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# Shear Strength Behavior of Unsaturated Clay

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**Abstract**: Studying the behavior of the unsaturated shear strength of soil leads to confirmation that the shear strength of unsaturated soils still in the stage of researcher's goals. To reach to a unique equation for determination of the shear strength of unsaturated clay, series of direct shear box tests were Conducted to investigate the unsaturated shear strength of (clay Middle Delta Nile Clay) in Egypt. Samples were tested at different water content (WC). Matric suction was measured at various values of water content using filter paper technic. The unsaturated shear strength behavior tests appear to be non-linear with matric suction. Mohr-Coulomb circle's failure envelope for results between unsaturated shear strength and matric suction approximated to two linear segments. Point of inflection for the two linear parts was around the matric suction at plastic limit. Design-Expert® software employs least square method (LSM) to fit a mathematical model to a set of experimental data. The Response Surface Methodology (RSM) program was used to deduce the compatible three dimensional equations to calculate the unsaturated shear strength of clay in two stages. The first equation presents the first stage of clay state which starts from matric suction at liquid limit (zero matric suction) up to matric suction at the plastic limit. The second equation presents the second zone of clay at matric suction between plastic limit and after shrinkage limit. Unsaturated shear strength depends on matric suction, soil cohesion, angle of internal friction and effective stresses .the internal friction increases by $^{b}$ ranges between $2.14^{o}$ and $0.27^{o}$ for zones before and after plastic limit respectively.

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**Key word:** Response Surface Methodology, Middle Delta Nile clay, Shear Strength of Unsaturated clay and matric suction.

## 1. Introduction

Whereas forty percent of natural soil on the earth's surface is unsaturated, so, it became an urgent need to investigate the behavior of unsaturated soil, specially the shear strength of unsaturated clay **(Uchaipichat, 2014)**. Generally, soil above the water table is considered to be unsaturated, where the degree of saturation is influenced by several factors such as capillary rise effect, infiltration, evaporation and transpiration near soil surface.

At the present, 20% of geotechnical publications in recent years have been either directly or indirectly related to field of unsaturated soil mechanism, **Vanapalli et al. (2008)**. Several constitutive models have been proposed in the field of unsaturated soil mechanics. A framework for unsaturated soil based on the extended critical state model for saturated soil in which additional variables for unsaturated soil were incorporated was proposed by **Toll (1990)**. a constitutive model was investigated for describing the stress-strain behavior of partially saturated soil based on the framework of hardening plasticity using two independent sets of stress variables **Alonso et al. (1990).** An alternative framework for unsaturated soil behavior based on a critical state model was represented **Wheeler (1996)**. More recently, investigated the relation between unsaturated shear strength parameters and soil properties and to predict the unsaturated shear strength parameters (c`, $\phi$` and $\phi^{b}$), **Khaboushan et al. (2018)**.

The soil water characteristic curve for a soil is defined as the relationship between water content and suction for the soil, **Williams (1982)**. The gravimetric water content WC is mostly used in the geotechnical engineering practice, **Fredulund and Xing (1994)** studying the effects of matric suction on the shear strength of highly plastic compacted clay A **Elshareif (2015)** has been concluded that the shear strength of the tested clay increase with the increase of matric suction in nonlinear form.

In this paper the Design–Expert program which is a statistical software package from Stat-Ease Inc. was used to get the suitable equation. That program is specifically dedicated to performing design of experiments (DOE) and offers comparative tests, screening, characterization, optimization, robust parameter design, mixture designs and combined designs. It provides test matrices for screening up to 50 factors. Statistical significance of these factors is established with analysis of variance (ANOVA).

