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Predicting the Strength Properties of Swelling Clay

Omer S. M. Hamza [1], Magdi M. E. Zumrawi [2], Awad E. M. Mohamed[3]

[1]PhD Candidate, Civil Engineering Department, Faculty of Engineering, University of Khartoum, Sudan

[2] Civil Engineering Department, Faculty of Engineering, University of Khartoum, Sudan

[3] Building and Road Research Institute, University of Khartoum, Sudan

Abstract: ***This paper studies empirical correlation between expansive soil index properties and soil strength.Disturb soil samples from different areas in Sudan were collected to represent the most expansively soils in the country. The samples were collected from Al-Qadarif (S1), Wad Medani (S2) and Al-Giraif East in Khartoum (S3). The basic properties of the soil samples were measured. The three soils give high plasticity and very weak strength. The chemical analysis shown that S1 has the highest montmorillonite mineral than the other two soils. Therefore S1 is considered as the most expansively soil compared with the other soils. The consistency factor which was developed can be used to correlate the basic properties of the soil with the soilstrength. The consistency factor is a combination of the moisture content, dry density, void ratio, liquid limit and plasticity index. These parameters are combined in a way reflecting the influence of each of them on the soil property. The strength properties (CBR and UCS) were measured for the soil samples compacted at different moisture content and different dry densities.Very good linear relationships were developed between the consistency factor and the strength properties. The correlations developed were verified by using the data of this study and the data reported by some previous researchers. The developed correlation was plotted on Nomograph.***

Keywords: Consistency factor,strength, swelling, nomograph

1. Introduction

Some soils that were capable of supporting a load in a natural unsaturated state were observed to either expand or collapse when wetted. These soils did not conform to the classical theories of soil mechanics and geotechnical engineering, and more research began to focus on the behavior of unsaturated soils. Within the general category of unsaturated soils, the expansive soils posed the greatest problems, and created the most financial burden. In response to major infrastructure development in the late 1950s and 1960s there was an upswing in research regarding the identification of expansive soils and factors influencing their behavior.

The expansive soil by virtue of its mineralogical composition exhibits significant volume changes due to changes in its moisture content along with loosing strength and tend to be compressible.

The presence of montmorillonite clay in these soils imparts them high swell-shrink potentials, [1]. The swell-shrink behavior definitely influence the soil strength. Differential Thermal Analysis and X-ray diffraction pattern analysis have shown that montmorillonite mineral is predominant in expansive soil, [2]. Swelling soils are known by their very weak strength.

The swelling phenomenon is known to be function of two basic variables; the intrinsic soil properties and placement factors. The intrinsic soil properties are those related to the mineralogical composition of the clay fraction, soil gradation and its pore water chemistry. The placement factors are the density, water content and loading whereas the environmental factors are related to the increase and loss of water. Intrinsic swelling is the inherent expansiveness resulting from the intrinsic properties of a soil and the potential of a soil for swelling is explained by combination of the intrinsic soil properties and its placement and environmental conditions,[3].

An intrinsically high potential expansive soil would not swell if it is below the ground water level, or subjected to loads greater than or equal to its swelling pressure.

The classification of expansive soils is performed on the basis of its intrinsic expansiveness. The parameters used are therefore combination of intrinsic parameters such as Atterberg's limits, clay fraction, activity and shrinkage index, [4]. However, classifying the soils according to their swelling potential or predicting swell potential test parameter will necessitate using combination of intrinsic parameters and placement parameters.

2. Literature Survey

Many researchers were found that the initial soil state such as dry density, water content and void ratio greatly influence soil swelling and strength. [5]was found that the soil initial state and testing conditions greatly influenced the un-soaked CBR and shear strength. Also he proved that a direct linear relationship between swell percent, swelling pressure, un-soaked CBR or shear strength and the soil initial state.

The data reported by the previous researchers show that the swellingof this soil is influenced by the surcharge pressure imposed on the soil as well as the initial state of the soil as described by the dry density, water content and void ratio. On the other hand, the CBR and shear strength of this soil is greatly influenced by the initial dry density, water content and void ratio of the soil as well as the testing conditions, [5].

