsaturated specimens were performed under drained conditions. These tests can be divided into two groups according to stress path followed, namely isotropic compression tests with controlled suction (ICT) and triaxial shrinkage tests with controlled net mean stress (TST). The stress paths for the two groups of tests are shown in Fig. 2*a*. A typical stress path for the isotropic com-

Fig. 1. Modified triaxial apparatus used for the test program.

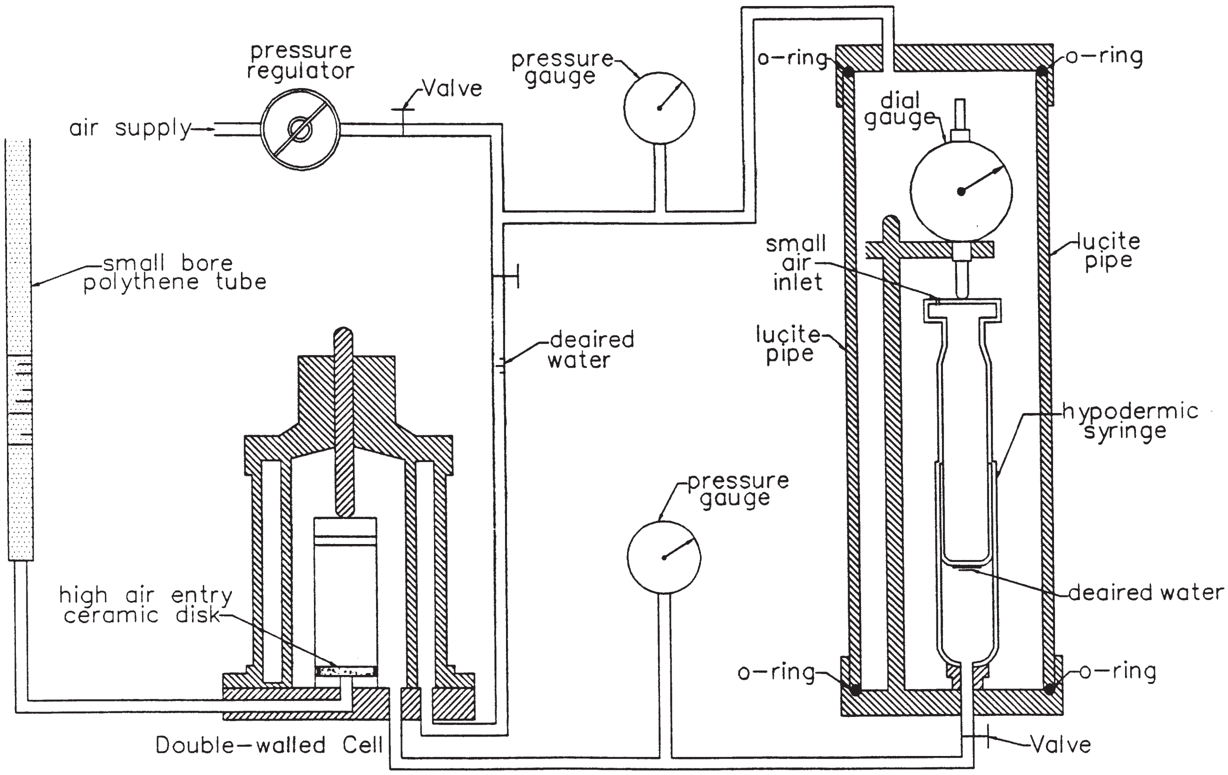


Table 1. Initial conditions of the compacted loess specimens.

Specific gravity G_s	Dry density ρ_d (Mg/m^3)	Water content w_0 (%)	Void ratio e_0	Degree of saturation S (%)	Soil suction (kPa)
2.72	1.70	17.15	0.6	77.8	20

pression test and a typical stress path for the triaxial shrinkage test are shown in Fig. 2*b*. All tests on the unsaturated soil specimen started from point A, where the net mean stress *p* and the soil suction *s* are 5 and 25 kPa, respectively. The isotropic compression test for the saturated soil started from zero net mean stress and was increased to a net mean stress of 500 kPa directly.

Triaxial shrinkage tests were conducted on four specimens. For each specimen the net mean stress was increased to a different selected value while the suction was held constant at 25 kPa. The selected net mean stress values for each of the four test specimens were 5, 50, 100, and 200 kPa. After the specimens had attained equilibrium condition relative to the applied net mean stresses, the suction values for each of the four respective specimens at 5, 50, 100, and 200 kPa net mean stress were then increased directly to 500, 450, 400, and 350 kPa, respectively.

Isotropic compression tests were conducted on three specimens. For each specimen the suction was increased to a different selected value while the net mean stress was maintained at 5 kPa. The selected suction values for each of the three test specimens were 50, 100, and 200 kPa. After the specimens had attained equilibrium condition relative to the applied suctions, the net mean stress values for each of the three specimens at 50, 100, and 200 kPa suction were then increased directly to 450, 400, and 350 kPa, respectively.