## 2. Experimental Preparation and Test Procedure

### 2.1 Experimental Equipment

In this paper, the variation of shear strength behavior of unsaturated clay with matric suction was investigated by performing a series of laboratory shear box tests on Middle Delta Nile clay MDNC. The tests performed at different values of matric suction,ψ. Group of those tests were performed at net vertical stress $\sigma_v$ = 40, 65, 140 and 200 kpa. Each value of one group was consistent and matric suction was variable. The second group was performed at values of matric suction ψ = 600, 1600, 3600 and 6000 kpa. with the same arrangement Each value of the second group was consistent and net vertical stress was variable.

### 2.2 Sample Preparation

The experiments were performed on laboratory remolded clay samples. The properties of tested soil are summarized in Table -1and the grain size distribution for tested clay was defined from hydrometer test is plotted in Figure-1. Liquid limit for tested clay was defined from hydrometer test D 422-63 (1998), and plotted in figure -1

Table-1 Soil properties

| Property | Value |
|---|---|
| Liquid limit | 63% |
| Plastic limit | 25% |
| Plasticity index | 38% |
| Shrinkage limit | 14% |
| Classification | CH |
| Specific gravity | 2.70 |
| Clay fraction | 10% |
| Silt fraction | 77% |
| Sand fraction | 13% |
| Activity | 2.7 |

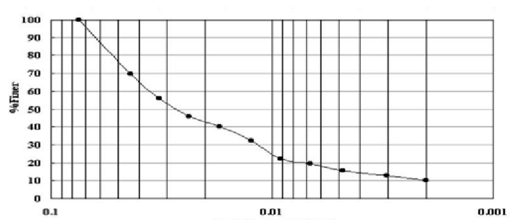



Figure -1. Grain size distribution (hydrometer test)

### 2.3 Measurement of Matric Suction

Forty samples were prepared for in cylinder mould with internal diameter of 85 mm and 100mm in height. Samples were kept in plastic box with constant humidity to keep samples without cracks. More than a week after keeping the samples in the constant humidity, the first group were taken out and filter paper technique were achieved to measure the matric suction through measuring the water content of filter paper and using the calibration curves suggested by ASTM D5298. **Uchaipichat and Man-koksung (2011)** used the contact filter paper technique. Figure-2 illustrates general set up for samples and filter paper. Partial drying (Exposed to air) was performed on sample groups to control degree of saturation and matric suction.

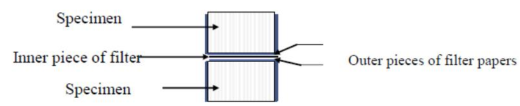



Figure-2 General set up for contact filter paper technique **(Uchaipichat and Man-koksung, 2011)**.

## 3. Results and Discussions

### 3.1 Soil Water Characteristic Curve

Figure-3 illustrates The Soil Water Characteristic Curve (SWCC) which represents the relation between matric suction and some measure of the water content. Samples were air drying constant humidity container. (SWCC) spent a duration of four weeks to reach to target values of water content , and one week was left between each group to reach the properly values of water content. Using results that will be adequate to plot the soil-water characteristic curve (SWCC) for tested clay. The soil water characteristic curve for Middle Delta Nile MDNC clay is presented in Figure -3.

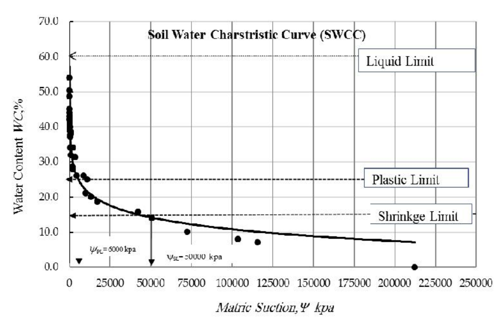



Figure -3 Soil -Water Characteristic Curve (SWCC) for MDNC

From soil water characteristic curve, the matric suction values at plastic limit and shrinkage limit be determinate, as $\psi_{PL}$ = 6000 kpa and $\psi_{SL}$ = 50000 kpa respectively. The best fit for data collected shown on the plot and can be represent in this form. $\psi = e^{\{(67- WC)/4.9\}}$

### 3.2 Direct Shear Box Results

Eighty remolded samples of MDNC were tested in direct shear box apparatus at different values of matric suction. The main parts of direct shear box assembly are shown in Figure-4.

