which expands the two-dimensional normal stress-shear stress Mohr circle for saturated soils to three-dimensional. The shear stress (τ) is used as vertical coordinates, while the net normal stress $(\sigma_n - u_a)$ and matric suction $(u_a - u_w)$ are horizontal coordinates. The first plane represents the relationship between shear stress and normal stress, while the other plane represents the relationship between shear stress and matric suction. When the effect of matric suction is considered, the equation for the shear strength of the unsaturated soil is expressed, as follows:

$$\tau_f = c' + (\sigma_n - u_a)_f \, tan\phi' + (u_a - u_w)_f \, tan\phi^b \quad (1)$$

Ho and Fredlund (1982) proposed the concept of apparent cohesion, and used it in the three-dimensional extended Mohr-Coulomb Failure Criterion. The obtained failure envelope is projected on the plane with zero matric suction, and the intersection point with the shear stress axis is the apparent cohesion, as shown in Fig. 1. Where C_1, C_2, and C_3 are apparent cohesion under different matric suction, which can be expressed, as follows:

$$C = c' + (u_a - u_w)_f \, tan\phi^b \quad (2)$$

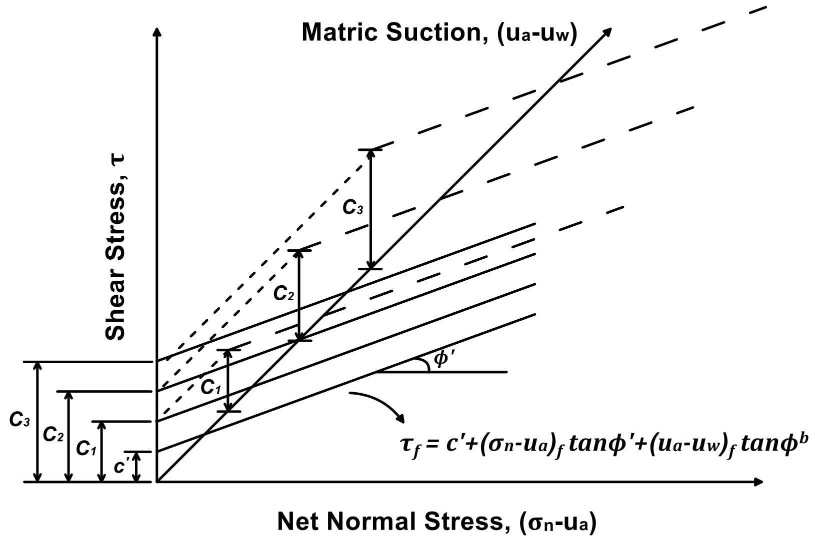

Fig. 1 Apparent cohesion under Extended Mohr-Coulomb theory

3.2 Relationship between unconfined compression test and apparent cohesion

As the unsaturated soil has matric suction, the Mohr circle of the unsaturated soil at triaxial test failure shall be on the $(u_a - u_w) \neq 0$ plane (see Mohr circle a in Fig. 2). The apparent cohesion corresponding to the failure envelope is C value. For the same soil specimen (i.e. same soil fabric and engineering behavior), if the unsaturated unconfined compression soil test is implemented under the same matric suction, and there is no change in pore air pressure u_a or pore water pressure u_w (i.e. if the pore air pressure and pore water pressure are not excited in the test process), the failure envelope shall be the same as the unsaturated triaxial test result. Therefore, the Mohr circle of the unsaturated unconfined compression test is Mohr circle b in Fig. 2. Although the changes in pore water pressure u_w cannot be measured during the unsaturated unconfined compression test, the measurement of pore water pressure u_w in the unsaturated triaxial test shows that the variation of u_w during specimen loading is 4~6kPa, which is only about 1% of deviator stress 400~600kPa. Based on this observation, pore water pressure is assumed unchanged during the unconfined compression test. However, the pore air pressure u_a excited in the test process is expected to be more significant than pore water pressure change and its effect shall not be neglected. The Mohr circle size of unsaturated unconfined compression testing shall be different from Mohr circle b, thus, the actual unconfined compression test result is Mohr circle c in Fig. 2.

In order to use the unsaturated unconfined compression test result to evaluate the triaxial apparent cohesion *C* value of unsaturated soil, this study assumes that the unsaturated triaxial and unsaturated unconfined compression test results have the same friction angle ϕ'. Therefore, the apparent cohesion C_{uc} of unsaturated unconfined compression test can be obtained, as shown in Fig. 2. It is observed that there shall be a proportion function relation between the cohesion C_{uc} value obtained by the unsaturated soil unconfined compression test and the apparent cohesion *C* value of the unsaturated triaxial test, expressed as Eq. (3), where α is the proportion function. The relationship between the unsaturated unconfined compression strength q_u and C_{uc} value is expressed as Eq. (4). The unsaturated triaxial apparent cohesion *C* can be evaluated by Eq. (2), as suggested by Ho and Fredlund (1982). If the proportion function can be determined with sound rationale it may be possible to develop a simple alternative to estimate the apparent cohesion using the unconfined compression test.

