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Chemical Stabilization of Expansive Dakhla Shale, Qena Region, Egypt

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Abstract— This study deals with a chemical stabilization of expansive Dakhla shale, which widely distributed on the surface at both West and East of Qena governorate, Egypt. Chemical stabilization program was used to enhance the geotechnical properties of the studied expansive shale using both lime and cement kiln dust (CKD). Optimum-Lime and -cement kiln dust (CKD) contents were determined using pH test according to Eades and Grimm method. Geotechnical properties of the natural and treated shale as plasticity, free swelling, ultrasonic velocity (Vp), and unconfined compressive strength (qu) were measured according to ASTM standard. The results showed that the studied samples mixed with CKD have a higher strengths and lower swelling potentials than those mixed with lime only or with both lime and CKD. Also the results approved that curing time from 7 to 90 days having a great effect on the geotechnical properties of the studied treated shale samples.

Index Terms— Expansive Shale, Chemical Stabilization, Lime, Cement Kiln Dust (CKD), Free Swelling, Unconfined Compressive Strength (qu). Ultrasonic velocity test.

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1 Introduction

Expansive shale has a potential to swell and shrink during wet and dry conditions respectively. This is due to their high content of expansive clay minerals. Swelling potential would effect on the construction or pavement above and destroy them. These problems developed the need to enhance their geotechnical properties using chemical stabilization.

Chemical stabilization for swelling shale is applied mostly by adding lime or cement or a mix of both. New techniques are developed which use Flay ash, which result from coal burning in the power plants, or Cement Kiln Dust (CKD), which result from the cement factories. These techniques have another advantage; as Flay-Ash and CKD are toxic to environment, they should to be buried in sanitary landfills at a certain depth or storage in a certain containers, this processes are so expensive. So that reusing them in chemical stabilization of expansive shale has environmental and economic benefits.

Lime stabilization used widely in road construction to enhance the geotechnical properties of sub-grade, sub-base, and base materials [1].

1.1 Location of the Study Area

The studied samples collected from El-Balas area, West of Qena City, at 26° 1' 3.8'' N and 32° 43' 18.7'' E, and from Gebel El-Quraya, East of Qena City, at 26° 24' 57.8'' N and 33° 5' 20.7'' E. the studied samples collected belong to Dakhla Formation which has high expansive characteristics (Figure 1 and 2).

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1.2 Previous work

Many studies were carried out on the studied area including geology, structures, tectonic, stratigraphy, and etc. Few studies were carried out on the studied area and in Egypt including chemical stabilization of expansive shale like [3], [4], [5], [7], [8], [9], [10], and [11].

Fig.1. Location of the study area.

1.3 Scope of the Study

This study investigates the effect of lime and cement kiln dust (CKD) on enhancing geotechnical properties of high expansive shale of Dakhla Formation distributed around Qena governorate. Also to compare between the potential of lime, CKD, and a mixture of them for increasing the bearing-capacity of tested shale and reducing its swelling potentials. This study also detects the effect of long term curing of the treated shale samples and continuity of pozzolanic reactions on enhancing geotechnical properties of tested samples.

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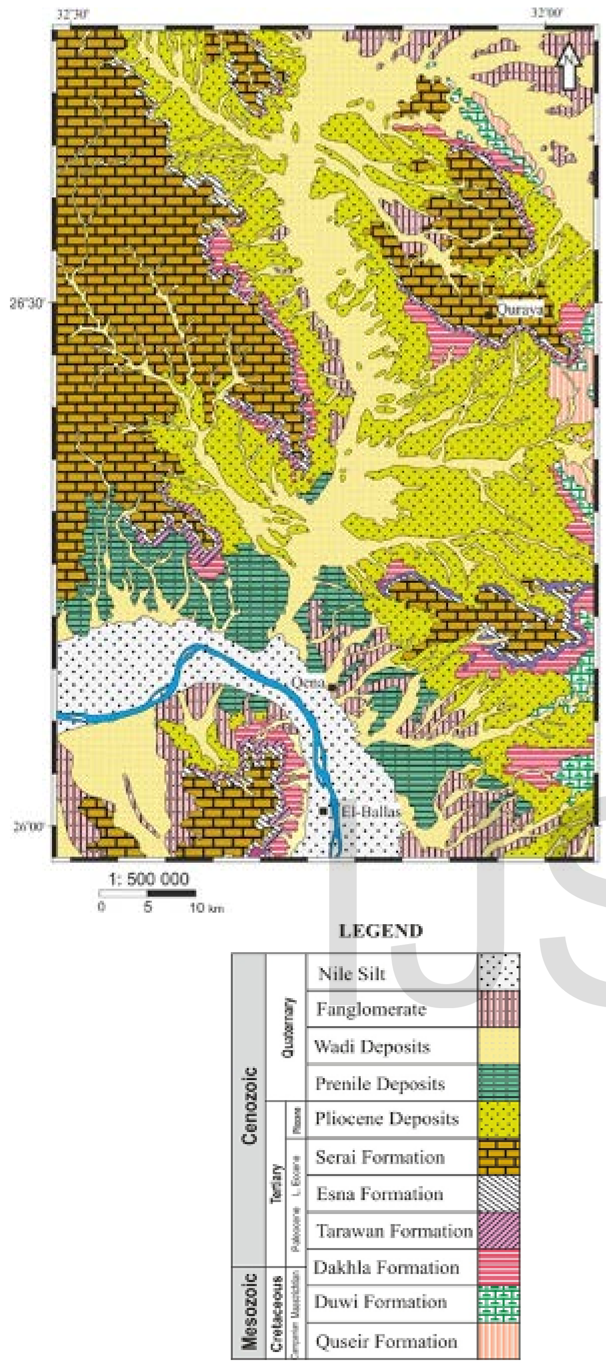