Equalization relative to each increment of net mean stress or suction was assumed to have been attained when the rates of volume change for both the soil structure and the water phase were less than 0.012 cm^3 over an interval of 2 h. Equalization was typically attained after about 3 days.

One of the triaxial shrinkage tests, for which the net mean stress was maintained at 200 kPa, was terminated when the suction reached 100 kPa due to leaking of the drain tube. Only the deformation data from this test are used in subsequent analyses.

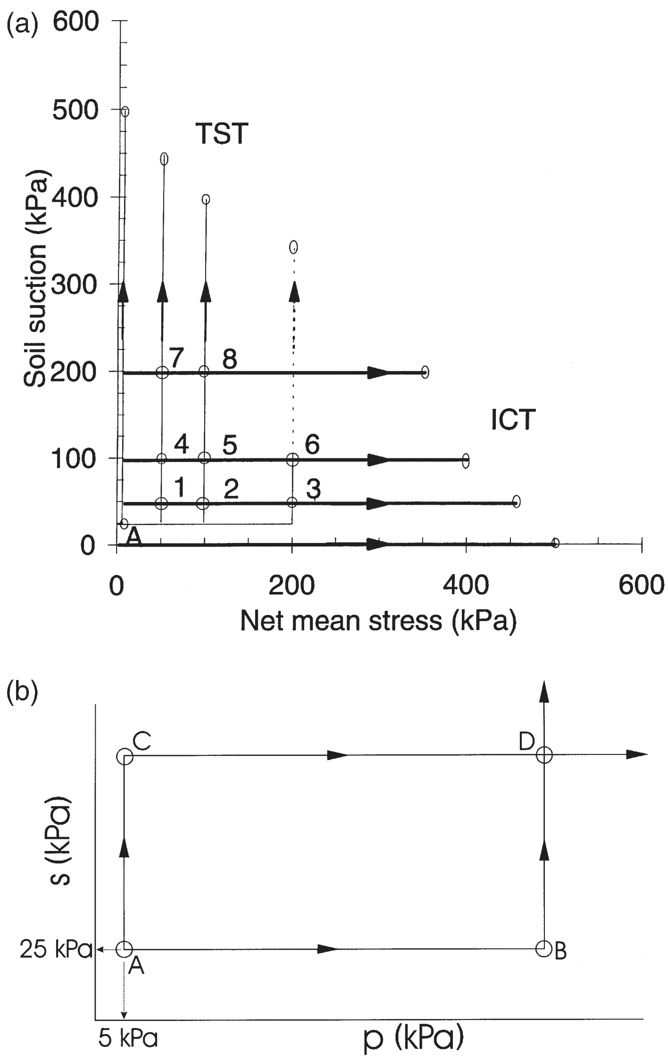
Each test took from 14 to 33 days to complete, depending on the target value of the net mean stress or the soil suction. At the end of each test, the specimen was divided into three parts. The water content was measured for each part and in every case the water contents were found to be approximately equal. From the water content measured at the end of the test and the initial water content values (i.e., w_0 = 17.15%, see Table 1), the amount of water that drained from the specimens could be calculated. The water volumes measured during the test were corrected according to the elapsed time into the test, since there were slight differences between the two sets of measurements. Some test data are shown in Table 2. The difference between the measured wa-

Table 2. Amount of water drained from the test specimens.

Test condition description	Elapsed time (days)	Measured value (cm^3)	Calculated value (cm^3)[a]	Difference (cm^3)	Relative error (%)
s = 50 kPa, ICT	17	3.28	3.48	0.20	5.75
s = 100 kPa, ICT	17	4.29	4.47	0.18	4.03
s = 200 kPa, ICT	14	5.98	6.18	0.20	3.24
p = 5 kPa, TST	33	9.83	9.11	0.72	7.90
p = 50 kPa, TST	24	9.97	9.79	0.18	1.84

[a]Calculated from the initial and final water contents.

Fig. 2. (*a*) Stress paths for the isotropic compression tests (ICT) and the triaxial shrinkage tests (TST). (*b*) Typical stress paths for the isotropic compression tests and the triaxial shrinkage tests.



ter volume changes and the corrected water volume changes is insignificant.

Analysis of test results

The test results for the isotropic compression tests (ICT) and the triaxial shrinkage test (TST) are presented and analyzed in the following sections.

The effect of stress path on the overall volume change and water volume change

The eight intersection points for the stress paths of the ICTs and the stress paths of the TSTs are shown in Fig. 2*a*. The volumetric strain for the soil structure, the water volume change, and the corresponding water content at each intersection point are presented in Table 3.

Figure 3*a* shows a comparison of the volumetric strain and the water volume change for the isotropic compression tests and the triaxial shrinkage tests. If the deformations (i.e., overall volume change and water volume change) were independent of the stress paths, all points would lie along a 45° line.