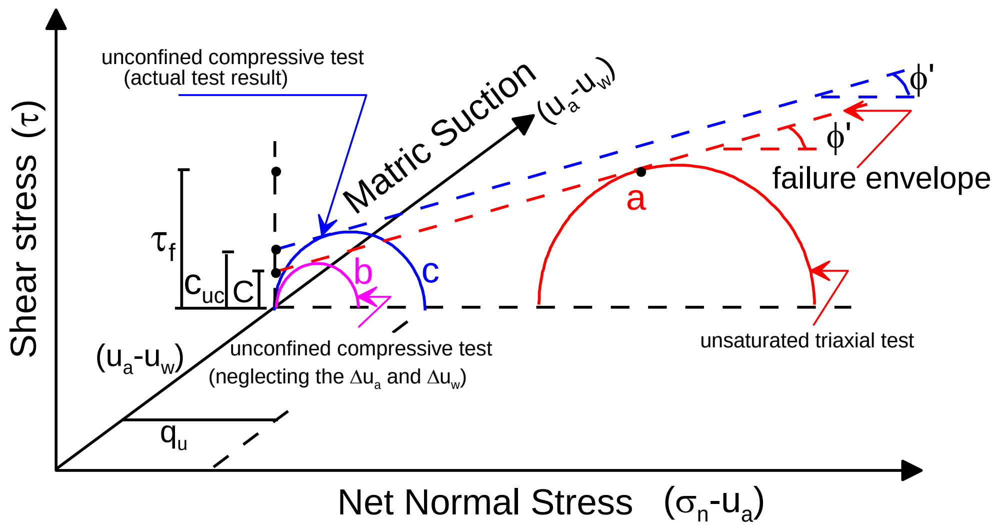

Fig. 2 Relationship between C and C_{uc}

$$\alpha\, C_{uc} = C \tag{3}$$

$$C_{uc} = \frac{q_u}{2} \times \frac{(1 - sin\phi')}{cos\phi'} \tag{4}$$

4. EXPERIMENTAL RESULTS AND PRELIMINARY ANALYSIS

4.1 Unconfined compression test

Soil specimens compacted at different initial compaction conditions (OMC -3%, OMC, OMC+3%) are simulated by drying/wetting simulation equipment, and then, the unconfined compression test and filter paper test are implemented for the dried and wetted specimens. The test results are as shown in Fig. 3. It is observed that the unconfined compressive strength increases with the matric suction. As the matric suction increases, the strength increasing amplitude of the OMC specimen is much larger than the specimens on dry and wet sides, which may be because the fabric of the OMC specimen has good compactness and water retaining capacity. The slope of strength changes of specimens on the drying path is far larger than that on the wetting path. As the water content is gradually saturated on the wetting path, the variation of matric suction is limited. Therefore, the strength change is less than that on the drying path. When the dry side specimen approaches to saturation, the strength is lower than the other two sides, which may be because the initial state of the dry side soil is flocculated fabric, and when the water is absorbed, the large swelling amount reduces the dry density, thus, the dry side soil strength decreases greatly. Regarding the apparent cohesion of unconfined compression test, the C_{uc} value can be obtained by Eq. (4).

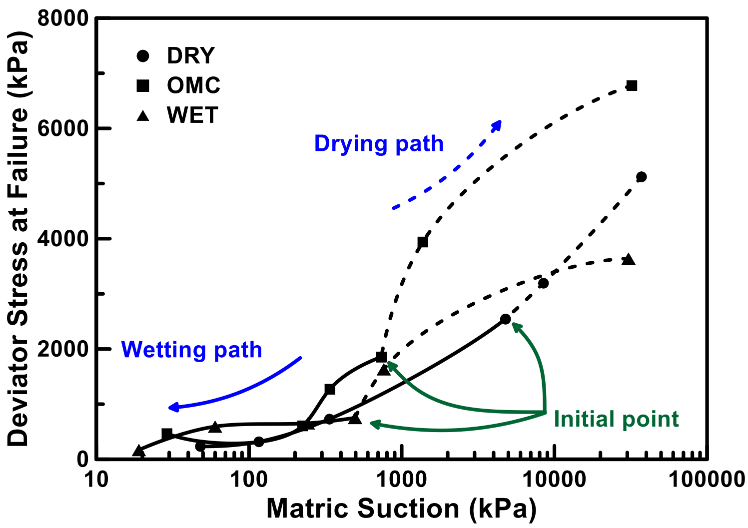

Fig. 3 The relationship between unconfined compression strength and matric suction

4.2 Unsaturated triaxial test

The specimens in different initial states (OMC-3%, OMC, OMC+3%) are placed in the unsaturated triaxial cell, all of the samples are pre-saturated and the specified suction is applied and maintained until balance. The OMC multistep load test result is shown in Fig. 4. The test result shows that the deviator stress increases with the matric suction. While the test results of the dry side and wet side states exhibit the same trend.

