RESEARCH ARTICLE

European Journal of Environment and Earth Sciences
www.ej-geo.org

The Chemical and Mineralogical Composition and Their Effects on Strength Parameters of Cohesive Soil Developed over Enugu Shale

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ABSTRACT

The results of the chemical and mineralogical composition of cohesive soils developed over Enugu Shale, as well as the effects on the strength parameters, are presented in this paper. The strength parameters were determined in the cohesive soil specimens in the study area, while the chemical and mineralogical tests were done on the representative soil types from the study area. Some correlations between chemical composition and strength parameters of cohesion and angle of internal friction as well as other physical parameters such as liquid limit, plastic limit, plasticity index and activity of soil were obtained. The effects of chemical and mineralogical composition on strength parameters, based on the correlation between chemical composition and strength parameters (cohesion and angle of internal friction) were examined. The results show that chemical and mineralogical compositions significantly affect the angle of internal friction and cohesion thereby impacting the strength of cohesive soils developed over Enugu Shale.

Keywords: chemical and mineralogical composition, cohesion, cohesive soils, Enugu Shale, and frictional angle.

Published Online: January 29, 2022

ISSN: 2684-446X

DOI :10.24018/ejgeo.2022.3.1.234

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I. Introduction

The physical behaviour of cohesive soils is dependent on clay type present, environment chemistry of water in contact with the soil, cation exchange capacity, amount of water adsorbed by the soil and so many other factors. The swelling, shrinkage, cracking and reduction in strength of geological materials are significant characteristics of soils that play important role in the determination of bearing capacity and workability of the soils in regard to engineering geology. The physical behaviour of fine argillaceous materials is dependent on geotechnical parameters, which are the function of soils' mineralogical and chemical composition as well as their formation history [1]. Fine argillaceous materials consist of a significant presence of clay minerals are problematic foundation material especially when in contact with water. This is because the materials tend to develop low geotechnical properties due to reduction in resistance parameters such as cohesion and angle of shear resistance and high compressibility of the materials. Many articles have emphasized on the effects of mineralogy and chemical composition on geotechnical properties of cohesive soils [2] and [3]. In Enugu (Fig. 1), south eastern Nigeria such problematic materials exist which have caused serious damage to engineering structures in the area. These problematic conditions have led many researchers to investigate the nature and cause of these challenges in the area [4]. This research work analyzed the mineralogical and chemical composition as well as physical properties of soils developed over Enugu Shale in Enugu and environs. The experimental results from mineralogical and chemical composition were related to results obtained from some mechanical properties. The effects of the mineralogical and chemical composition were thoroughly determined on physical properties of soils developed over Enugu Shale in Enugu.

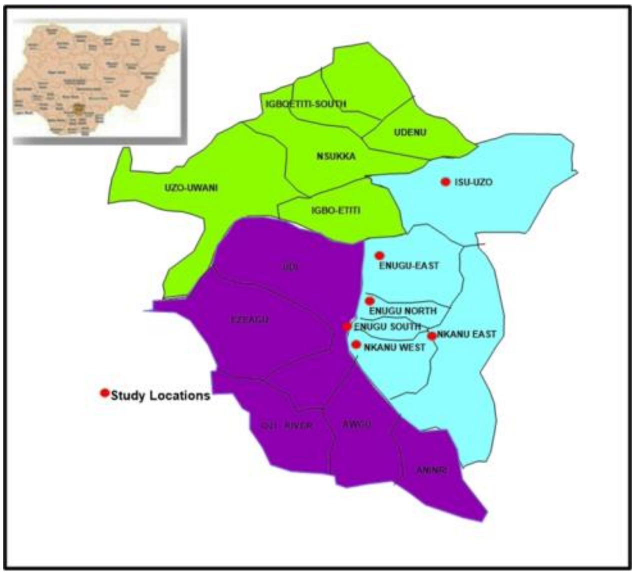


Fig. 1. Map of Nigeria showing Enugu State and study locations.

II. Materials and Methods

Eastern part of Enugu is composed of expansive soils; during the dry season, the materials shrink and crack and during the wet season, the materials swell by the water of adsorption. Twelve soil samples of the cohesive soil were collected in the different parts of the area at a depth between 0.5-1 m. These samples were subjected to X-ray diffraction test (XRD), X-ray fluorescence (XRF) test, triaxial test and Atterberg's limits test. XRD tests were determined using pulverized soil samples loaded in a magazine in the XRD machine by Panalytical Holland of the Empyream model. The X-High Score Plus displays the diffractogram which plotted the intensity of the diffraction signal on the vertical against the diffraction angle on the horizontal axis at wavelength of 1.54 (Å) (Cuka). XRF tests were obtained using XRF spectrometer (EDX-700) by reducing the diameters below 54 (µm) and analyzed in a dispersive energy spectrometer. The spectra were obtained at 300 seconds intervals in a vacuum and semi quantitative mode. Atterberg's limit tests were obtained in accordance with [5]. Triaxial tests were determined through undrained consolidated method using triaxial apparatus.

