Laboratory determination and model prediction of the characteristics of the expansive soil in the new administrative capital city of Egypt

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ABSTRACT: Expansive soils are globally problematic geomaterials known for their high swell properties and low strength behavior. Precise determination of the swell parameters is required for the proper design of structures on expansive soils. The presented lab-based experimental study assesses fundamental swell properties of undisturbed and remolded samples of the expansive soil taken from the new administrative capital city of Egypt. The laboratory investigation is completed by estimating the swell characteristics of the tested soil using empirical swell prediction models based on laboratory index properties, including water content, density, moisture, clay minerals content, and non-expansive materials content. Interpretation of the results obtained reveals a significant difference between the swell characteristics of the undisturbed and remolded soil samples. The study shows that prediction models tested yielded swell characteristics that are acceptable within the standard error limits.

Keywords: Expansive soil, swelling parameters, different pressure method, Consolidometer method, constant volume method, Huger-Amber method, free swell index

1 INTRODUCTION

Expansive soils have an unusual volume variation behavior, swelling in wet conditions and shrinking in desiccated conditions. These soils contain swelling clay minerals, which may attract and absorb large quantities of water (Fattah et al., 2010; Bardanis and Grifiza, 2016; Abbas et al., 2022). Volumetric changes in these soils cause cyclic swell and shrinkage movements, resulting in squeaky damage to structures built above them (Nelson and Miller, 1997; El-Kasaby et al., 2019). These soils appear generally to have moderate to high plasticity, low to moderate strength, and high swell and shrinkage properties (Holtz and Gibbs 1956). Expansive soils are formed from mafic igneous rocks, metamorphic gneiss rocks, calcareous materials, basalts, and carboniferous shales through processes of mechanical disintegration and chemical decomposition (Murthy et al., 1982; Ahmad, 1996; Mermut et al. 1996; Gidigasu & Gawu, 2013; Uge, 2016; and Rao, 2023).

The distribution of expansive soils is determined by geological history, sedimentation, and local climatic conditions. Their occurrence depends on geology, climate, hydrology, geomorphology, and vegetation (Nelson et al., 2019). Egypt has several sites with swelling soils, including Nasr City, Cairo-Suez Road, El-Fayoum, Kom Ombo, Aswan, New Cairo, Madinty City, AlShrouk City, and the New Administrative Capital City (El-Kasaby et al., 2019).

Soil classification is a systematic approach to classifying soils based on their potential engineering behavior. Several soil classification systems, including the Casagrande unified soil classification system (USCS) and the American Association of State Highway and Transportation

Officials (AASHTO) system, are used in civil engineering practice (Sridharan & Prakash, 2000;2016; Daryati et al.,2019). Using any showing classification system, soil properties and indices such as liquid limit, shrinkage limit, particle size composition, activity, free swell index (FSI), plasticity index, shrinkage index, and other parameters can be used to estimate the swell parameters and classify the swelling degree of the soils (Sridharan & Prakash, 2016).

The basic characteristics of expansive soils are grouped into two categories: chemical properties and physical properties; according to these characteristics, expansive soil could be evaluated for its degree of swelling, and the pressure of swelling it may develop. Chemical and physical tests comprise particle size distribution (Sieve analysis – Hydrometer), Atterberg limits (Liquid Limit – Plastic Limit – Shrinkage Limit), water content, specific gravity, bulk density, free swell index (FSI), pH value, and chemical elemental composition. (El-Kasaby et.al, 2019). Engineering properties are indicated by the compaction and swelling parameters that could be determined from proctor test methods and different odometer test methods. According to these soil properties, the main swell problem will be assessed, and the effective actions to solve it could be designed appropriately.

The preliminary properties indicating the expansive character of the soil are medium to high free swell index (60% - 300%), low water content (5% - 25%) in dry climatic conditions, high liquid limit and plasticity index (50% - 150% and 30% - 80%), low shrinkage limit (between 10% and 12%), medium-specific gravity (2.52 – 2.87), Medium bulk unit weight (1.49 – 1.96) Mg/m^3, Medium dry unit weight (1.34- 1.83) Mg/m^3 and Acidity pH (5.5 -7.5). The engineering characteristics of expansive swollen soil are compaction parameters and swelling parameters that have high compressibility, " high swell potential (more than 90% of the swelling occurs during the early few hours or days)", and low bearing capacity "low strength (swell pressure S.P=10-200kPa)".