According to Eqs. (1) and (2), the apparent cohesion of unsaturated compacted lateritic soil specimens of different initial compaction condition and matric suction can be obtained. The ϕ^b value also can be calculated by the apparent cohesion equation of Eq. (2). The results are summarized in Table 1, where c' and ϕ' are obtained from the saturated triaxial consolidated undrained test result, i.e. the effective cohesion and effective friction angle corresponding to zero matric suction. The test results show that regardless of the initial compaction state the ϕ^b value decreases gradually as the matric suction increases. This tendency and the range of the ϕ^b value are all in good agreement with previous findings reported in the literature. In other words, the apparent cohesion of unsaturated soil exhibits nonlinear increasing relation with the matric suction. It may be note that the specimen compacted at dry-of-optimum swelled most significantly during the pre-saturation process and thus exhibits lower ϕ^b value than the wet side specimen. The effects of pre-saturation warrant further study.

Table 1 Apparent cohesion and ϕ^b value of unsaturated triaxial test

DRY			OMC			WET		
$u_a - u_w$ (kPa)	C (kPa)	$\phi^b(°)$	$u_a - u_w$ (kPa)	C (kPa)	$\phi^b(°)$	$u_a - u_w$ (kPa)	C (kPa)	$\phi^b(°)$
0	43.09	27.12	0	47.54	36.65	0	66.26	32.12
40	63.07	26.54	40	78.00	37.28	40	94.02	34.76
100	94.81	27.34	100	95.48	25.61	100	121.62	28.97
200	132.49	24.08	200	118.86	19.63	200	150.36	22.81

Note: $\phi^b = \phi'$ and $C = c'$ when matric suction equals to zero.

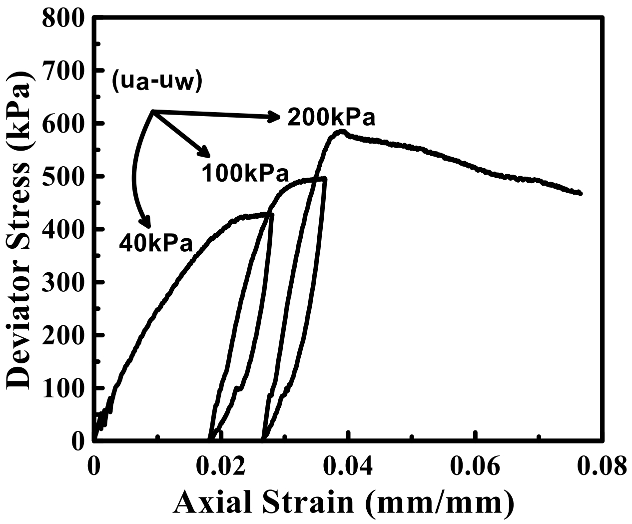

Fig. 4 Stress-strain curve of unsaturated triaxial test at OMC condition

4.3 Relationship between apparent cohesion of unconfined compression C_{uc} value and unsaturated triaxial apparent cohesion C value

Fig. 5 shows the relationship of the apparent cohesion (C) obtained from the unsaturated triaxial test results (Table 1) and the apparent cohesion (C_{uc}) derived from the unconfined compression results (Fig. 3). Because the matric suction used for the unsaturated triaxial tests are 40kPa, 100kPa, and 200kPa the apparent cohesion of unconfined compression C_{uc} corresponding to these suction values was determined by interpolation of the results shown in Fig. 3. The analytical results show that the unsaturated triaxial apparent cohesion C value is approximately in linear increasing relation to the apparent cohesion of the unconfined compression C_{uc} value, where the proportion function α value is about 0.65~1.04, as shown in Fig. 5.