The results in Fig. 3*a* indicate that the volumetric strains produced along the triaxial shrinkage test path are approximately 35% greater than that produced along the isotropic compression test path. The results also indicate that the amount of water draining from the specimen when following the triaxial shrinkage test path is approximately 27% greater than that draining from the isotropic compression test path. Figure 3*b* shows the water contents in the specimen as a result of following the two stress paths (i.e., ICT and TST paths). The water contents from the triaxial shrinkage tests are 6% less than those from the isotropic compression tests.

These differences from the two stress paths can be explained as follows. The triaxial shrinkage test follows the path A→B→D, and the isotropic compression test follows the path A→C→D (Fig. 2*b*). The soil suction along path AB is less than that along path CD, so the compressibility along path AB is greater than that along path CD (Matyas and Radhakrishna 1968; Maatouk et al. 1995; Cui and Delage 1996) (also see Table 4). The soil suction change along path BD is the same as that along path AC, whereas the net mean stress along path BD is much larger than that along path AC. Thus, the volumetric deformation along path BD is larger than that along path AC. Finally, it is apparent from the continuity equation for an unsaturated soil (Fredlund and Rahardjo 1993) that the larger the overall volume change, the greater will be the water volume change.

The stress paths appear to have a significant effect on the overall volume change and water volume change.

Isotropic compression tests

The overall volume change and water volume change for the isotropic compression tests are presented and discussed in this section.

Yield upon loading

Figures 4*a* and 4*b* show the ε_v – log *p* relationship and the

Table 3. Volumetric strains and change of water volume (as well as water content) at intersection points of stress paths.

No. of points:		1	2	3	4	5	6	7	8
Stress state	p (kPa):	50	100	200	50	100	200	50	100
	s (kPa):	50	50	50	100	100	100	200	200
ε_v (%)	ICT	1.27	1.75	2.35	1.44	1.80	2.46	1.73	2.11
	TST	1.63	2.53	3.02	2.26	3.28	3.63	3.03	4.10
ε_w (%)	ICT	1.77	2.09	2.59	3.11	3.58	3.90	4.71	5.03
	TST	2.19	2.82	*	4.17	5.00	*	6.59	7.90
w (%)	ICT	16.12	15.93	15.63	15.32	15.16	14.87	14.39	14.20
	TST	15.87	15.50	*	14.71	14.22	*	13.28	12.51

[a]One test of the triaxial shrinkage tests (TST) at 200 kPa of net mean stress was terminated when suction reached 100 kPa due to leaking of the drain tube.

Table 4. Values of soil parameters related to the isotropic compression tests.

	Yielding stress (kPa)			Compression indices		Water volume change induces (10^{-5}/kPa)	
Soil suction (kPa)	Using ε_v – log p curve	Using v – log p curve	Mean	$\lambda_\varepsilon(s)$	$\lambda(s)$	$\lambda_w(s)$	$\beta(s)$
0	170	165	167.5	0.0685	0.1099	10.65	6.51
50	185	180	182.5	0.0412	0.0658	4.52	2.81
100	190	200	195	0.0385	0.0615	4.55	2.58
200	200	210	205	0.0303	0.0507	6.40	3.89

v – log p relationship, respectively. Both relationships are similar in shape. Each curve in Figs. 4*a* and 4*b* can be defined by two intersecting linear lines. The intersection point can be defined as the yield point. The net mean stress corresponding to the intersection point is referred to as the yield stress, $p_0(s)$. The yield stresses associated with suction can be determined using either Fig. 4*a* or 4*b*. The yield stress values are given in Table 4. The results show that the higher the suction values, the larger the yield stress. There is no significant difference in the yield stresses obtained from either Fig. 4*a* or 4*b*. If the yield points are plotted on the p–s plane shown in Fig. 4*c*, a yield curve can be drawn through these points. The yield curve is called the loading-collapse yield curve or the LC curve (Alonso et al. 1990). The shape of the yield curve obtained above appears to support the concept of the loading-collapse yield curve or the LC model.

Indices associated with overall volume change and water volume change

The slopes of the curves after yielding (i.e., $\lambda_\varepsilon(s)$ in Fig. 4*a* and $\lambda(s)$ in Fig. 4*b*) are listed in Table 4. Using eq. [5] it can be shown that

$$[9] \qquad \lambda(s) = -(1 + e_0)\lambda_\varepsilon(s)$$

where the negative sign means that the void ratio decreases with overall volume change. The soil parameters $\lambda_\varepsilon(s)$ and $\lambda(s)$ are determined from the test data using the least squares method and decrease with suction, particularly in the low suction range. For example, $\lambda_\varepsilon(0)$ for the saturated soil specimen is 1.66 times as large as $\lambda_\varepsilon(50)$ for the unsaturated soil specimen with soil suction of 50 kPa. The effect of suction on the compressibility of unsaturated specimens is not significant. Wheeler and Sivakumar (1995) obtained similar results using rammed consolidation tests maintained at a constant suction.