The factors which influence swelling pressure could be grouped into compositional intrinsic factors such as clay mineralogy, clay content, gradation and pore water chemistry; environmental or placement factors such as water content, density, soil structure, stress history and temperature and procedural factors such as size and shape of the tested specimen, its level of disturbance, methods of swell and load measurements, [4]. Previous studies haveshown that for a certain soil type, swelling pressure is function of dry density and initial moisture content [6].Analysis of the experimental results indicated that it is possible to combine the initial state parameters such as dry density, water content and void ratio in a way reflecting the influence of each of them on the swell percent, swelling pressure, un-soaked CBR and shear strength. Therefore a new concept was developed; this is called the initial state factor, [5].

Attempts have been made to predict swelling pressure and percentage swelling using a single factor that combines more than one soil intrinsic or placement parameter. [7] introduced the placement condition factor (F) which combines two placement parameters, dry density and moisture content and is defined as:

$$F = \frac{\gamma d}{mc} \ldots\ldots(1)$$

Where (γd) the dry density and (mc) is the water content. [7] applied (F) to swell percent data of compacted swelling soils from Sudan and found that (F) predicts very well the swell percent for the same soil.

[8] modified the placement factor (Fi) to a new one called the initial state factor,(Fi) and is defined by:

$$Fi = \frac{\gamma d}{\gamma w . mc . e} \ldots\ldots(2)$$

Where (γw) the density of water and (e) is the void ratio. A linear relationship was found between (Fi) and swelling pressure for the same soil, the coefficients of which depends on plasticity index and clay content. It is noted that the two factors (F) and(Fi) considered only placement parameters, i.e., moisture content, dry density and void ratio[9]. Several statistical multiple regression relationships using intrinsic and placement parameters were developed by[8] for the prediction of swelling pressure and California Bearing Ratio.

[10]was suggested that the initial state factor (Fi) was empirically formulated upon three liner relationships between swell percent vs. initial dry density, swell percent vs. moisture content and swell percent vs. void ratio depend on an experimental results. He was indicated a liner relationship between swell percent and initial dry density and between swell percent and moisture content for the same soil. [5]was indicated an inverse relationship between swell percent and void ratio of the same soil at the same moisture content.

A well-known consistency factor combining placement parameter (mc) and Atterberg's limit is the liquidity index (LI). Liquidity index is a good indicator of where the soil moisture content lies in relation to its Atterberg's limits and is defined as:

$$LI = \frac{mc - PL}{PI} \ldots\ldots(3)$$

The LI is negative when the moisture content is lower than the plastic limit and is zero when the moisture content equals to the plastic limit. A less often known consistency indicator is the consistency index, CI. This index is defined as:

$$CI = \frac{LL - mc}{PI} \ldots\ldots(4)$$

It is arithmetically 1-LI. The indicator CI is 1.0 when moisture content equals the plastic limit and zero when moisture content equals the liquid limit. It is noted that the consistency factors LI and CI do not include the dry density which is a major parameter affecting swelling. This study was performed to improve our understanding of the swelling behavior of expansive soils and to develop some models or factors which combine both soil placement conditions and soil intrinsic parameters for predicting swelling pressure.

The consistency factor of compacted soil was introduced by [7] and then modified by [8]. The consistency factor (Fc) is defined as a combination of the soil index parameters such as dry density (γd), moisture content (w), void ratio (e) and soil consistency index (CI) and can be expressed as:

$$Fc = \frac{\gamma d * CI}{\gamma w * e} \ldots\ldots(5)$$

The linear relationship exists between swell percent, swelling pressure, CBR or shear strength and soil state factors (Fi and Fc) can be of great use of in the characterization of the swelling and strength variation with water content and dry density of a given expansive soil, [11].

3. Materials and Methods of Testing

3.1 Soils Used

Disturb soil samples from different regions in Sudan were collected to represent the most expansively soils. The samples were collected from Al-Qadarif (**S1**), Wad Medani (**S2**) and Al-Giraif East in Khartoum (**S3**). The soil samples were taken from depth between 0.5 to 1m.

3.2 Specimen Preparation

The soils were initially air dried, crushed into small sizes and pulverized. The tested samples were prepared by sieving the soil through sieve No.4 (4.75mm). The fine materials passing sieve No.4 were used in the experimental work. The soil samples were oven dried at 105-110 C for 24 hours.

250 gm of each soil were subjected to further pulverization, packed and sent for the X-ray diffraction (XRD) tests. Then the remaining of each soil were divided into two quantities, the first quantities were assigned for the basic propertiesand strength tests while the second quantities were compacted at different dry densities and different moisture contents for further testing.