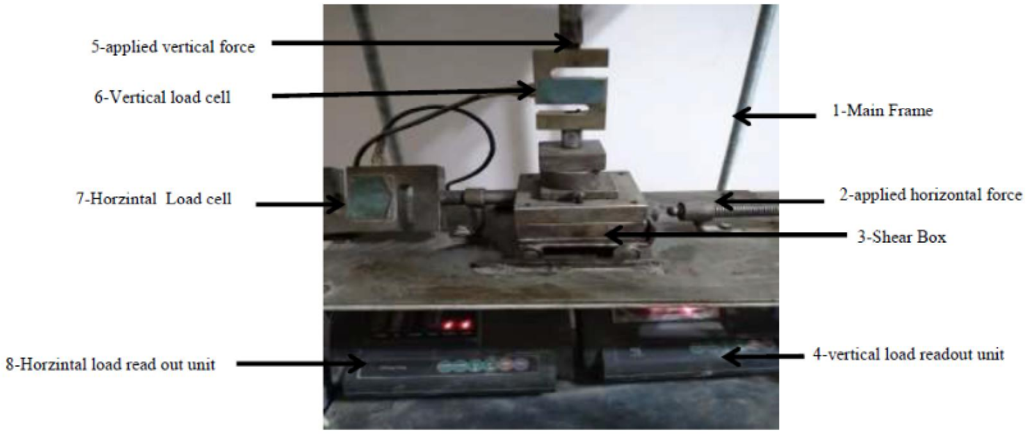



Figure -4 details of direct shear test

Figure -5 indicates that the relation between the shear strength of unsaturated clay and corresponding matric suction is nonlinear at all values of matric suction. Figures -6 and 7 illustrate the results of direct shear box between unsaturated MDNC and matric suction at net vertical stress of 200 kpa.

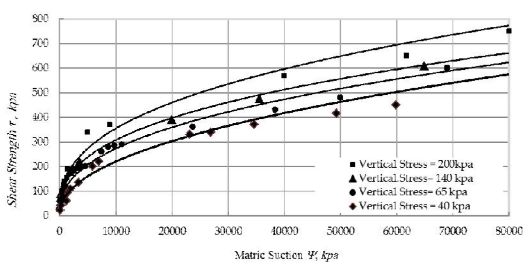



Figure -5 Shear Strength Variations with Matric Suction at Four Values of Net Vertical Stress

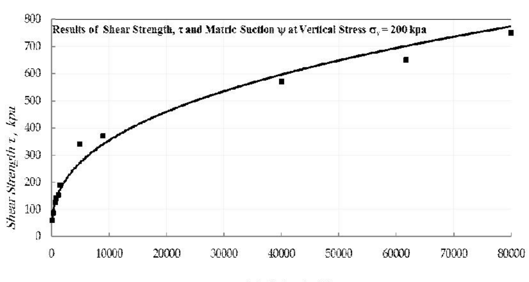



Figure -6 Shear Strength Variations with Matric Suction at Net Vertical Stress= 200 kpa

Figure -7 illustrates that Initially, in stage I the angle of internal friction with respect to Matric Suction $\phi_1^b$ has a higher value to a certain limit around the matric suction at plastic limit. In the second stage II value of the angle of internal friction with respect to Matric Suction $\phi_2^b$ has a lower value from the limit around the matric suction at plastic limit till higher than the matric suction at shrinkage limit. Therefore, an approximation the relation into two straight lines is reasonable and accepted as shown in Figure -7.