The swelling pressure is defined as the minimum pressure that should be applied to the soil sample to maintain constant soil volume or to restore the soil's original void ratio of the sample that has already swollen (Shuai, 1998). In the laboratory, an odometer could be used to measure the swelling pressure and potential. These methods were described in various standards and previous studies, which defined swelling pressure and swelling potential based on different measuring procedures. These methods include the constant volume method, restricted swell test, swell-consolidation test, double oedometer test, zero swell test, flexible oedometer test, Huder & Amberg (1970) method, different pressure method, Henke et al. (1975) method, Kirschke (1987) and Kirschke et al. (1991) method, and powder swelling test (Thuro - 1993 method).

Several studies have, on the other hand, proposed and discussed empirical models used to estimate the swelling parameters "swell pressure and swell potential" on the basis of some simple soil index parameters (Atterberg limits, clay fraction, bulk density, natural water content, and water content after 24 hours) (Al-Rawas & Goosen, 2006). The swelling parameters estimated using empirical equations should be nearly identical to the experimental swelling parameters. In this study, laboratory tests were carried out to assess the characteristics of expansive soil taken from Egypt's new Administrative Capital city region.

The purpose of this paper is to determine the main characteristics and swelling parameters for the expansive soil in the city of New Administrative Capital, which include the swelling pressure and potential of undisturbed and remolded samples. The swelling potential and pressure are estimated using prediction model equations. The expansive soil characteristics of the study site are assessed, and the usefulness of empirical models for estimating the swelling parameters is tested.

2 EXPERIMENTAL PROGRAM

Before performing laboratory tests, one can determine whether the soil is expansive or not by finger feeling. Laboratory tests were used in this study to determine the geotechnical index and mechanical properties of expansive soil samples taken from Egypt's new administrative capital. Empirical models were used to estimate the swelling parameters of the study soils. The location of the study area where the expansive soil samples were taken is shown in Figure 1. Forty-three undistributed samples were obtained from four zones distributed around the new administrative capital. The remolded samples were obtained by crushing undisturbed samples and compacting the homogenously mixed material. The difference between the swell behavior of undistributed and remolded samples will be highlighted. The results of laboratory tests and empirical equations are compared.

The laboratory tests are divided into three categories: chemical properties, such as pH tests and chemical composition. Physical properties include particle size distribution (Sieve analysis - hydrometer), Atterberg limits (liquid limit, plastic limit), water content, water content after 24 hours, specific gravity, bulk density, and free swell index (FSI). The third category includes mechanical properties like swell pressure and swell potential. The mechanical tests include modified proctor compaction tests and swelling parameter tests, which will be performed with the odometer device. There are several methods for determining swell pressure and strain, including the constant volume method (CVM), the Consolidometer Method (COM), the Different Pressure Method (DPM), and the Huder Amber Method (HAM).

The empirical model equations are divided by the parameters that have been determined. Equations 1 to 14 used to estimate the swell characteristics are presented in Table 1. These models are used to estimate the swelling pressure of the remolded sample (SWR), the swelling pressure of the undisturbed sample (SWUD), the swelling potential of the remolded sample (SPR), and the swelling potential of the undisturbed sample (SPUD) (Equations 1-4). In addition to the empirical equation shown, another equation uses the liquid limit, plasticity index, and clay fraction to predict swell potential. The empirical model for each parameter is shown in (Equations 5-14).

