**Unsaturated Soil Shear Strength Parameters Measurements**

- **Control of Stress States**

  The stresses $\sigma$, $u_a$ and $u_W$ can be measured or controlled so that the stress state variables $(\sigma - u_a)$, $(\sigma_1 - \sigma_3)$ and $(u_a - u_W)$ will be known.

  The axis translation method is used to obtain matric suction pressures greater than atmospheric.

  Use extended Mohr-Coulomb failure envelope to determine shear strength parameters $c'$, $\phi'$ and $\phi^b$.

  Use shear strength testing to determine parameters for other shear strength theories.
• **Triaxial Shear Testing**

**Consolidated Drained Test**

Both the air and water are permitted to drain and the pressures are controlled.

The matric suction pressure can therefore be held constant throughout the test.

The strain rate must be sufficiently slow to allow for flow of water from the soil through the high air entry material.

**Constant Water Content Test**

Only the air is permitted to drain so the gravimetric water content remains constant (undrained) and the water pressure must be measured.

The strain rate can be faster since air permeability is much higher than water permeability.

The matric suction does not remain constant but changes. The variation of matric suction can be explained in terms of volumetric strain.

See Fig. 9.32 below for an explanation.
When the loads are applied (low strains) the volume decreases (negative volumetric strain) and the pore water pressure increases (decrease in matric suction).

At higher strain levels the volumetric strain becomes less negative or becomes positive. Matric suction typically increases as the sample dilates.

The pore water pressure increases (decrease in matric suction) when the volume decreases are significant; and the pore water pressure decreases (increase in matric suction) when the soil volume increases.

The behavior described summarizes undrained behavior.
Consolidated, Undrained Test

Both the air and water are prevented from drainage so both pressures must be measured.

The air pressure increases since the air compresses and the pore water pressure increases as the soil volume decreases.

Air diffusion through the membrane causes problems because the soil is not undrained.

The strain rate must be slow enough to allow for a uniform water pressure distribution.

Unconsolidated, Undrained Test

Both the air and water are prevented from draining as the total confining (cell) pressure is applied.

The air pressure increases as the air compresses and the pore water pressure increases as the volume of the voids decreases.

The net confining pressure increases as the total confining pressure increases because the increase in fluid pressure is less than the increase in total pressure.
Both the net confining pressure and the matric suction pressure decrease during shearing because fluid pressures increase.

The strain rate must be slow enough to allow for a uniform distribution of water pressure.

**Unconfined Compression Test**

The net confining stress decreases slightly due to an increase in air pressure.

The pore water pressure increases resulting in a decrease in matric suction pressure.

Samples must be same water content and density as the in situ conditions.

- **Direct Shear Testing**

Usually conducted as drained tests.

Lines of equal matric suction pressure can be used to determine $\phi'$. Lines of equal net normal stress are used to determine $\phi^b$.

Shear strength increases are larger for increases in the net normal stress than for increases in the matric suction pressure because $\phi^b < \phi'$. 

• The Effects of Strain Rates

As stress is applied to soil, the pore fluid pressures increase.

For a drained test where the applied fluid pressure is controlled, the excess pore pressures will dissipate due to the gradients.

Thus, tests must be run slow enough to allow fluids to flow from soil to reduce the excess pore pressure.

Results of undrained tests at various rates indicate that:

a) the deviator stress at failure is not sensitive to strain rate;

b) the matric suction changes are higher for larger strain rates.

A solution for the required time to failure (strain rate) must include the effects of impeded drainage in the high air entry material.
• Multistage Testing

Use of extended Mohr-Coulomb failure envelope requires three "identical" samples, i.e.; a) same initial water content and void ratio prior to consolidation, or b) "representative" samples that would have the same water content and void ratio if the state of stress is the same.

An alternative is to use one sample tested at different stress levels in order to characterize shear strength behavior.

Constant Net Normal Stress

A sample is tested to "failure" at predetermined values of $(\sigma - u_a)$, $u_a$ and $u_w$.

After "failure" occurs, the confining stress and the air pressures are increased by the same magnitude and the water pressure is held constant.

Thus the net normal stress remains constant but the matric suction increases.
Two loading procedures that can be used are:

a) cyclic loading procedure, reduce the axial load until the deviator stress is zero before increasing the stress;

b) sustained loading procedure, maintain deviator stress as the matric suction is increased and then increase the deviator stress.

Deviator stress versus axial strain results as shown below.

Results of testing are used to illustrate extended Mohr-Coulomb failure envelope and to characterize shear strength behavior.
Constant Matric Suction

After "failure" occurs, the confining stress is increased while maintaining constant air and water pressure so the matric suction remains constant and the net normal stress increases.

Effects of Repeated Shear

Since the sample is tested to "failure" with each successive loading, the shear strength may be more representative of the ultimate or residual strength.

The internal structure of the soil in the shear zone is changed from flocculated (edge-to-face) to dispersed (face-to-face).

Less energy will be required to shear the soil.
• **Nonlinearity of $\phi^b$**

A soil with matric suction pressure less than the air entry value, can be partially saturated.

Under these conditions, the soil will behave like a saturated soil so the increase in shear strength with increase in matric suction can be obtained using $\phi' = \phi^b$.

After air enters the soil for higher matric suction pressures, the angle effectively decreases to a constant value $\phi^b$ that is less than $\phi'$.

The failure envelope would then be:
Approximation for Effective Stress

Recall Bishop's effective stress equation:

\[ \sigma' = (\sigma - u_a) + \chi (u_a - u_w) \]

\[ \chi = \text{Chi parameter (function of degree of saturation).} \]

Bishop also proposed an shear strength equation:

\[ \tau_{ff} = c' + \left\{ (\sigma_f - u_a) + \chi (u_a - u_w) \right\}_f \tan \phi' \]

The shear strength equation given earlier is:

\[ \tau_{ff} = c' + (\sigma_f - u_a)_f \tan \phi' + (u_a - u_w)_f \tan \phi^b \]

Setting the two equations equal and simplifying gives;

\[ \chi = \frac{\tan \phi^b}{\tan \phi'} \]

For linear behavior for \( \phi^b \), the Chi parameter should be a constant.

It may be possible to derive an expression for Chi using shear strength results to characterize shear strength.