Fig.2. Geologic map.

2 Materials and Methods

2.1 Materials

2.1.1 Dakhla Formation

Dakhla Formation deposited during Late Cretaceous to Paleocene. It consists of gray marine shale and marl. Also it contains intercalated siltstone, sandstone, and limestone layers. Dakhla Formation has a wide distribution in the central and southern parts of both Eastern and Western Deserts of Egypt and along the Red Sea [12]. Their index properties and classification are listed in Table 1.

TABLE 1
Index Properties of Studied Shale

Sample	LL %	PL %	PI	Wn %	On %	δd	MDD	OMC	Classification	
									USCS	AASHTO
DB	54.6	27.34	27.26	2.89	4.16	1.97	1.46	24	MH	A-7-5
DQ	63.5	36.72	26.78	0.98	3.83	1.4	1.463	24	MH	A-7-5

LL = Liquid Limit

PL = Plastic Limit

PI = Plasticity Index

Wn = Natural Water Content

On = Natural Organic Content

δd = Natural Density

MDD = Maximum Dry Density

OMC = Optimum Moisture Content

DB = Dakhla Shale of Balas Section

DQ = Dakhla Shale of Quraya Section

USCS = Unified Soil Classification System

AASHTO = American Association of State Highway and Transportation Officials

2.1.2 Lime

Hydrated lime Ca(OH)2 (Calcium hydroxide) is used. The hydrated lime resulted from reaction between quicklime (CaO) (Calcium oxide) with water as the following equation [4].

$$CaO + H_2O \longrightarrow Ca(OH)_2 + Heat$$

Lime can react with all clay minerals; however it has a more significant effect on montmorillonites than kaolinites, as montmorillonites have a higher plasticity index (PI) [13]. Adding of lime has two stages of reactions; flocculation and pozzolanic reactions.

Firstly; flocculation processes occur immediately after adding lime to the soil with sufficient amounts of water, so that it is referred to as short term reaction. Flocculation results from cation exchange processes; as the Sodium and other cations on the surfaces of clay minerals exchanged by Calcium cations of lime, causing the fine grains of the soil to flocculate forming aggregates. These process resulting in increasing the grain size to a sand size [1].

Secondly; pozzolanic reactions take place after flocculation, when there is sufficient lime and water content, this means that optimum lime content will be not sufficient for pozzolanic reactions, and additional lime content will be needed. Lime content above the fixation point will produce a high alkaline environment which resulted in dissolution of alumino-silicates of clay mineral lattice, then precipitated as cementing materials. This process is slow and time dependent [13], [14], [15], [16], and [17].

2.1.3 Cement Kiln Dust (CKD)

CKD is a fine material, 75-80% passing 200 mesh, its appearance similar to Portland cement [18]. It is produced as a waste material from Portland cement manufacturing. The studied CKD was obtained from Qena Cement Factory, Qift, Qena, Egypt.

2.2 Methods

X-ray diffraction and fluorescence (XRD and XRF) were used to detect mineral and chemical composition of the studied materials. Soils classified using grain size analysis tests and according to their plasticity properties [21]. Optimum-lime and -CKD were detected using pH method as pozzolanic reactions are most likely to occur in 12.4 pH environment [13], while optimum water content for mixtures were detected using standard proctor test according to ASTM. The chemical stabilization program was carried out using lime, CKD, and mixture of lime and CKD. The treated shale samples were cured in a water bath (under about 98% moisture environment to minimize evaporation effect for the water inside preserved samples and under chamber temperature) for 7, 28 and 90 days to study the effect of curing time on enhancing geotechnical properties of the treated samples. Free swelling test of natural and treated samples was carried out according to [23]. Geotechnical properties of natural and treated samples were tested using destructive method using unconfined compressive strength test according to [22]. Also they tested using nondestructive method using ultrasonic velocity (longitudinal velocities) [19] using JAMES instrument.