The different moisture contents were obtained by moistening the soils to 7.5, 10, 15, 20, 25, 30 and 40% by weight. While the different dry densities were obtained by compacting the soils in the standard Proctor mold using the standard Proctor hammer. The soils hammered 10, 30 and 65 blows. The compaction was done to soils moistened at each moisture content recorded. The tests results were analyzed and discussed.

3.3 Testing Procedure

Physical properties of the three soils were measured as well asstrength characteristics. The tests include gradation, consistency limits, specific gravity and compaction. The strength tests include CBR and UCS. The tests were conducted according to the standard procedures of BS (1990), [12]. Then the three soils were mixed with distilled water to different initial moisture contents and manually compacted to different dry densities. The strength characteristics of the compacted samples were measured according to the standard procedures of BS (1990), [12].

4. Results and Analysis

4.1 Basic Properties

The basic properties of the three soils were measured as depicted in Table 4.1. Gradation, Specific gravity, consistency limits, compaction parameters, strength characteristics and chemical composition.

Depend on the gradation analysis performed, the three soils contain great amount of clay fraction. The consistency tests showed that the three soils demonstrated high plasticity, so they were classified as highly expansive soils. The micro fabric test results shown that the three soils contain montmorillonite mineral more than 70%. The results indicated that soil S1 has the highest montmorillonite than the other two soils. Therefore S1 is considered as the most expansively soil compared with the other soils. The strength characteristics tests showed that the three soils give very weak strength. S3 gives the lowest CBR and highest UCS valuecompared with the other two. While soil S2 gives the highest CBR and lowest UCS values. Finally the compaction characteristics that shown in the Table evident the tested soils are likely perform very low strength.

Table 4.1: Properties of the studied soils

Property	*S1*	*S2*	*S3*
Gravel (%)	2.8	1.8	0.5
Sand (%)	5	10.4	3.4
Silt (%)	16.3	14.1	21.9
Clay (%)	75.9	73.7	74.3
GS	2.712	2.711	2.792
LL (%)	80	72	106
PL (%)	32	30	28
PI (%)	48	42	78
Kaolinite (%)	12.3	42.5	22.9
Illite (%)	1.3	1.3	0.8
Montmorillonite (%)	86.2	55.4	75.9
Chlorite (%)	0.2	0.5	0.3
Property	*S1*	*S2*	*S3*
OMC (%)	27.4	27	23.3
MDD (KN/m^3)	13.8	14.2	15
CBR (%)	1.1	1.6	0.9
UCS (Kpa)	477	274	460

4.2 Development of Linear Relationship

To develop and verify the linear relationships between the consistency factor (F_c) which introduced in Equations(5) and CBR as well as UCS, values of CBR and UCS of the three soils were measured. The tests results obtained were analyzed as given in Table 4.2. The relationship of the analyzed data for the three soils are shown in Figures 4.1 and 4.2. The plot in this Figures and the value of the correlation coefficient, R^2 have clearly shown good linear relationships between the soil strength and the consistency factor (F_c) for the data analyzed. The straight lines shown in the plots of Figures 4.1 to 4.4 can be expressed as:

$$CBR = M\,(F_c - F_0)\ldots\ldots\ldots\ldots (6)$$

$$UCS = M\,(F_c - F_0)\ldots\ldots\ldots\ldots (7)$$

Where: F_0 is the value of F_c at zero Swelling. And M is the gradient of the straight line. The values of M, F_0 and R^2 for the three soils which obtained from the plot of Figures 4.1 and 4.2 are given in Table 4.3

Table 4.3: Values of M, F_0 and R^2 of the three soils

Property		*S1*	*S2*	*S3*
CBR	M	20.7	18.0	17.7
	F_0	0.74	0.83	0.87
	R^2	0.92	0.88	0.88
UCS	M	175	384	210
	F_0	0.51	0.72	0.38
	R^2	0.90	0.87	0.98