The ε_w–p relationships, shown in Fig. 5*a*, are linear for net mean stresses greater than 100 kPa. The slopes of the lines, $\lambda_w(s)$, are listed in Table 4. Apparently, the value of $\lambda_w(s)$ drops dramatically when suction increases from 0 to 50 kPa. Figure 5*b* shows the w–p relationship for various suctions. All the w–p relationships are linear and the slopes of the w–p lines, $\beta(s)$, are listed in Table 4. The relationship between $\lambda_w(s)$ and $\beta(s)$ can be obtained by differentiating eq. [7] with respect to the net mean stress p

$$[10] \qquad \lambda_w(s) = -\frac{G_s}{1 + e_0}\beta(s)$$

where G_s is equal to 2.72 and e_0 is equal to 0.6 from Table 1. The negative sign on the right-hand side of eq. [10] indicates that water content decreases with water drainage. Equation [10] shows that $\lambda_w(s)$ is 1.7 times as large as $\beta(s)$. The relationship is found to be true for the test data listed in Table 4.

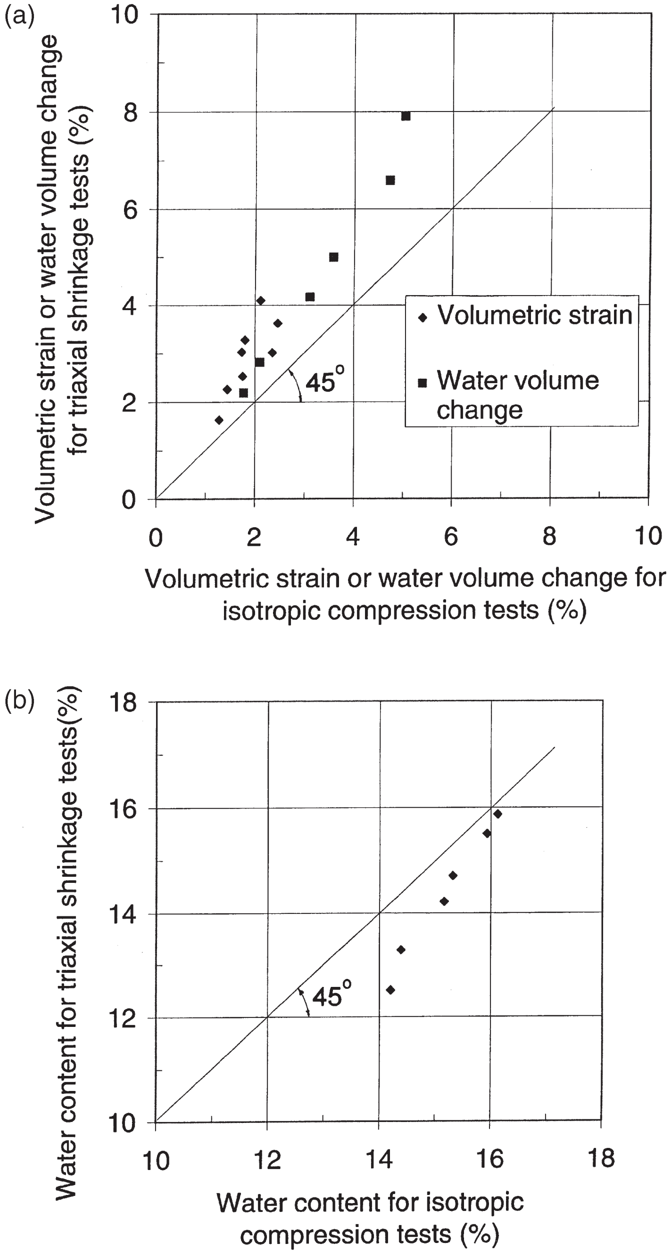
Triaxial shrinkage tests

The overall volume change and water volume change for the triaxial shrinkage tests are presented and discussed in this section.

Indices associated with overall volume change and water volume change

The suction versus water content relationships from the triaxial shrinkage tests are presented on a semilogarithmic plot in Fig. 6*a*. The suction versus water content curves corresponding to various net mean stresses are different, indi-