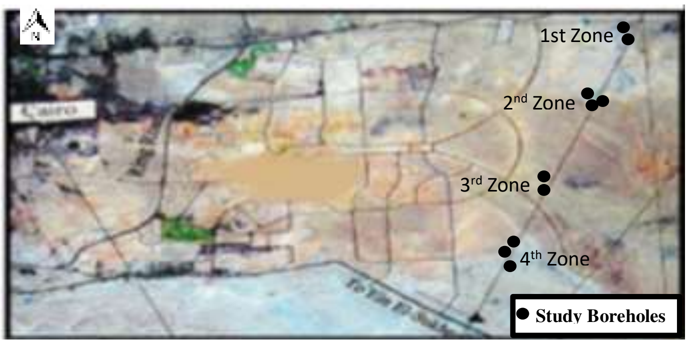

Figure 1 Location of study soils

Table 1 Empirical Equation models

$SWUD = -637.2+12.8W_{max24}+0.012LL$	=====> coefficient of correlation (r - 0.86)	1
$SWR = -923.4+26.5LL-9.8PL$	=====> coefficient of correlation (r - 0.81)	2
$SPUD = -18.13+0.4LL+0.13PL$	=====> coefficient of correlation (r - 0.79)	3
$SPR = -21.8+0.62LL-0.08PL$	=====> coefficient of correlation (r - 0.82)	4
Plasticity Index (PI)	$SP(\%) = 1.035(PI)^{0.816}$	5
	$SP(\%) = 10.106e^{0.056(PI)}$	6
	$SP(\%) = 2.231 + 0.453(PI)$	7
Clay Fraction (CF)	$SP(\%) = 2.919(CF)^{0.535}$	8
	$SP(\%) = 11.418e^{0.0135(CF)}$	9
	$SP(\%) = 7.518 + 0.323(CF)$	10
Liquid Limit (LL)	$SP(\%) = 0.109(LL)^{1.236}$	11
	$SP(\%) = 6.871e^{0.0149(LL)}$	12
	$SP(\%) = 0.393(LL) - 6.298$	13
Multi-linear regression:	$SP(\%) = 0.171CF + 0.0012LL + 0.409PI - 1.869$	14

3 RESULTS AND DISCUSSION

The results of the experimental programme were analyzed for undisturbed expansive soils and remolded soils compacted at each zone's Proctor conditions. In addition to the experimental programme, the empirical program's results were examined.

3.1 *Preliminary properties*

The physical and chemical characteristics of expansive study soil were determined using ASTM, IS standard, and ECP 202, as shown in Table 2 and Figure 2. The soil classification is shown in Figure 3, which shows that the study soil is a clay of high plasticity (CH). These soils are classified as sand with clay soil or sandy clay.

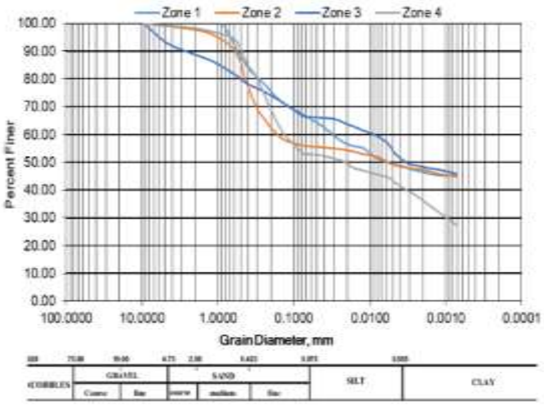

Figure 2 Grain Size Distribution

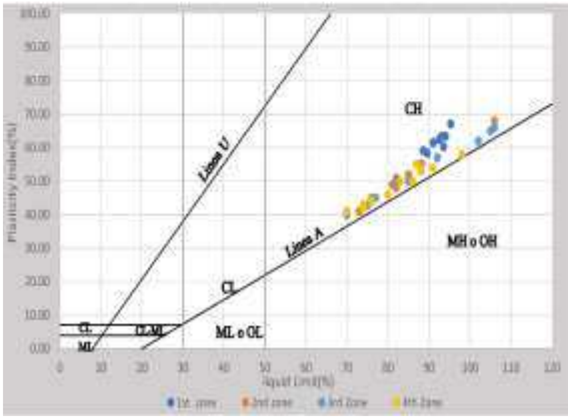

Figure 3 USCS Classification

Table 2 Preliminary properties

Zone	First Zone	Second Zone	Third zone	Forth Zone	Average
W_c (%)	15.91	24.64	23.10	19.33	20.75
LL (%)	93.17	82.09	88.20	82.92	86.59
PL (%)	31.30	32.09	35.10	33.75	33.20
PI (%)	61.87	49.45	53.10	49.17	53.40
CI (%)	1.25	1.16	1.23	1.29	1.23
FSI (%)	80.79	138.18	127.50	116.25	115.68
γ_s (kN/m^3)	19.50	18.08	17.75	18.01	18.54
γ_d (kN/m^3)	17.02	14.54	13.96	14.44	14.99
G_s (-)	2.53	2.74	2.73	2.74	2.69
CF (%)	49	48	55	43	48.75
A (%)	1.26	1.03	097	1.14	1.10
W_{max24}(%)	82.45	97.63	96.80	96.00	93.22
pH	7.60	7.30	7.40	7.35	7.41