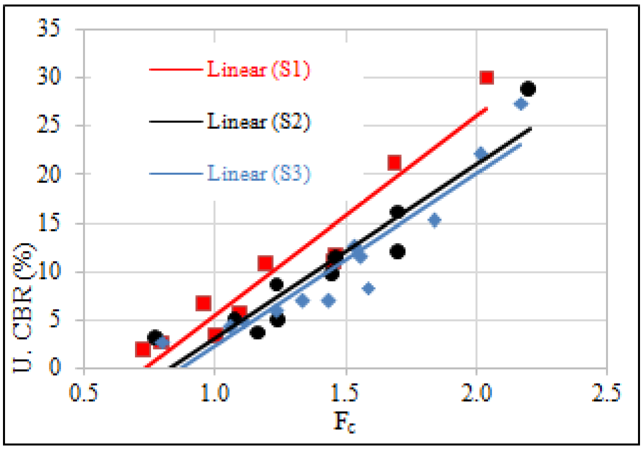

Figure 4.1: CBR versus F_c of the three soils

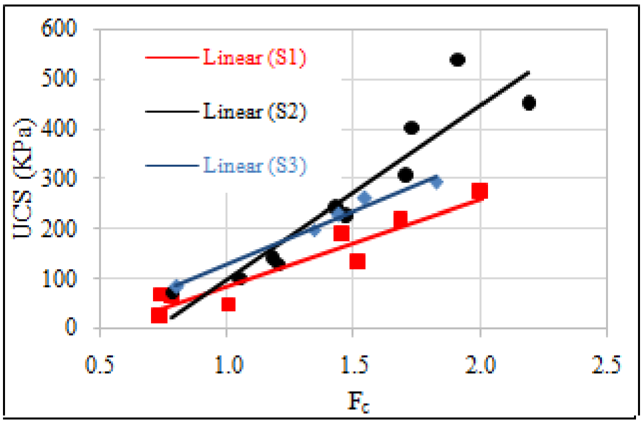

Figure 4.2: UCS versus F_c of the three soil

Table 4.2: The strength characteristics measured values of the three soils under different placement conditions

Soil	*m.c (%)*	$\Upsilon_d (gm/cm^3)$	*e*	*CI*	F_c	*Measured CBR (%)*	*Measured UCS (Kpa)*
S1	14.2	1.397	0.9	1.4	2.0	30.7	273
	14.8	1.271	1.1	1.3	1.5	*	132
	15.3	1.256	1.2	1.4	1.5	11.5	*
	15.8	1.136	1.4	1.4	1.1	5.8	*
	18.9	1.280	1.1	1.3	1.5	10.9	190
	19.5	1.000	1.7	1.3	0.7	*	25
	19.8	1.107	1.5	1.3	1.0	6.6	*
	20.4	1.356	1.0	1.3	1.7	21.0	217
	24.2	1.233	1.2	1.2	1.2	10.7	*
	24.7	1.163	1.3	1.2	1.0	3.3	50
	29.3	1.107	1.5	1.1	0.8	2.7	63
	39.4	1.156	1.4	0.9	0.7	1.8	71
S2	14.7	1.440	0.88	1.4	2.2	28.7	*
	14.9	1.438	0.9	1.4	2.2	*	451
	15.0	1.188	1.28	1.4	1.2	4.9	*
	19.4	1.369	1.0	1.2	1.7	*	403
	19.7	1.200	1.3	1.2	1.2	*	140
	19.8	1.366	1.0	1.2	1.7	11.9	*
	19.9	1.199	1.3	1.2	1.2	3.8	*
	20.0	1.420	0.9	1.2	1.9	*	540
	24.1	1.198	1.3	1.1	1.1	5.2	*
	24.5	1.193	1.3	1.1	1.1	*	102
	24.6	1.337	1.0	1.1	1.5	9.6	226
	24.8	1.411	0.9	1.1	1.7	16.2	306
	29.0	1.386	1.0	1.0	1.5	11.3	*
	29.2	1.309	1.1	1.0	1.2	8.7	*
	29.3	1.110	1.4	1.0	0.8	3.0	74
	29.4	1.378	1.0	1.0	1.4	*	241
	29.8	1.303	1.0	1.0	1.2	*	131
S3	14.3	1.528	0.8	1.2	2.2	27.3	*
	14.8	1.269	1.2	1.2	1.2	5.9	*
	15.1	1.377	1.0	1.2	1.6	11.5	*
	19.2	1.397	1.0	1.1	1.5	*	261
	19.4	1.244	1.2	1.1	1.1	4.8	*
	19.5	1.521	0.8	1.1	2.0	22.1	*
	19.7	1.394	1.0	1.1	1.5	12.5	*
	24.5	1.505	0.9	1.0	1.8	15.2	*
	24.6	1.436	0.9	1.0	1.6	8.3	*
	24.8	1.254	1.2	1.0	1.1	4.3	*
	24.9	1.504	0.9	1.0	1.8	*	292
	29.4	1.384	1.0	1.0	1.3	7.0	*
	29.5	1.419	1.0	1.0	1.4	7.0	229
	29.7	1.388	1.0	1.0	1.3	*	199
	29.6	1.157	1.4	1.0	0.8	2.7	84

** The tests were not performed due to technical difficulties*

5. Previous Researches Data

For validation of the developed empirical correlations in this paper (Equations 6 and 7), related data of previous researches were analyzed. The data of some selected researchers involved soil strength and soil index properties. The selected researchers are [8] and [13].