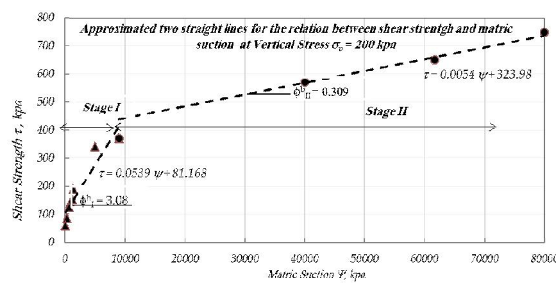



Figure -7 Shear Strength Variations with Matric Suction at Net Vertical Stress= 200 kpa approximated to two straight-line equation.

Accordingly, the angle of internal friction with respect to Matric Suction $\phi^b$ will give two values for each corresponding vertical stress. Due to this approximation for this relation as two straight lines, two slopes equal to tan$\phi_1^b$ and tan$\phi_2^b$ were defined. Table -2 shows the values of $\phi^b$ corresponding to the vertical stresses values.

Table-2 Values of Angle of Internal Friction with respect to Matric Suction

| $\sigma_v$(kpa) | $\phi^b_1$ (deg.) | $\phi^b_2$ (deg.) | $\phi^b_1$ av. | $\phi^b_2$ av. |
|---|---|---|---|---|
| 200 | 3.08 | 0.309 | 2.14 | 0.27 |
| 140 | 2.10 | 0.291 | | |
| 65 | 1.80 | 0.280 | | |
| 40 | 1.57 | 0.198 | | |

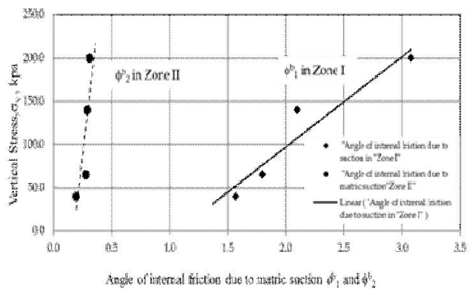



Figure -8.Variation of angle of internal friction due to matric suction $\phi^{b}_{1}$, and $\phi^{b}_{2}$ with Vertical stress

Figure -9 explains the relation between the shear strength and vertical stress determined from direct shear test results at certain levels of matric suctions. The figure shows that the effective internal friction angle has a values more than zero and that, values of effective cohesion are mainly depends on the matric suction values in unsaturated clay. The values of angle of internal friction and cohesion inferred from figure-10 presented in table 3and plotted in figure 10 and 11.

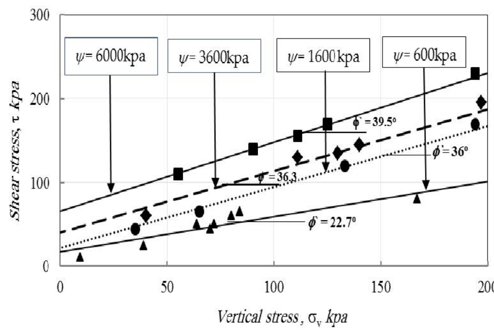



Figure -9. Shear Strength Variation with Net Vertical Stress at different Values of Matric Suction

Table- 3 Cohesion and Effective Internal Angle of Friction

| Ψ (kpa) | C`(kpa) | ϕ` (deg.) | $\phi_{av}$`(deg.) |
|---|---|---|---|
| 6000 | 66 | 39.5 | 33.63 |
| 3600 | 40.56 | 36.3 | |
| 1600 | 22 | 36.0 | |
| 600 | 17 | 22.7 | |

Figure -10 and table-3 illustrate the variation of eefective cohrsion of unsaturated clay with vertical stress $\sigma_v$ .it observef from tesults that incrasing vertical stresess causes increasing of effective cohesion at all values of matric suction.