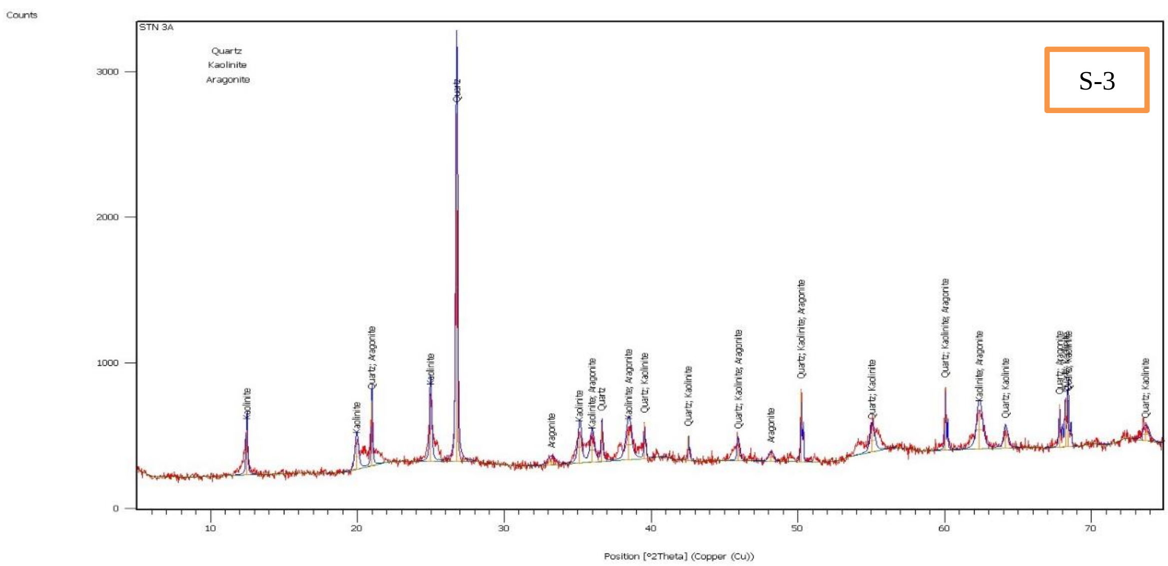
III. Results and Discussions

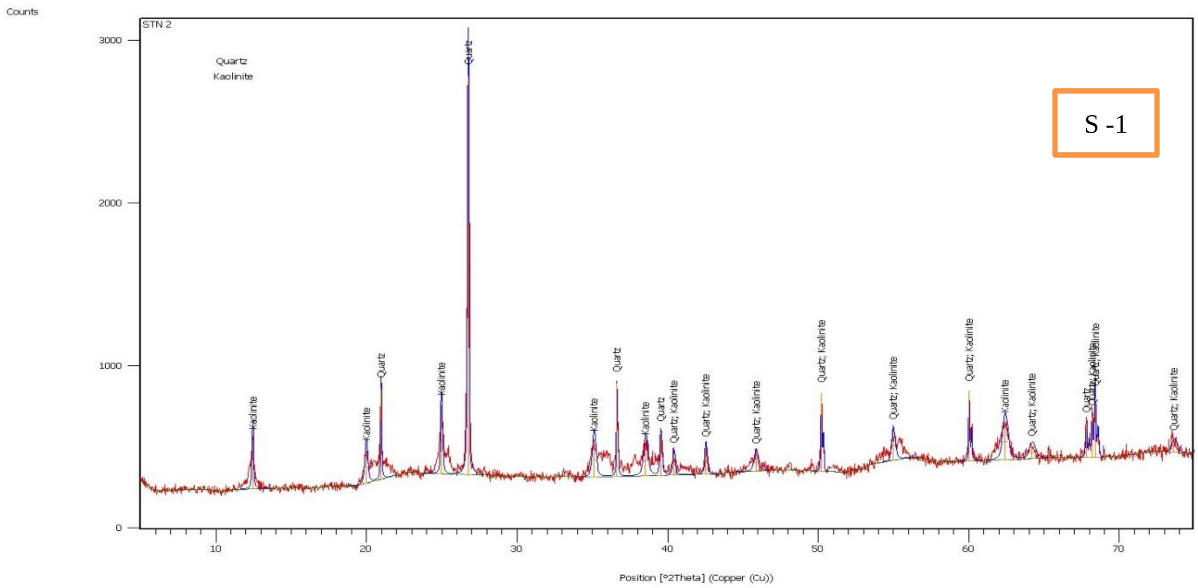
A. Mineralogy

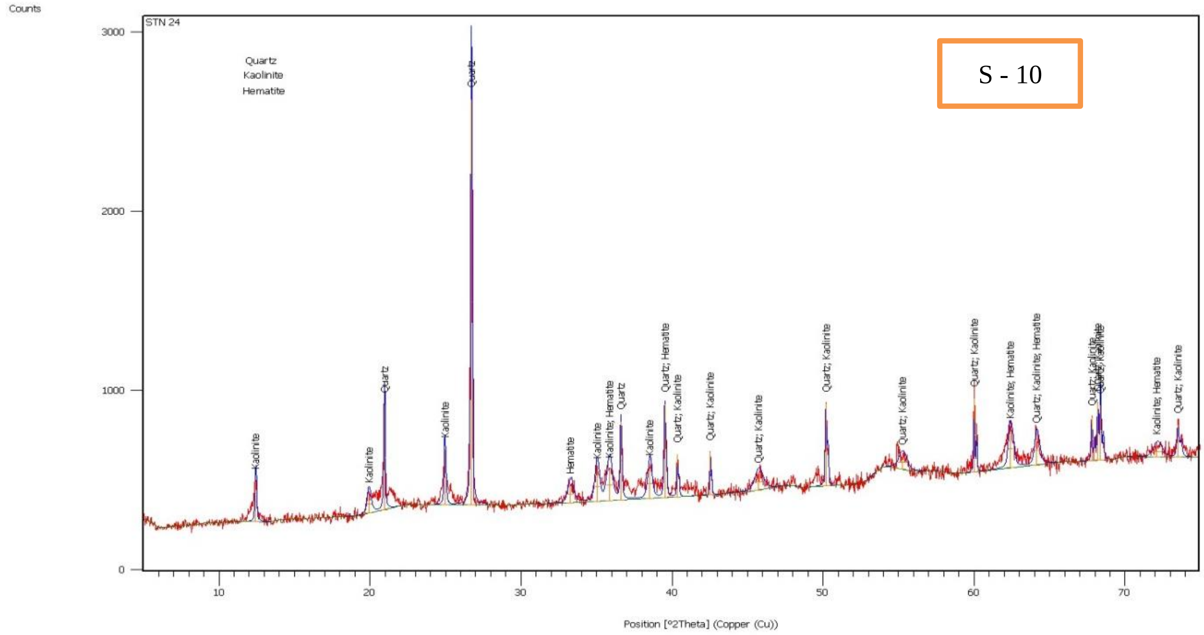
X-ray diffraction method was used to determine mineral present from soils developed over Enugu Shale in Enugu and environs. Eight samples from the study area were analyzed for mineralogical composition through XRD. The results obtained are presented in Table I and Fig. 2.

TABLE I: Mineralogical Composition of Cohesive Soils Developed over Enugu Shale

Sample no.	Quartz	Kaolinite	Aragonite	Muscovite	Microcline	Hematite	Anorthoclase
1	44	56	-	-	-	-	-
2	30	70	-	-	-	-	-
3	24.2	44.4	31.3	-	-	-	-
4	23.8	13.9	-	-	62.4	-	-
5	62	38	-	-	-	-	-
10	60	24	-	-	-	16	-
11	74	26	-	-	-	-	-
12	27	-	-	44	-	-	29