[13] studied the predicting of bearing strength from the soil index properties of compacted expansive soil taken from Halfayah in Khartoum north. The soil index properties were *LL = 55, PI = 28 and Gs = 2.78.* Their experimental data are given in Table 5.1. Their data are analyzed as given in Figure 5.1

Table 5.1: The data of CBR as reported by [13]

m.c (%)	*Ɣd (gm/cm3)*	*Measured CBR*
24	1.505	17
25	1.508	18
27	1.547	19
30	1.52	7
31	1.48	6

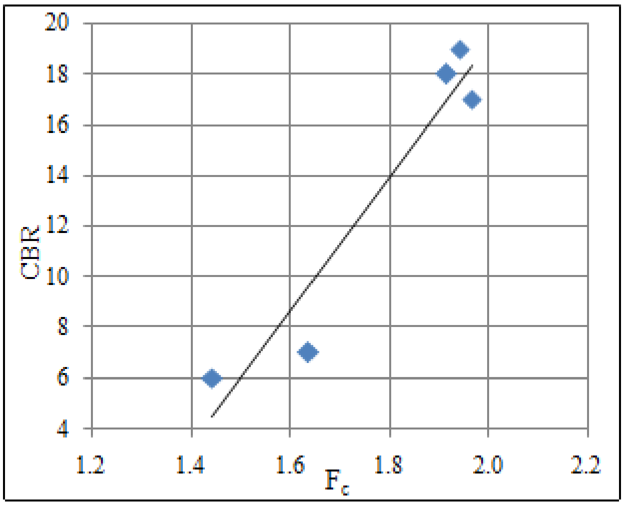

Figure 5.1: Relationship between CBR and F_c for the analyzed data reported by [13]

CBR of expansive soil in China was studied by [8] at different placement condition. The properties of the soil studied were LL = 58.9, PI = 32.8 and Gs = 2.72. The data of the tested soil as reported by [8] are given in Table 5.2. The data are analyzed as shown Figure 5.2.

Table 5.2: The data of CBR as reported by [8]

m.c (%)	*Ɣd (gm/cm3)*	*Measured CBR*
5.88	1.701	0.63
9.48	1.695	0.61
10.71	1.814	0.94
14.18	1.893	1.11
15.08	1.862	1.03
17.68	1.766	0.81
17.93	1.835	0.88
Continue		
m.c (%)	*Ɣd (gm/cm3)*	*Measured CBR*
19.78	1.804	0.9
24.3	1.699	0.68
25.02	1.648	0.6
27.08	1.592	0.52
29.72	1.51	0.33

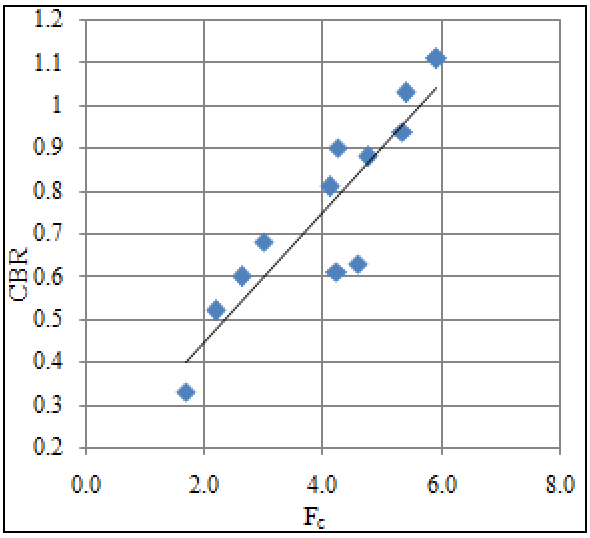

Figure 5.2: Relationship between CBR and F_c for the analyzed data reported by [8]

The correlation coefficients of CBR data of previous researchers are summarized in Table 5.3.