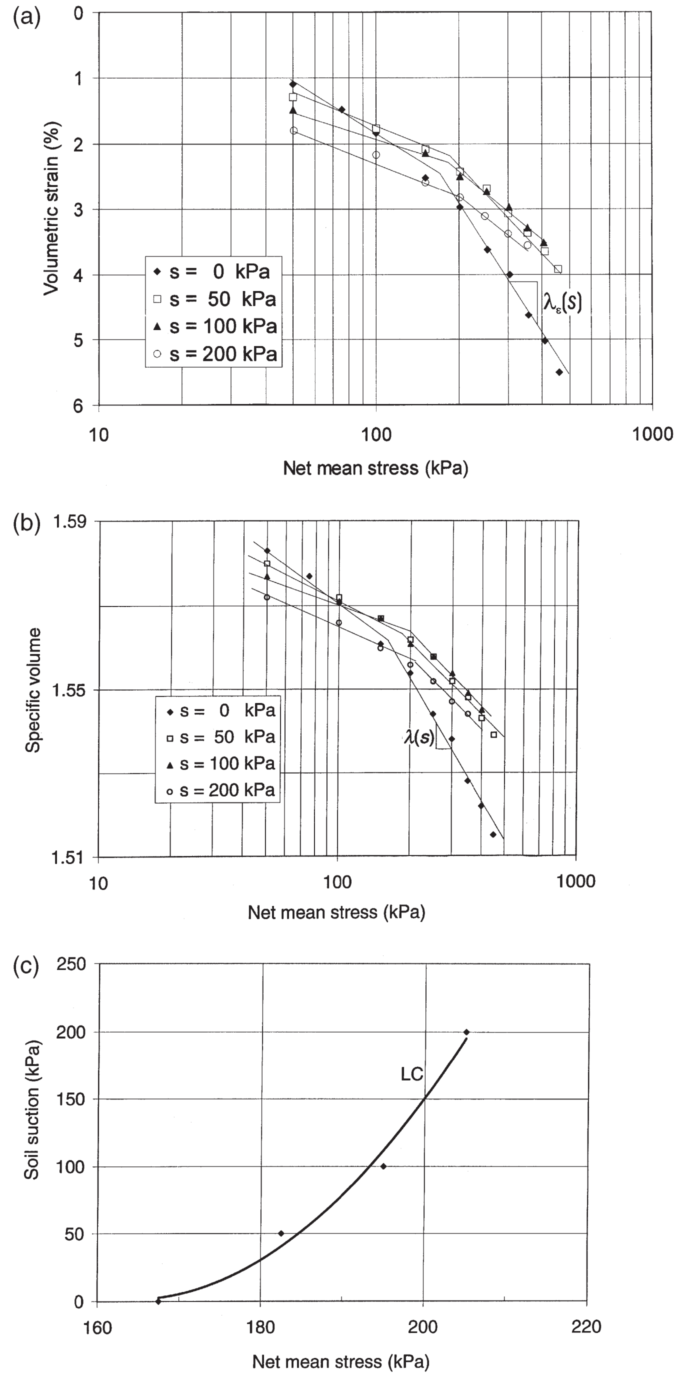
Fig. 3. (*a*) Comparison of volumetric strain and water volume change between the isotropic compression tests and the triaxial shrinkage tests. (*b*) Comparison of the water contents from the isotropic compression tests and the triaxial shrinkage tests.



cating that there is no unique one-to-one relationship between the matric suction and the water content. The soil suction versus degree of saturation relationship is shown in Fig. 6*b*. The suction versus degree of saturation curves are again different for various net mean stresses. The results in Figs. 6*a* and 6*b* show that a single-valued function between the degree of saturation (or water content) and soil suction does not exist as assumed in some research literature (Gens et al. 1995; Shen 1996).

The results from the triaxial shrinkage tests are presented in an alternative form in Fig. 7. Linear relationships appear to hold for ε_v, ε_w, and w versus $\log[(s + p_{atm})/p_{atm}]$, where p_{atm} is atmospheric pressure (see Figs. 7*a*–7*c*). The slopes of

Fig. 4. (*a*) Volumetric strains for the isotropic compression tests. (*b*) Specific volume changes for the isotropic compression tests. (*c*) Loading-collapse yield curve (LC).



the lines in Figs. 7*a*–7*c* are denoted by $\lambda_\varepsilon(p)$, $\lambda_w(p)$, and $\beta(p)$, respectively. The values for these parameters are listed in Table 5. Changes in the $\lambda_w(p)$ parameter with respect to p are insignificant. The average value of $\lambda_w(p)$ is 14.95. The relationship between $\lambda_w(p)$ and $\beta(p)$ is similar to that given in eq. [10], i.e.,

$$[11] \quad \lambda_w(p) = -\frac{G_s}{1 + e_0}\beta(p)$$

Fig. 5. (*a*) Water volume change for the isotropic compression tests. (*b*) Water content change for the isotropic compression tests.