The study examined four expansive soil zones: (W_n), ($W_{max24hr}$), and (γ_s) with values ranging from 8.25 to 28.0 percent, 82.45 to 99.55 percent, and 17.17 to 19.80 kN/m^3, respectively. (LL), (PL), (PI), and (CI) varied from 70 to 106 percent, 28.26 to 40 percent, 40 to 68 percent, and 1.07 to 1.38, respectively. (G_s) ranged from 2.5 to 2.7, which is roughly equivalent to around 2.69. (CF) ranges from 43 to 55 percent. Silt particles range from 8 to 19%, whereas sand particles range from 32 to 47%. The FSI ranged from 60 to 210 percent, or approximately 116%. (A) ranges from 0.73 to 1.42, with an average value of 1.10.

3.2 *Mechanical properties*

Compaction characteristics of expansive study soil were determined using the modified proctor method; the swelling parameters were also established using HAM, CVM, COM, and DPM. The compaction parameters are used to prepare the remolded samples, which are used to determine the swelling parameters for comparison with undisturbed soil samples. The CVM and COM are used to compare between remolded and undistributed samples. Four methods are used to compare between experimental and empirical results. The compaction parameters are shown in Figure 4 and Table 3; the swelling parameters are shown in Figures 5 – 10.

Table 3 Compaction Properties

Zone	Average of max. dry unit weight (kN/m^3)	Average of max. optimum water content (%)	Average of all – dry unit weight (kN/m^3)	Average of all – optimum water content (%)
1	17.82	12.00	16.453	17.063
2	16.45	18.50		
3	14.82	19.25		
4	16.72	18.50		