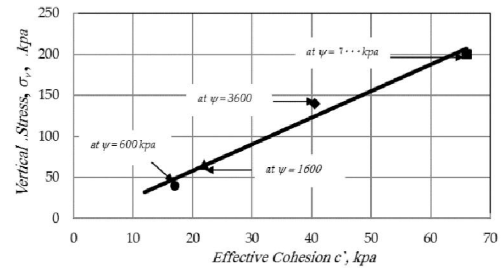



Figure- 10 Variation of Effective cohesion c` with vertical Stress $\sigma_v$

Figure -11 and table-3 explain the variation of efective cangle of internal friction of unsaturated clay with vertical stress $\sigma_v$ . It observed from tesults that incrasing vertical stresess causes increasing of effective angle of inernal frictionat all values of matric suction.


Figure- 11 Variation of angle of internal friction ϕ` with Vertical Stress $\sigma_v$

where: $\tau_{ff}$ = shear stress on the failure plane at failure,

Data presented in figure -6 shows the nonlinearity of the failure envelope for the relation between unsaturated shear strength and matric suction of MDNC. Figures -7 and 8 appears that the failure envelope has point of inflection around the matric suction at water content equal to the plastic limit. Two linear equation was suggested in two zones. So, as shown in table-2, two groups of rate of increasing matric suction are presented. Each group can generate one average value for each zone. In zone I, first average angle of internal friction due to matric suction can be represented by $\phi^{b}_{1av}$ and in zone II will be presented by$\phi^{b}_{2av}$ .

Design-Expert® software employs least square method (LSM) which is a multiple regression technique used to fit a mathematical model to a set of experimental data and generating the lowest residual using the Response Surface Methodology (RSM), two equations for evaluate the shear strength of unsaturated clay was deduced. The equations contains two variable parameters ( $_v$ and ψ) which mainly have the main impact on shear strength of unsaturated clay. The program used the actual results from direct shear box to fix two equations for calculate the unsaturated shear strength.

With the aid of the program and using the actual data results, first equation toke the following form:

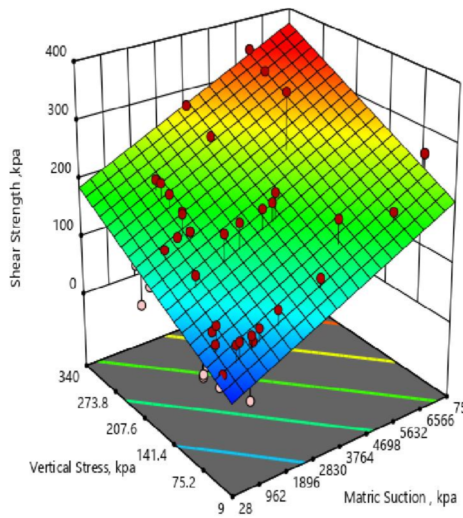
$\tau_{1un.} = 13.0 + 0.6 (\sigma_v) + 0.025(\psi)$ Zone I from $WC<LL>PL$ (2)

With the interpretation of soil mechanics concept equation (2) will take the following form:

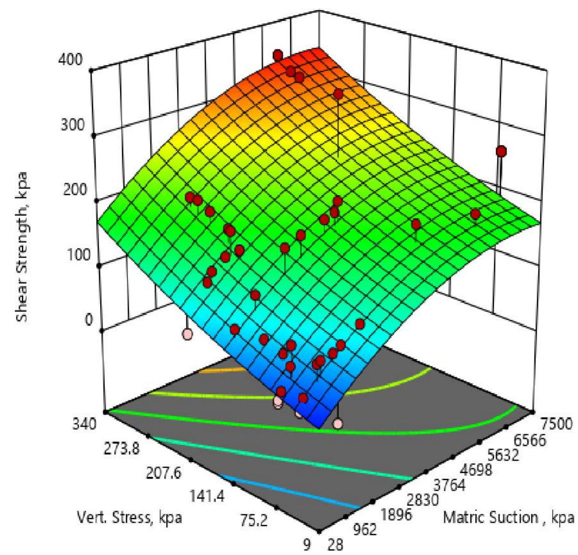
$\tau_{1un} = 1.5\, c` + (\sigma_v) \tan \phi`_{av.} + 1.5\, (\psi) \tan\phi^{b}_{1av.}$ Zone I from $WC < LL > PL$ (3)

Equation (3) will be valid in the stage (I) from water content less than the liquid limit till water content of clay equal the plastic limit. Equation (3) can be illustrated in figure-12 (three models, linear, quadratic and cubic).