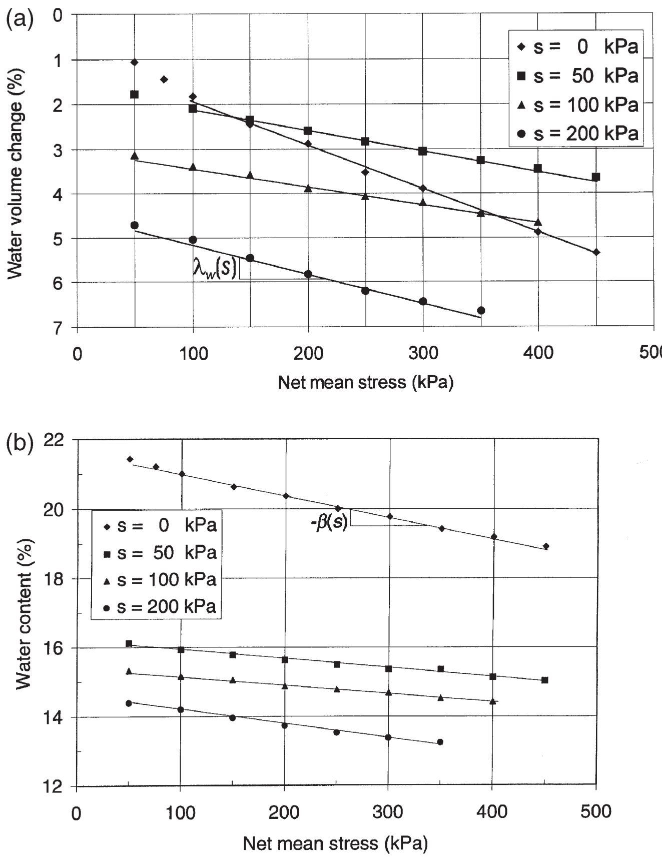
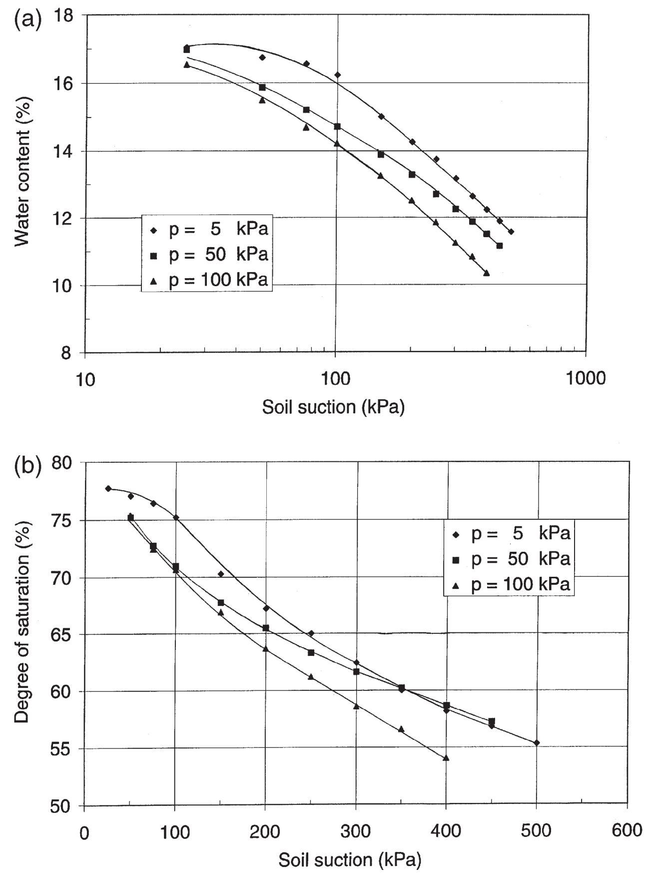


Fig. 6. (*a*) Soil-water characteristic curves at various net mean stresses (i.e., *w* – log *s*). (*b*) Degree of saturation versus matric suction curves at various net mean stresses.



The test data in Table 5 are consistent with the theoretical relationship given in eq. [11]. The parameter $\lambda_\varepsilon(p)$ increases with *p*, and the relationship can be written as follows (see Fig. 7*d*):

$$[12] \qquad \lambda_\varepsilon(p) = \lambda_\varepsilon^0(p) + m_3 \log\left(\frac{p + p_{\mathrm{atm}}}{p_{\mathrm{atm}}}\right)$$

where $\lambda_\varepsilon^0(p)$ is the intercept of the line corresponding to the value of $\lambda_\varepsilon(p)$ when *p* is zero, and m_3 is the slope of the line. The values for $\lambda_\varepsilon^0(p)$ and m_3 are 0.0256 and 0.0930, respectively.

The values for $\lambda_w(p)$ are much greater than those for $\lambda_\varepsilon(p)$ (see Table 5), implying that the water volume change is more than the overall volume change of the soil in the triaxial shrinkage tests. This is because some space occupied by water was replaced by air entering the soil specimen when suction was increased, resulting in a decrease of the degree of saturation. In other words, water can drain from the specimens with or without a change in the overall soil volume.

Yield due to an increase in soil suction

Yield due to an increasing suction is an interesting and important problem in unsaturated soils. Alonso et al. (1990) proposed that two yield loci were needed to describe volume yield of unsaturated soils in the (*p*, *s*) plane. The two yield loci are designated as the LC and the SI yield curves (SI for suction increase) as shown in Fig. 8. The yield condition for the SI yield curve can be written as

$$[13] \qquad s = s_o = \text{constant}$$

where s_o is the maximum past suction experienced by the soil. The LC and SI yield loci enclose an elastic region in the [*p*, *s*] plane. When suction increases beyond the maximum past suction s_o, yield occurs. The test data from the triaxial shrinkage tests are presented in Fig. 9*a* to show the ε_v versus log *s* relationship. Yield points corresponding to the specimens with 5, 50, and 100 kPa mean net stress can be identified in Fig. 9*a*. The suctions for the three yield points are identical at 100 kPa. The maximum past suction experienced by the specimens is 20 kPa (Table 1). The test for the specimen with a net mean stress of 200 kPa was not complete, with no data above *s* = 100 kPa, and no distinct yield point could be identified. In the LC model of Alonso et al. (1990), when yield occurs the LC curve is not crossed. Instead, the LC curve moves towards the right and the SI curve moves upwards as shown in Fig. 8.