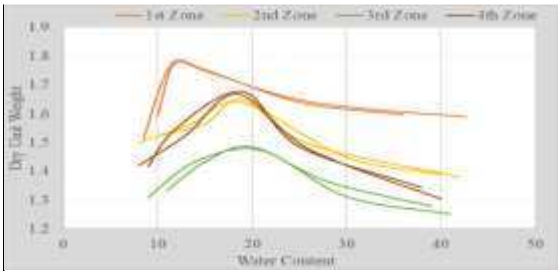

Figure 4 Compaction Curves

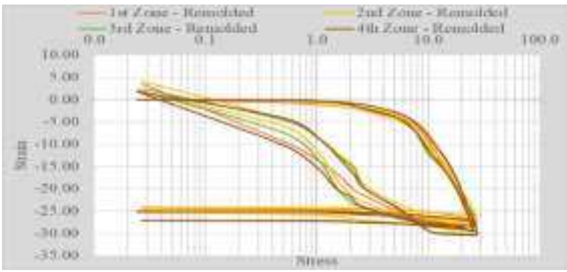

Figure 5 (HAM) – Remolded

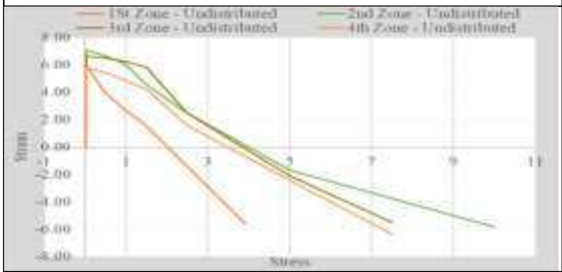

Figure 6 (CVM) – Undistributed

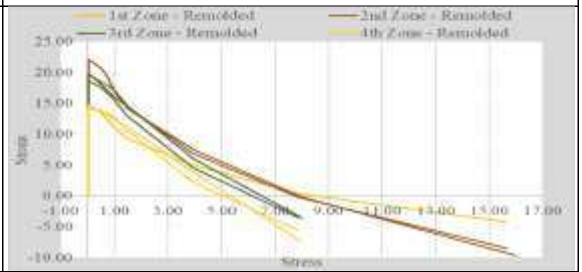

Figure 7 (CVM) – Remolded

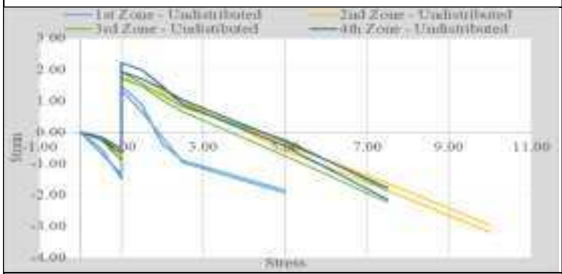

Figure 8 (COM) – Undistributed

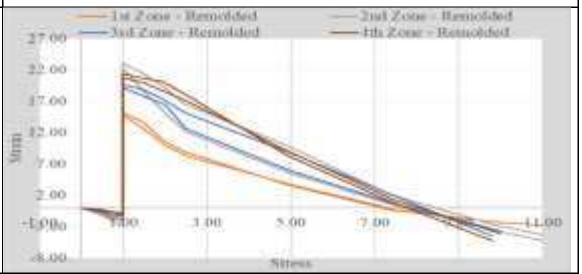

Figure 9 (COM) – Remolded

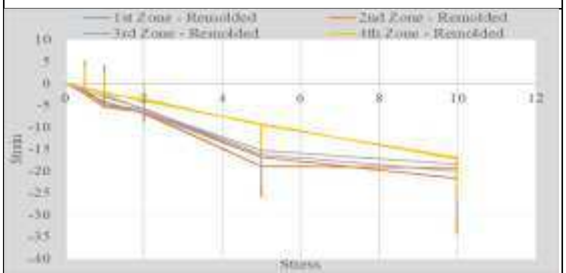

Figure 10 (DPM) - Remolded

The OMC and γ_{dmax} values varied from 12 to 19.25 percent and 1.482 to 1.782 gm/cm^3, respectively. The swelling pressure (SP) for undistributed samples using COM and CVM ranged from 3.62 to 5.95 kg/cm^2 and 2.05 to 4.0 kg/cm^2, respectively, while the swell potential ranged from 2.56 to 2.82 percent and 5.83 to 7.08 percent. The swelling parameters of remolded samples that were tested with COM, CVM, HAM, and DPM ranged from 1.75 to 12.0 kg/cm^2 and 14.23 to 32.65 percent, respectively.

3.3 *Empirical swelling parameters*

The swelling parameters determined from the previous equation are compared with those determined from the four methods of the odometer device test. The parameters of empirical equations are shown in Table 4-6.

Table 4 Swell Pressure and Potential

Zone	SWR (kPa)	SWUD (kPa)	SPR (%)	SPUD (%)
1	1003.51	360.58	27.44	19.07
2	755.06	527.59	21.72	15.62
3	866.64	518.49	24.66	17.86
4	763.94	509.63	22.06	16.00
Average	847.29	479.07	23.97	17.13

Table 5 Swell Potential

Zone	S.P by P.I (%)		
	Equ.5	Equ.6	Equ.7
1	29.97	330.12	30.26
2	24.93	177.89	24.63
3	26.41	222.53	26.29
4	24.83	166.27	24.50
Average	26.53	224.20	26.42

Table 6 Swell Potential

Zone	S.P by CF (%)			SP by LL (%)			SP by PI, CF, LL (%)
	Equ.8	Equ.9	Equ.10	Equ.11	Equ.12	Equ.13	Equ.14
1	23.41	22.12	23.35	29.62	27.61	30.32	31.93
2	23.16	21.83	23.02	25.36	23.57	25.96	26.66
3	24.91	23.99	25.28	27.75	26.00	28.36	29.36
4	21.83	20.40	21.41	25.67	23.80	26.29	25.69
Average	23.33	22.09	23.26	27.10	25.24	27.73	28.41

4 CONCLUSIONS

The study examined four expansive soil zones; these soils are classified as "CH," or high plasticity clay, and medium to highly active. The swell potential of this soil is medium to high and critical problematic soil, and the free swell index is between 50 and 200 %. The undisturbed and remolded expansive characteristics show the difference between swell pressure and potential that the remolded swell pressure increases the undistributed swell pressure with a range from 1.46 to 2.60 times. Additionally, the remolded swell potential increases the undistributed swell potential with a range from 2.4 to 10.16 times. DPM is given the smallest remolded swelling pressure. The empirical equations' results are within the experimental range. Therefore, these equations could be applied. The equations for swelling pressure "SWR - SWUD" are useful for determining undistributed and remolded samples. The empirical equations for swelling potential "SPR - SPUD" are valid with standard acceptable error.