Table 5.3: Coefficients and linearity of the developed correlation of CBR

Reference	*M*	F_o	R^2
Present study Gedarif clay	20.70	0.74	0.92
Present study Madani clay	18.00	0.83	0.88
Present study Giraif East clay	17.70	0.87	0.88
[13] Khartoum North	26.36	1.27	0.92
[8] China clay	0.15	-0.97	0.80

6. Development of Nomograph

The relationship between F_c and the soil strength can be simply plotted by parallel Nomograph as depicted in Figure 6.1. The Nomograph was drawn using AutoCAD program. It is to be noted that different scales are used to draw each property on the Nomograph.

The Nomograph plots the CBR and UCS with the corresponding values of F_c. The predicted soil properties used to draw the Nomograph are the averages values of the tested soils in the present study which obtained from the devolved equation (Equations 6 and 7).

The Nomographs are easy and simply describe the relations between F_c and bothCBR and UCS of a soil as exemplified by the index line on the Nomograph. These soil properties correspond together to the $F_c$horizontally.

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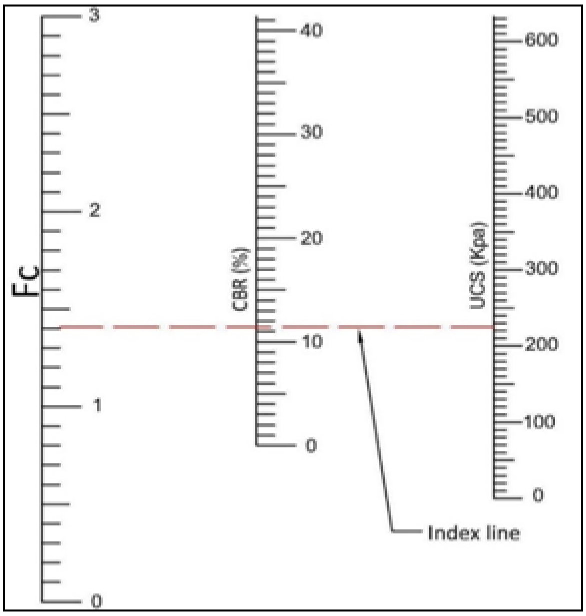

Figure 6.1: Nomograph of strength properties

7. Discussion

The developed correlations between soil index properties and soil strength which introduced in Equations 6 and 7have demonstrated good linear relationship. The linearity's of the correlations were expressed by (R^2) given in Tables 4.3 and 5.3. The correlations linearity mentioned in the Tables are almost ranging between 80 to 98% which indicate acceptable linear relationships to predict soil strength.

To verify the validity of the developed correlations, the measured and predicted values of the CBR and UCS are plotted in Figures 7.1 and 7.2 respectively. The measured and predicted values of soil strength engaged were that experimented in this study together with selected previous related studies of[8] and [13].

The predicted CBR and UCS were obtained from the developed Equations 6 and 7. The correlation coefficients (M and F_0) of this study were obtained from the Table 4.3. The correlation coefficients (M and F_0) of the previous studies were obtained from the Tables 5.3.

In this study, 32 samples were measured for CBR and 23 samples for UCS as given before in Table 4.2. From the previous studies, 17 samples were engaged for CBR as given before in Tables 5.1 and 5.2.

The data provided in Figures 7.1 and 7.2 show all points are almost laying on the Iso-line which indicate considerable rapprochement between the measured and predicted values of CBR and UCS and this evidenced the validity of the developed equation.

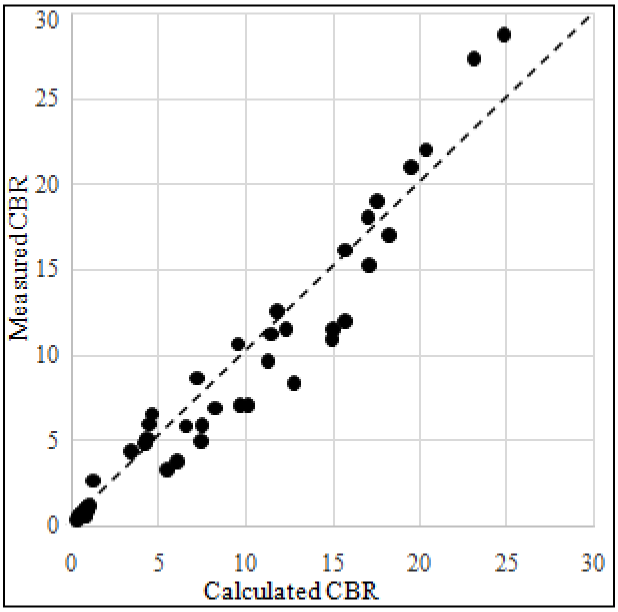

Figure 7.1: Comparison between measured and predicted CBR of the present study and some previous studies