Yield due to increasing suction appears to be dependent not only on the drying–wetting history of soil but also on the initial density of the soil and the net mean stress. If the initial density of the soil is low, then yield may occur at a low suction during drying. Similar results can be found in the study by Fleureau et al. (1993) for 11 clayey soils under zero net total stress on drying–wetting paths with specimens

Fig. 7. (*a*) Volumetric strains for the triaxial shrinkage tests. (*b*) Water volume changes for the triaxial shrinkage tests. (*c*) Water contents for the triaxial shrinkage tests. (*d*) Volumetric strain rate changes with net mean stress for the triaxial shrinkage tests.

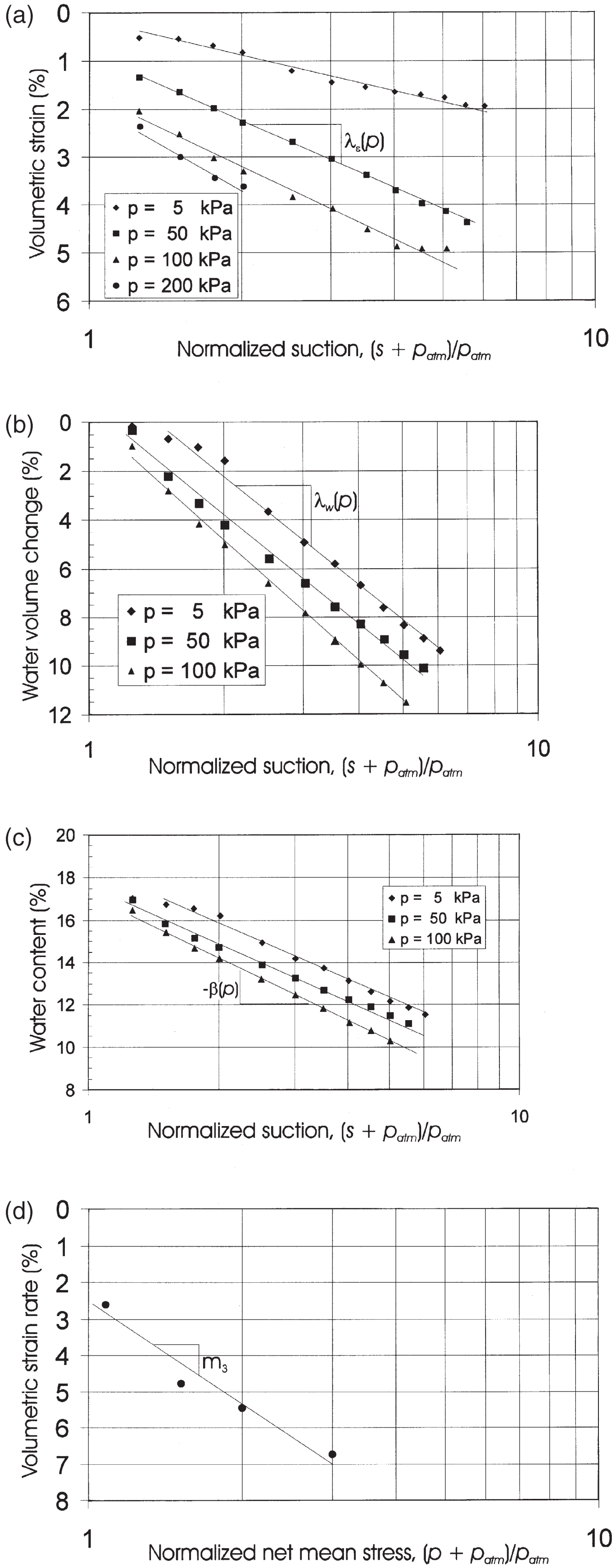


Table 5. Slopes of the lines in Figs. 7*a*–7*c*.

p (kPa)	$\lambda_\varepsilon(p)$ (%)	$\lambda_w(p)$ (%)	$\beta(p)$ (%)
5	2.56	15.08	
50	4.88	13.72	8.57
100	5.45	16.04	
200	6.83		
Average		14.95	$1.70\beta(p)$ = 14.57

Fig. 8. Yield loci for the compacted loess in the *p*–*s* plane and stress path A→B→C→D for the specimen at a net mean stress of 200 kPa.