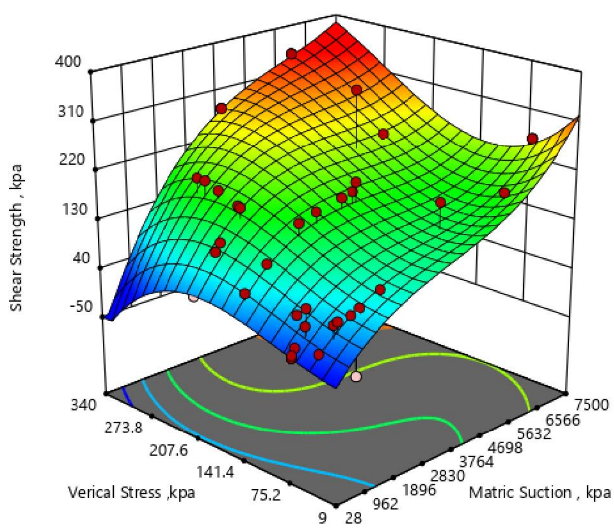
Figure -12 presents beside to the linear model, other two models to explain the 3D graph in case of using quadratic model or Quebec model. In this paper, equation (3) are presented by the first linear model.




First model ,Linear Equation ( $R^2$= 0.866)




Second model, Quadratic Equation ( $R^2$= 0.882)




Third model ,Qubic Equation ( $R^2$= 0.913)

Figure- 12 Shear Strength of Unsaturated Clay Zone(I)

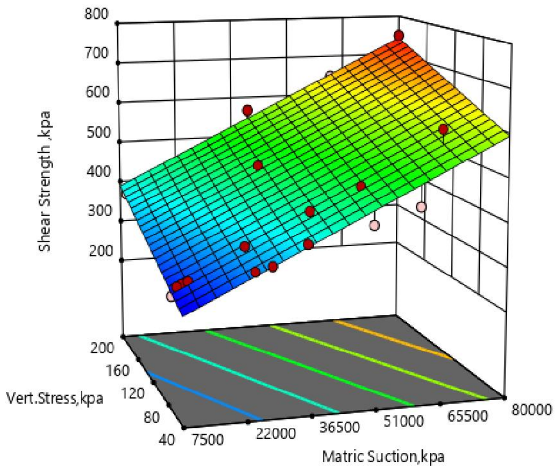
In the second stage which cover the domain of water content equal the plastic limit till more than water content more than the shrinkage limit, shear strength of unsaturated clay can represent by the following equation:

$\tau_{2unsat} = 171.35334 + 0.959675(\sigma_v) + 0.004771(\psi_2)$ .Zone II, (WC<PL) (4)

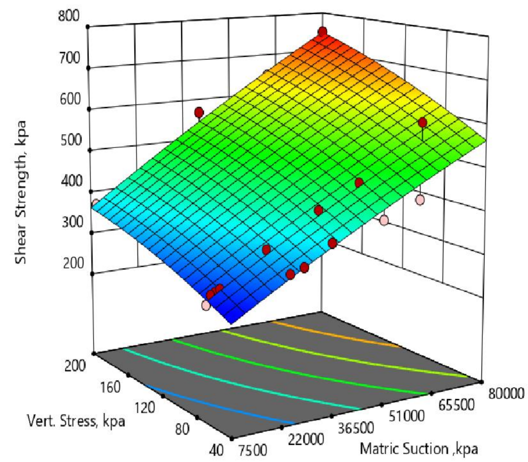
Using the same concept equation (4) can be take the soil mechanics form to be as the following:

$\tau_{2unsat.} = 20\ c` + 1.5\ (\sigma_v)\ \tan\phi`_{av} + (\psi_2)\ \tan\phi^b_{2av\ldots}$ Zone II, WC<PL) (5)

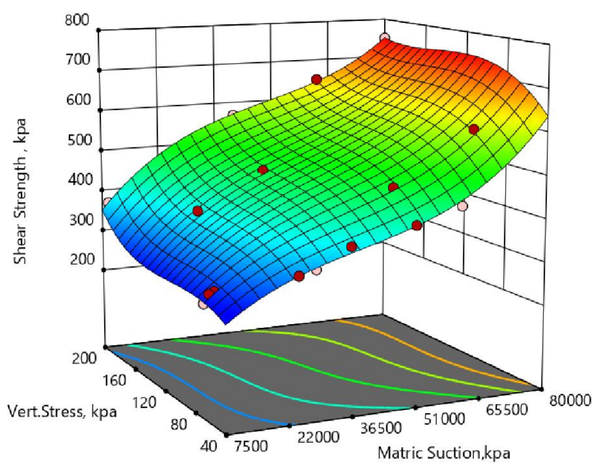
Figure- 13 illustrates Equation (5) with the linear model and quadratic model and qubic graph are illustrated in the figure.




First model, Linear Equation ( $R^2 = 0.982$)




Second model, Quadratic Equation ( $R^2 = 0.986$)




Third model ,Qubic Equation ( $R^2 = 0.998$)

Figure- 13 Shear Strength of Unsaturated Clay Zone(II)

## 4. Conclusions

The following conclusion can be made:

C, $\sigma$, $\phi$ are common shear parameters affect shear strength of saturated and unsaturated tested soil, while $\phi^b$ and $\psi$ only mainly affect unsaturated soil.

Rate of increase of shear strength of unsaturated clay ($\phi^b_1$) changes with average rate $2.63^0$ through zone (I) which start from water content of clay equal to liquid limit till plastic limit state of clay. On the other hand, in zone ( II ) which start at water content of clay equal to plastic limit state until after shrinkage limit state, the rate of increasing ($\phi^b_1$) shear strength of the same unsaturated clay goes with average rate ($\phi^b_2$) $0.28^o$ which less than the rate of change in the first zone ( I ).

To predict equation of shear strength of unsaturated clay, result of eighty clay samples in direct shear apparatus with aid of response surface methodology (RSM) program was used to predict that equation.

The research concluded that the undrained internal friction angle of research experimental results $\phi_u$ show that it has a value of $22^0$ at matric suction ($\psi$ = 600 kpa ) and $39.5^0$ at higher levels of matric suction ($\psi$ =6000 kpa). Four values of effective angle of internal friction was presented in Table-3.

Equation of **Fredlund et al. (1978**) deal with the unsaturated shear strength parameter ($\phi^b$) as a constant value, but results from the experimental research program insured that it has a value ranges from $0.198^o$ at high levels of suction and $3.08^o$ at the low values of suction. Which mean that ($\phi^b$) value changes with the increasing of amount of matric suction ($\psi$).

For MDN clay studied, the unsaturated shear strength according to research results is given as :

$\tau_{1unsat} = 1.5\ c` + (\sigma_v)\tan\phi`_{av.} + 1.5\ (\psi)\tan\phi^b_{1av.}$ Zone I from (WC < LL > PL)

$\tau_{2unsat.} = 20\ c` + 1.5\ (\sigma_v)\tan\phi`_{av.} + (\psi_2)\tan\phi^b_{2av.}$ Zone II, from (WC<PL)

Where :c`, $\phi`_{av}$ are the effective cohesion at zero suction and average effective internal friction angle of clay within the four values of suction which 6000,3600,1600 and 600 kpa. .

$\phi^b_{1av.}$ is the average internal friction angle due to matric suction in zone I.

$\phi^b_{2av.}$ is the average internal friction angle due to matric suction in zone II.

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