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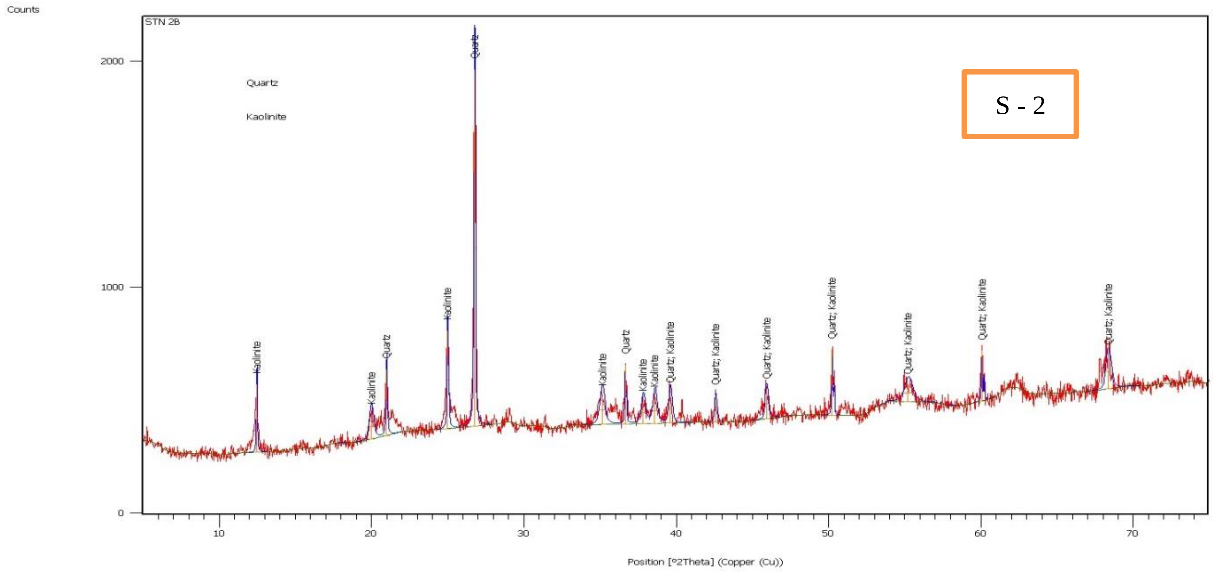
Quartz
Kaolinite
Hematite
S - 10
Position [°2Theta] (Copper (Cu))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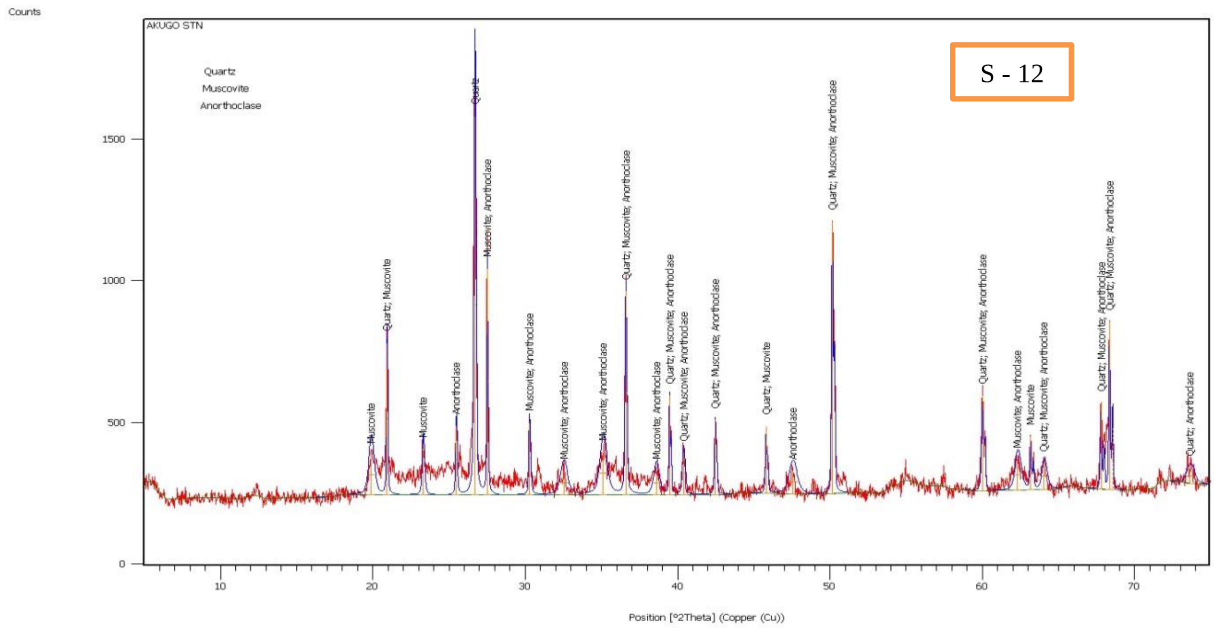
STN 2B
Quartz
Kaolinite
S - 2
Position [°2Theta] (Copper (Cu))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Muscovite
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Position [°2Theta] (Copper (Cu))