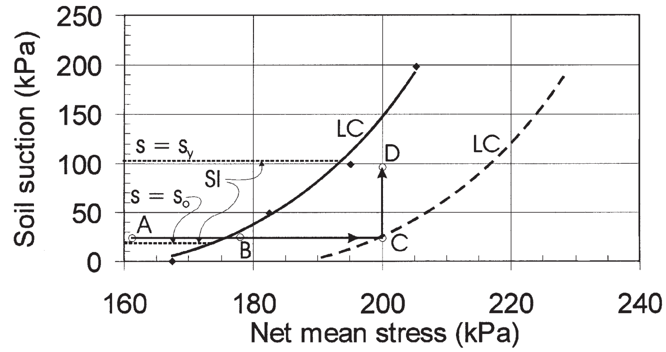
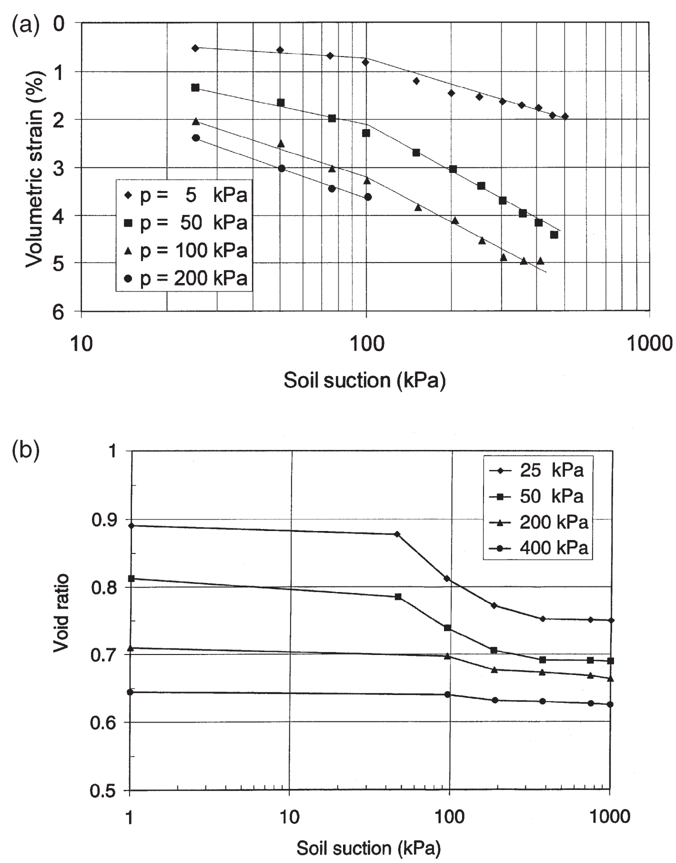


Fig. 9. (*a*) The relationship between yield and an increase in soil suction. (*b*) Data from oedometer tests on the normally consolidated Jossigny silt by Vicol (1990, cited in Delage and Graham 1996).



starting from slurries. On the other hand, if the initial density is high (i.e., 1.70 Mg/m^3 in this study), then a higher suction will be needed to cause yielding under drying. If the initial void ratio is lower than a limit value or if the net mean stress is high enough to cause LC yield, the compressibility of the soil will decrease significantly and the soil becomes insensitive to subsequent increases in suction and may exhibit elastic mechanical behavior. In other words, the SI yield is affected by the LC yield. Test data from Ho et al. (1992) and Vicol (1990, cited in Delage and Graham 1996) support these observations. For example, the results in Fig. 9*b* from Vicol (1990) suggest that the yield suction is 50 kPa rather than 0 kPa (i.e., the initial suction).

According to the above analysis, the SI yield condition (i.e., eq. [13]) for the low-plasticity loess can be modified as follows:

$$[14] \quad s = s_y = \text{constant}$$

where s_y is the yield suction which can be determined from routine shrinkage tests under zero net mean stress. Since $s_y \geq s_o$, the elastic region enclosed by a suction equal to s_y and the LC yield curve in the suction – net mean stress plane may be much larger than that proposed by Alonso et al. (1990) (see Fig. 8).

Conclusions

(1) Stress path has a significant effect on the overall volume change and the water volume change of unsaturated soil.

(2) The compressibility indices, $\lambda_\varepsilon(s)$ or $\lambda(s)$, for the unsaturated compacted loess in the isotropic compression test vary insignificantly with increasing suction. However, the compressibility indices for soil structure and the soil parameters corresponding to water volume change, $\lambda_w(s)$ or $\beta(s)$, vary significantly in the low suction range.

(3) The overall volume change and the water volume change soil parameters associated with the triaxial shrinkage tests (i.e., $\lambda_\varepsilon(p)$, $\lambda_w(p)$, and $\beta(p)$) exhibit gradual change. The parameters $\lambda_\varepsilon(p)$, $\lambda_w(p)$, and $\beta(p)$ can be determined using triaxial shrinkage tests.

(4) The yield net mean stress increases with suction, consistent with the concept of the LC yield. On the other hand, the yield suction during drying (i.e., shrinkage) does not equal the maximum suction experienced by the soil. A modified yield condition is proposed on the basis of the test data from this research using a low-plasticity loess and from other sources. The proposed modified criterion should be valid for loess and silts of similar densities and plasticities. The validity of the proposed modified yield criterion for other unsaturated soils (i.e., more plastic soils of different densities) needs to be experimentally investigated.

(5) The overall volumetric strain, ε_v, and the water volume strain, e_w, are suitable variables for describing overall volume change and water volume change in an unsaturated soil.

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