Fig. 6 shows the comparison of the apparent cohesion (C_{uc}) directly obtained from the unconfined compression tests (Fig. 3) and the derived traxial apparent cohesion (C). For the unconfined compression tests, the matric suction was measured by the filter paper method and covered a wide range. Some of the specimens exhibit very high matric suction and exceed the limit that can be conducted by the unsaturated triaxial test. Therefore, an alternative was adopted to estimate the corresponding apparent cohesion (C) by applying Eq. (2). With c' value known if $\phi^b$is reasonably assumed then the apparent cohesion at different matric suction can be calculated form this equation. This linear relationship is related to the ϕ^b value decreasing as the matric suction increases. According to previous studies of Linkou lateritic soil, the reasonable range of ϕ^b value is 14^0 to 34^0. If $\phi^b=25^0$, then the proportion function α values are about 0.64~1.17, as shown in Fig. 6. When ϕ^b $=14^0$ and 34^0, the α values are 0.44~0.82 and 0.83~1.51, respectively.

Based on all the results discussed above, the apparent cohesion (C_{uc}) estimated by the unconfined compression test exhibit a strong positive relationship with the actual apparent cohesion (C). The difference may be because of the pore air pressure excitation and dissipation in the soil specimen. When the specimen is being sheared in an unconfined compression test, the pores in the soil are compressed, and the pore air pressure is changed, thus, the net normal stress is no longer zero at failure. Further study is being conducted to clarify this phenomenon and to develop a more comprehensive method to quantify the proportion function for practical application.

5. CONCLUSIONS

1. The apparent cohesion (C_{uc}) of the unsaturated compacted lateritic soil estimated by the unconfined compression test together with the filter paper test exhibits a strong positive relationship with the actual apparent cohesion (C). The matric suction has been shown to act as a key parameter to bridge these two apparent cohesions. Based on the unsaturated triaxial test results of matric suction below 200 kPa, the proportion ratio of C to C_{uc} ranges from 0.65 to1.04. Further study is being conducted to develop a comprehensive method to quantify the proportion function for practical application.

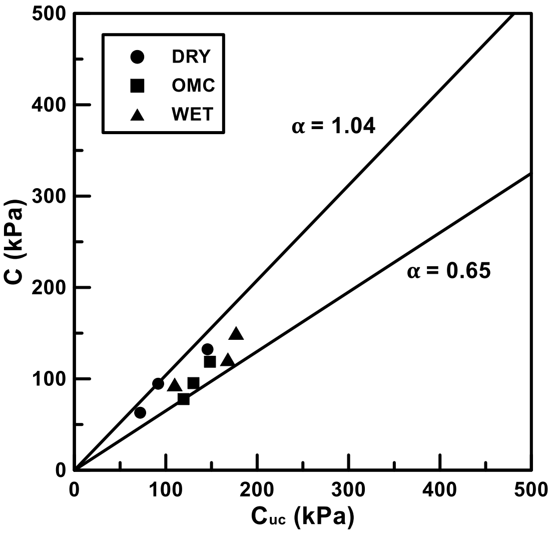

Fig. 5 Comparison of apparent cohesion C and interpolated C_{uc}

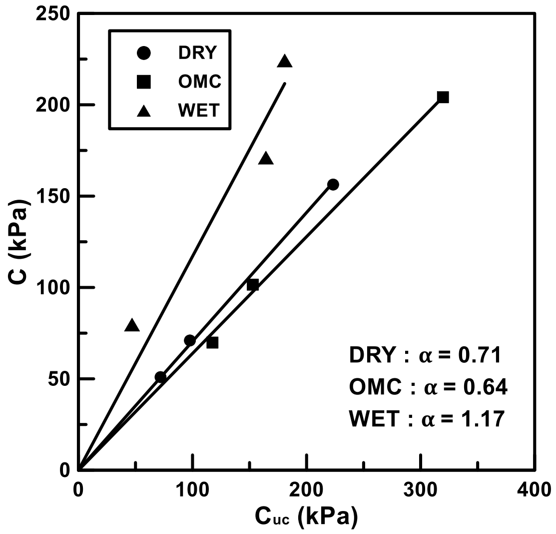

Fig. 6 Apparent cohesion C_{uc} vs. derived apparent cohesion with ϕ^b=25°

2. The unconfined compressive strength increases with the matric suction for specimens compacted at OMC-3%, OMC, and OMC+3%. When the matric suction increases, the strength of the OMC specimen increases much larger than the specimens of dry and wet sides, probably due to compact soil fabric of high water retaining capacity. Regardless of the compaction condition, the strength change on the drying path is far larger than that on the wetting path. Because along the wetting path he specimen is gradually saturated, thus, the change in matric suction and the strength are limited.

3. A series of multi-step unsaturated triaxial tests were conducted on specimens of different initial compaction conditions and pre-saturation before deviator loading. Test results show clear trend of strength increase with matric suction despite of its compaction condition. The unsaturated triaxial test result also shows that the ϕ^b value decreases as the matric suction increases. This tendency and the amount are in good agreement with previous findings reported.

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