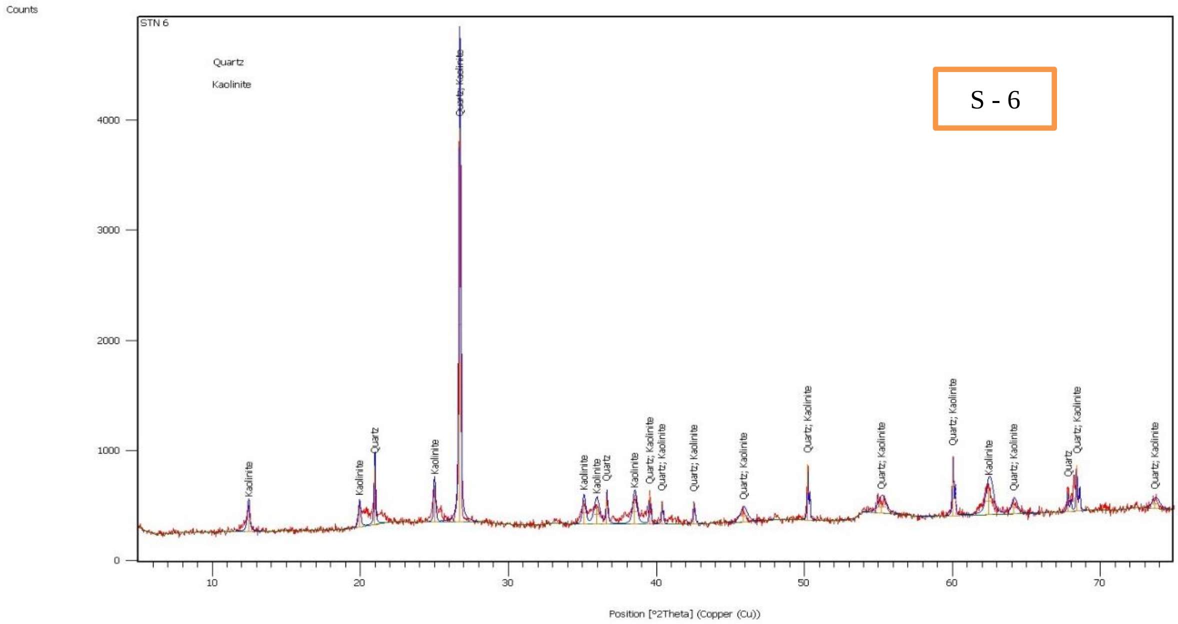

Fig. 2. The XRD diffractogram of some selected cohesive soils developed over Enugu Shale.

B. *Chemical Composition*

The chemical components of cohesive soils in the study area include SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O and K_2O which play an important role both in the physical and mechanical properties of the soil. The chemical compositions of cohesive soils in the study area were determined using XRF spectrometer (EDX-700) by reducing the diameters below 54 (μm) and analyzed in a dispersive energy spectrometer. 20 soil samples were analyzed in Enugu and environs and their chemical composition is presented in Table II.

TABLE II: CHEMICAL COMPOSITION OF COHESIVE SOILS DEVELOPED OVER ENUGU SHALE

Sample no.	SiO_2	Al203	Fe_2O_3	CaO	MgO	Na_2O	K_2O
1	84.98	12.53	1.3	1.39	0.51	0.26	0.43
2	72.19	17.95	1.39	0.53	0.79	0.24	0.33
3	52	24.11	12.21	0.4	3	0.47	1.28
4	57.85	19.45	11.75	0.2	2.31	0.13	1.68
5	62.6	21.57	6.21	0.06	0.51	0.39	0.95
6	69.41	17.04	3.44	0.01	1.04	0.82	0.56
7	84.64	6.26	0.98	0.02	0.63	0.49	0.47
8	76.5	9.02	3.64	0.38	0.46	0.34	1.42
9	52.78	24.16	10.65	0.2	2.53	0.84	1.04
10	52.78	24.16	10.65	0.2	2.53	0.84	1.04
11	56.26	23.42	7.63	0.23	3.54	0.55	1.32
12	80.52	10.78	1.45	0.46	0.4	0.27	0.3

The XRF results of expansive soil samples show that major chemical elements have noticeable variation in composition from one place to another. The chemical composition test results in the study area, it was found that the variations in the composition are consistent with a change in elevation and geomorphology. Quartz content is higher in the area with high topography/elevation. The iron oxide and aluminum oxide which contribute much to the cohesive nature of the study area have a significant presence in the area with low elevation/topography.

C. *Atterberg Limits*

Atterberg limit tests were carried out in the twelve soil samples collected in Enugu. The Atterberg limit tests which include the liquid limit (LL) and plastic limit (PL) were obtained. Also, plasticity index (PI) was obtained from the results of liquid limit and plastic limit.

D. *Liquid Limit*

The liquid limit was obtained using Casagrande test apparatus. The test results are shown in Table III. The results show that test values range from 42-66%. The results obtained from liquid limit tests show that variation in value is consistent with a change in topography. This can be significantly attributed to change in chemical composition from topography change in the area. Based on [6] classifications, the results obtained show that the liquid limit ranges from intermediate to high plastic clay.

E. *Plastic Limit*

The plastic limit was determined by rolling out a thread of the fine portion of the soil on a glass plate to 3 mm in diameter before cracking. The plastic limit values were observed in the study area as shown in Table III. The results obtained show that the values ranged from 17-33 (%). The variation of plastic limit in the study area is consistent with a change in chemical composition, mineralogical content, and topography. The result is consistent with the work of [7].

F. *Plasticity Index*

Plasticity index is the difference between liquid limit and plastic limit. It is an important index property of a soil which is widely used in soil engineering classification systems. It is an indicator to soil expansivity. The soils of the study area have plasticity index values ranging from 17-33 (%). [6] classified such soil as intermediate to fat plasticity.