References

Abbas, M.F., Shaker, A.A., & Al-Shamrani, M.A. 2022. Hydraulic and volume change behaviors of compacted highly expansive soil under cyclic wetting and drying. *Journal of Rock Mechanics and Geotechnical Engineering, 15(2), 486-499.*

Ahmad, N. 1996. *Occurrence and distribution of Vertisols*. In: Ahmad N, Mermut A (eds) Vertisols and technologies for their management. Elsevier, Amsterdam, pp 1–41

Al-Rawas, A.A. & Goosen, M.F. 2006. *Expansive Soils - Recent advances in characterization and treatment*, the Taylor & Francis e-Library.

Bardanis, M., Grifiza, S., 2016. Swelling and collapse of compacted soils to be used as earth dam cores. In: *Proceedings of the 3rd European Conference on Unsaturated Soils*.

Daryati, D., Widiasanti, I., Septiandini, E., Ramadhan, M. A., Sambowo, K. A., & Purnomo, A. 2019. Soil characteristics analysis based on the unified soil classification system. *In Journal of Physics: Conference Series (Vol. 1402, No. 2, p. 022028). IOP Publishing.*

El-Kasaby, E.A., Easa, A.A., Abd-Elmagied, M.F., & El-Abd, M.G. 2019. Experimental study of expansive soil in new urban areas surrounding Cairo. *ERJ. Engineering Research Journal*, *42*(1), 49-59.

Fattah, M.Y., Salman, F.A., & Nareeman, B.J. 2010. A treatment of expansive soil using different additives. *Acta Montanistica Slovaca*, *15*(4), 290-297.

Gidigasu, S.R., & Gawu, S.K. 2013. The mode of formation, nature and geotechnical characteristics of black cotton soils-a review. *Sci Res Essays*, *1*, 377-390.

Henke, K.F., Kaiser, W., & Nagel, D. 1975. Geomechanische Untersuchungen im Gipskeuper. *Strassenbau und Strassenverkehrstechnik*, *184*, 149-169.

Holtz, W.G., & Gibbs, H.J. 1956. Engineering properties of expansive clays. *Transactions of the American Society of Civil Engineers, 121(1), 641-663.*

Huder, J., & Amberg, G. 1970. Quellung in mergel, opalinuston und anhydrit. *Schweizerische Bauzeitung= Revue polytechnique suisse,* 88(43), 975-980.

Kirschke, D. 1987. Laboratory and in situ swelling test for the Freudenstein tunnel. *Proc. 6th ICRM, Montreal,* 3, 1492-1496.

Kirschke, K., Kovári, K., & Prommersberger, G. 1991. Bemessungsgrundlagen und Konstruktion der Sohle des Freudensteintunnels. *Ingenieurbauwerke-DB Neubaustrecke Mannheim-Stuttgart: Der Freudensteintunnel*, *7*, 40-57.

Mermut A.R., Padmanabham F., Eswaran H., Dosog, G.S., 1996 Pedogenesis. In Ahmad N, Mermut A (eds) *Vertisols and technologies for their management. Elsevier, New York, pp 43–61*

Murthy, R.S., Bhattacharjee, J.C., Landey, R.J., & Pofali, R.M. 1982. Distribution, characteristics, and classification of Vertisols. *In Vertisols and rice soils of the tropics (Vol. 3, pp. 1-27). New Delhi, India:*

Nelson, J., & Miller, D.J. 1997. *Expansive soils: problems and practice in foundation and pavement engineering*. John Wiley & Sons.

Nelson, J.D., Garcia, D.C., Nelson E.J., & Chao K.C. 2019. A Case History of Structures Constructed on Expansive Soils. *Proceedings of the 16th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering, Taipei, Taiwan*.

Rao, S.M. 2023. Index Property to Characterize the Proportion of Primary Minerals Transforming to Clay Residues During Expansive Soil Formation. *Geotechnical and Geological Engineering, 41(1), 405-412*.

Shuai, F. 1998. *Simulation of swelling pressure measurements on expansive soils* (pp. 6716-6716). University of Saskatchewan.

Sridharan, A. and Prakash, K. 2016. Expansive soil characterization: an appraisal." *INAE Letters 1.*

Sridharan, A., & Prakash, K. 2000. Classification procedures for expansive soils. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering,* 143(4), 235-240.

Thuro, K. 1993. Der pulver-quellversuch-ein neuer quellhebungsversuch. *Geotechnik*, 16(3), 101-106.

Uge, B.U. 2016. Investigation on the Swelling characteristics and unsaturated shear strength of expansive soils from Arba Minch in Ethiopia. *Journal of Geotechnical and Transportation Engineering, 2(2), 51-61.*