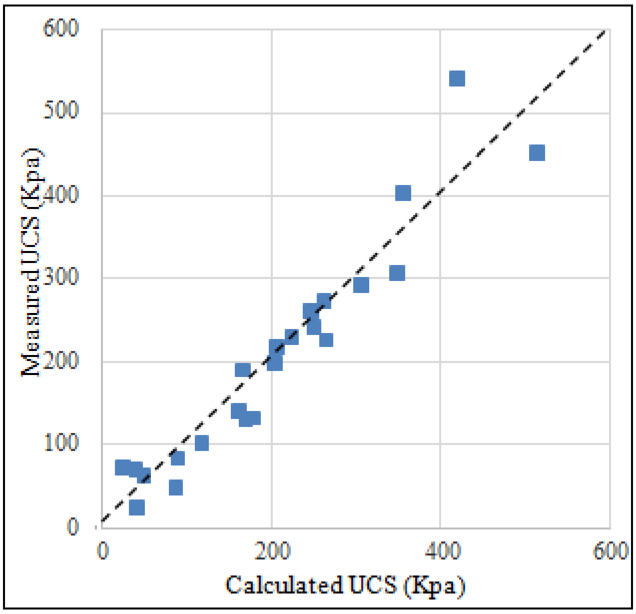

Figure 7.2: Comparison between measured and predicted UCS of the present study

Conclusion

The paper methodology is experimental works conducted on different disturb expansive soils samples taken from different regions in Sudan. The samples were collected from Al-Qadarif (**S1**), Wad Medani (**S2**) and Al-Giraif East in Khartoum (**S3**).

The basic properties of the soil samples were measured. The three soils have high plasticity, so they were classified as highly expansive soils.

The XRD testshown that the three soils contain montmorillonite mineral. The test result showed that soil **S1** has the highest montmorillonite than the other two soils. Therefore **S1** is considered as the most expansively soil compared with the other soils.

The strength characteristics of the thee soils were measured. The three soils were classified as high potential soils with very low strength.
The consistency factor which was developed can be used to correlate the basic properties of the soil with the strength properties. The consistency factor is a combination of the moisture content, dry density, void ratio, liquid limit and plasticity index. These parameters are combined in a way reflecting the influence of each of them on the soil property. The strength properties were measured for the soil samples compacted at different moisture content and different dry densities.

A very good linear relationship was developed between the consistency factor and the strength properties. The correlation developed was verified by using the data of this study and the data reported by some previous researchers.

Nomographs are matching soil properties, which make it easy and simple to estimate the soilproperties instantly. Predicted soil properties in this studywere plotted on

Nomographs in different scales and that make it directly in lines to match properties together.

From the regression analysis, the linearity index (R^2) was found to be in the range 0.80 to 0.98 which indicated very good linear relationship exist.

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Authors Profiles

Omer S. M. Hamzawas born in Kassala, Sudan, 21July 1981. He received the B.Sc. and M.Sc. degrees in Civil Engineering from Omdurman Islamic University (2005) and University of Khartoum (2014). Now he is a Ph.D. candidate in Civil Engineering, University of Khartoum since April 2016. He joined Petro-energy Co., an oil and gas company working in Sudan since 2012. He has published an article in IJSR as co-author in 2014. He is a member of Sudanese Society for Soil Mechanics and Geotechnical Engineering.

Dr. MagdiZumrawiwas born in Omdurman, Sudan, 19 May 1963. He received the B.Sc. degree in Civil Engineering and M.Sc. degree in Road Technology from University of Khartoum in 1987 and 1991, respectively. He achieved Ph.D. in Highway and Railway Engineering, Chang'An University, Xi'an, in Sept. 2000. Now he is Associate Professor in Highway Engineering. His present occupation is Head, Soil and road Section in the Civil Engineering Department, Faculty of Eng., Khartoum University, since Nov. 2014. He is a highway expert working with local and international consultant firms. He has published many articles in local and international journals and attended national and international conferences. He is a member of International Society for Soil Mechanics and Geotechnical Engineering. He is a senior member of the APCBEES.