G. *Clay Activity*

The clay activity (A) of a soil is the ratio of plasticity index to the percentage clay fraction of the soil. The activity of the soils in the study area ranges from 0.31-2.02. From the activity values, the dominant clay type can be predicted [8] and [9]. High activity indicates a large volume change in the presence of water and large shrinkage when dried. Soils with high clay activity are classified as active soils. [8] noted that activity of clay less than 0.75 is considered to be inactive soil, between 0.75-1.25 the soil is regarded as normal soil and for activity greater than 1.25, it is considered as an active soil. Most of the soil samples under study fall between inactive to normal active soil with the exception of one sample which falls within active soil in the study area. This means that kaolinite and iolite are the dominant clay minerals in the study area.

H. Cohesion and Angle of Internal Friction

The shear strength is the major engineering property of the soil. It is a determinant factor in assessing the suitability of soil for engineering construction. The strength of expansive soils is dependent two factors: the *cohesion* which depends on void ratio and water of adsorption, and the *angle of internal friction* which is a function of effective stress. These two parameters are needed to assess the geotechenical characteristics of construction sites in order to determine the bearing capacity for foundations and slope stability of an inclined surface. The triaxial tests were done through undrained consolidated method using triaxial apparatus in a close chamber. The cohesion of the studied samples varied from 12.19-36.96 (KNm^{-2}) with mean value of 28.46 (KNm^{-2}), and angle of internal friction of ranging from 4.42-14.85^o with mean value of 6.71^o. The strength of the studied samples is mainly derived from cohesion of the soil.

TABLE III: GEOTECHNICAL PROPERTIES OF COHESIVE SOILS DEVELOPED OVER ENUGU SHALE

Sample no.	LL (%)	PL (%)	PI (%)	Activity	frictional angle (^{o})	Cohesion (KNm^{-2})	Strength (KNm^{-2})
1	59	28	31	0.78	4.42	30.21	62.13
2	56	17	39	2.02	5.49	22.37	61.97
3	66	31	35	0.8	5.22	30.55	69.47
4	59	39	20	0.97	6.32	27.53	75.71
5	44	17	17	0.45	5.85	26.82	68.15
6	42	22	20	0.63	5.53	33.66	75.97
7	50	24	26	0.76	14.85	12.19	154.84
8	48	35	13	0.31	5.93	30.58	75.87
9	44	31	13	0.34	7.08	27.6	82.99
10	55	25	30	0.86	7.4	36.15	97.19
11	46	27	19	0.5	5.58	36.94	80.42
12	54	33	21	0.46	6.83	26.97	79.79

I. Effect of Chemical/Mineralogical Composition on the Strength of the Soils of the Study Area

The physical/mechanical behaviours of expansive soils, such as crack, shrinkage, swelling and some other geotechnical attributes, which can be obtained in the presence of water or absence of water, are very important features that play major roles in engineering construction. The physical/mechanical behaviours of soils are closely dependent on geotechnical parameters, which are related to their mineralogy and chemical composition of the expansive soils, as well as formation history and environmental compositions of fluid in the time it was formed. The chemical characteristics of expansive soils are mainly due to the chemistry of the main minerals, cementing materials, as well as adsorbed cations and anions on the surfaces of clay minerals. [7] reported that swelling and other geotechnical properties of soils are controlled by the chemical composition of soils and availability of water in the area. [10] noted that soils that contained a high percentage of magnesium had their structural properties deteriorated and infiltration rates were negatively affected during the rainy season. Therefore, increase in magnesium ions in the soil result in soil surface sealing [11] which leads to water logging. Also, more swelling would occur in soil having a large quantity of exchangeable Na^+ ions than in the soil with a large quantity of Ca^{2+} ions. Evaluation of chemical/mineralogical composition of expansive soils is very important with regards to the construction of engineering projects. From the revised Coulomb's equation which stated that $s = c' + \partial' tan\emptyset'$. Where s is the shear strength; c' is effective cohesion; ∂' is effective stress; and $\emptyset'$ is effective angle of internal friction. The shear strength is dependent on the physical parameters of cohesion and frictional angle. Fig. 3a–3h shows the relationship between the major chemical elements with each other. From the relationship, it was observed that an increase in Al_2O_3, Fe_2O_3, MgO and K_2O will decrease SiO_2(Fig. 3a, b, d & g). This implies that the lesser the Al_2O_3, Fe_2O_3, MgO and K_2O in the study area higher the silica content. Fig. 4 shows that SiO_2 has a moderately positive correlation with frictional angle. Also, Fig. 4 shows that the relationship between frictional angle and comprehensive strength of studied soil in Enugu metropolis is a near perfect relationship (0.976). The result is consistent with works of [12] and [13] in using silica content to improve the compressive strength of soils. Fig. 3c & e show that Fe_2O_3 and MgO have a positive strong relationship with Al_2O_3. The Fe_2O_3, MgO and Al_2O_3 have a moderate to a strong relationship with cohesion based on the result of Pearson correlation matrix (Table IV). The correlation matrix shows that increase in Fe_2O_3, MgO and Al_2O_3 will likely increase the cohesion of the soils of the study area. Fig. 4 shows that at the beginning, an increase in cohesion and angle of internal friction increases the compressive strength of the soils in the study area until a stage reached whereby increase the angle of internal friction and decrease in cohesion off shoot the compressive strength of soils in the study area. At this point, the best compressive strength was obtained. This result tends to show that there is a threshold for cohesion in other to obtain the best compressive strength in the study area. At this point, the angle of internal friction, cohesion and compressive strength stand at 15^o, 12.19 kNm^{-2} and 154 kNm^{-2}, respectively. This is the best compressive strength in the study area.

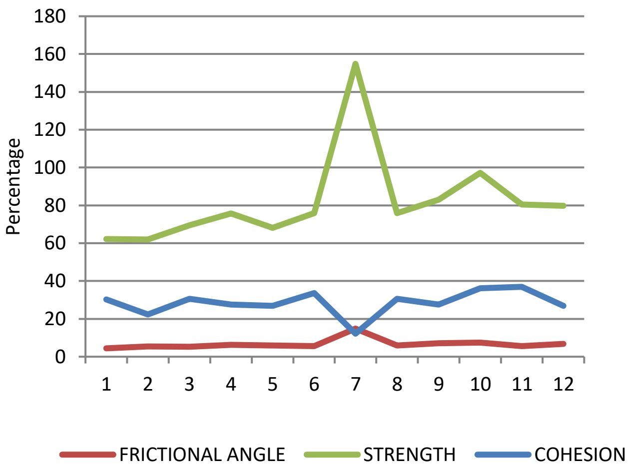

Fig. 4. Diagram showing the peak of compressive strength at the point cohesion decreases.

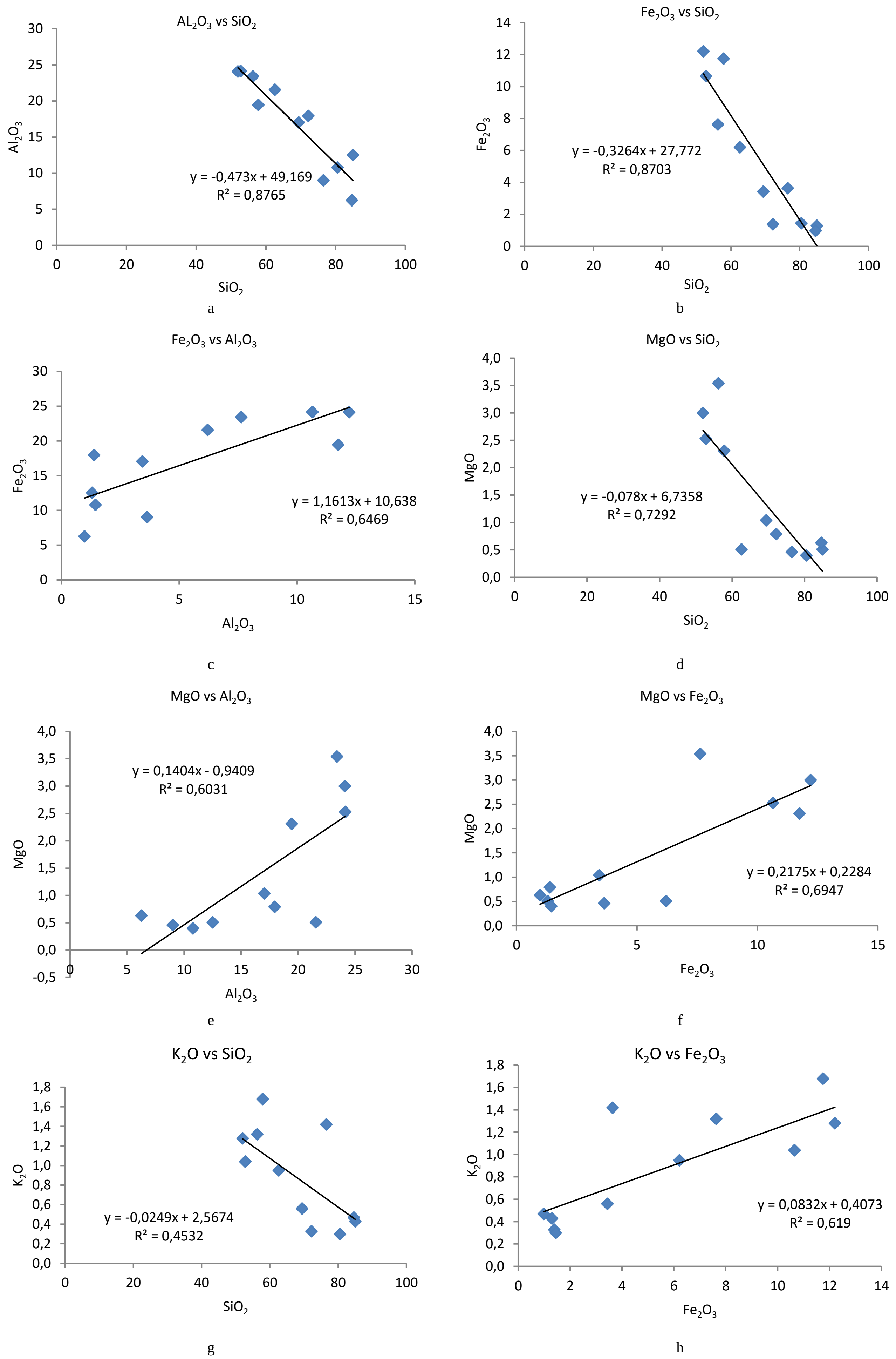

Fig. 3a-h. The relationship between the chemical compositions and each other.

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TABLE IV: CORRELATION MATRIX OF THE CHEMICAL COMPOSITIONS AND SOME GEOTECHNICAL PROPERTIES

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	S-S ratio	LL	PL	PI	ACT	FA	Cohesion	Strength
SiO_2	1														
Al_2O_3	-0.9362413	1													
Fe_2O_3	-0.9328957	0.804314	1												
CaO	0.42608672	-0.23027	-0.32756	1											
MgO	-0.8539518	0.776596	0.833472	-0.24730483	1										
Na_2O	-0.4486279	0.421205	0.3172124	-0.450708482	0.401424852	1									
K_2O	-0.6731902	0.45716	0.786787	-0.305490518	0.631844887	0.017530984	1								
S-S ratio	-0.4176324	0.449443	0.2606377	-0.085521199	0.142272531	0.313727025	0.36327506	1							
LL	-0.0260676	0.036897	0.2114224	0.513489171	0.165584331	-0.486695718	0.06672412	-0.32952	1						
PL	-0.0996103	-0.12265	0.3712914	0.139013835	0.270746033	-0.241131652	0.5484277	-0.1273	0.33232333	1					
PI	0.09335315	0.063979	-0.120265	0.418716816	0.020109606	-0.197666866	-0.3942472	-0.27196	0.72274889	-0.35069811	1				
ACT	0.06894791	0.065301	-0.164323	0.205170622	-0.064133071	-0.326347348	-0.3073971	-0.19321	0.46662616	-0.38908167	0.790378	1			
FA	0.30198366	-0.46081	-0.217243	-0.425146162	-0.163272	0.148142152	-0.2175578	-0.70458	-0.14908143	-0.07928625	-0.03263	-0.057829	1		
cohesion	-0.5173548	0.560996	0.4414992	0.107689827	0.498858169	0.344200644	0.42020717	0.694321	-0.05212674	0.178145877	-0.16242	-0.28709	-0.73057	1	

where LL= Liquid Limit, PL= Plastic Limit, PI= Plasticity Index, ACT= Activity of the soil and FA= Frictional Angle.

IV. Conclusions

The chemical/mineralogical compositions of cohesive soils and, especially, of clays and clay-size soils, greatly affect the cohesion, angle of internal friction and compressive strength of soils in the Enugu and environs.

The liquid limit, plastic limit and plasticity index of the studied soils fall within the intermediate to high plasticity range according to [6] classification and the activity ranges from inactive to active.

From the relationship of the chemical composition of the soils and strength parameters, it can be concluded on the following:

The increasing of SiO_2 content increases the frictional angle of the studied soil moderately.

- That frictional angle has a near positive perfect relationship with compressive strength of studied soil sample with a correlation coefficient of 0.97.
- The increase in SiO_2 decreases Al_2O_3, Fe_2O_3, MgO, K_2O and cohesion of the soils of the Enugu and environs
- The cohesion has a positively moderate to a strong relationship with Al_2O_3, Fe_2O_3, MgO and K_2O in the study area.
- The relationship shows that cohesion has a negative influence on the compressive strength of the soils of Enugu and environs. This might be attributed to tensile strength exhibited by soil dominated by Al_2O_3 and Fe_2O_3. The cracking that is prominent in the study area can be linked to this tensile strength phenomenon and not on the swelling clay type as it was not found in the study area.

The study shows that there is a threshold for cohesion in the determination of shear strength in the Enugu and environs.

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