3 Results

3.1 XRD and XRF Analysis

Tested shale samples and studied CKD were analyzed by XRF to indicate their chemical composition, and by XRD to discriminate their mineral contents. The results listed in Tables (2 and 3). CKD is mostly similar in its composition to Portland cement containing a high percent of CaO (67.7%) and a low percent of SO (<2%). Sulfide oxides are considered harmful for hydration reactions as they result in forming ettringite. Tested samples have a high percent of SiO2 and Al2O3 around 60-70%. All tested shale samples consist of more than 10% of quartz, while clay minerals were very abundant range between 29.3 to 67.9% varying between montmorillonite and kaolinite. Calcite also present in a high percent 17.7%. Anhydrite is less abundant than calcite, it found in a percent around 11.5%.

3.2 pH-Test Results

pH value of 12.4 is the most suitable environment for proceeding hydration reactions [20]. So that it is concluded that the optimum percent of lime content which are 3% for Dakhla shale samples collected from El-Balas area (DB) and 5% for Dakhla shale samples collected from Gebel El-Quraya (DQ). The optimum CKD content of DB shale sample and of DQ shale samples is 8 and 12% respectively. The optimum lime and CKD content of DB shale sample and of DQ shale samples is 2% L + 6% CKD and 3% L + 8% CKD, respectively (Table 4).

TABLE 2
CHEMICAL COMPOSITION OF BOTH STUDIED SHALE AND CKD

Compound Formula	Concentration (wt %)		
	DB	DQ	CKD
Na_2O	2.176	1.649	0.138
MgO	1.56	1.988	0.564
Al_2O_3	22.015	16.989	3.52
SiO_2	37.81	55.226	7.332
P_2O_5	0.665	0.205	0.263
SO_3	0.55	2.23	1.847
K_2O	1.147	0.726	0.474
CaO	6.687	0.354	67.722
TiO_2	1.296	1.404	0.32
Cr_2O_3	0.093	0.028	0.037
MnO	0.016	0.015	0.021
$Fe_2O_3^{tot}$	9.116	6.49	3.543
NiO	0.024	0.015	0.014
CuO	0.013	0.013	----
ZnO	0.034	0.022	0.015
SrO	0.04	0.012	0.245
ZrO_2	0.035	0.046	----
Cl	0.718	0.258	0.356
L.O.I	16.0	12.3	13.5

TABLE 3
MINERAL COMPOSITION OF THE STUDIED SHALE SAMPLES

Sample/Minerals	DB	DQ
Quartz SiO_2	11.2	38.3
Kaolinite $Al_2Si_2O_5(OH)_4$	47.3	----
Monmorillonite $NaMgAlSiO_2(OH)_4$	19.6	29.3
Albite $NaAlSi_3O_8$	----	20.5
Calcite $CaCO_3$	17.7	----
Anhydrite $CaSO_4$	----	11.9
Halite NaCl	4.2	----

TABLE 4

OPTIMUM CONTENTS OF CHEMICAL ADDITIVES

Sample	Lime (L)	CKD	Mixture	
			L	CKD
DB	3%	8%	2%	6%
DQ	5%	12%	3%	8%

3.3 Proctor Compaction Test Results

Optimum water content (OWC) and maximum dry density (MDD) were detected using standard proctor test. The results illustrated in Table (5) and Figure (3). The results proved that addition of lime, CKD, and/or mixture of them can decrease MDD and increase OMC. MDD of DB decreased from 1.44 g/cm3 for the natural compacted sample to 1.36, 1.37, and 1.33 for lime, CKD, and the mixture, respectively. While OWC increased from 24% for the natural sample to 31, 32, and 33% for lime, CKD, and the mixture, respectively. However, for DQ the MDD decreased from 1.463 g/cm3 for the natural compacted sample to 1.354, 1.36, and 1.35 for lime, CKD, and the mixture, respectively. While OWC increased from 24% for the natural sample to 32, 33, and 33.8% for lime, CKD, and the mixture, respectively.

TABLE 5

PROCTOR COMPACTION TEST RESULTS

Sample	Additives	MDD (g/cm^3)	OWC (%)
DB	Natural compacted soil	1.46	24
	3% lime	1.36	31
	8% CKD	1.37	32
	2L + 6CKD	1.33	33
DQ	Natural compacted soil	1.463	24
	5% lime	1.354	32
	12% CKD	1.36	33
	3L + 8CKD	1.35	33.8

3.4 Unconfined Compressive Strength Test Results

Results of unconfined compressive strength test listed in Table (6). In case of DB, using optimum lime content, the strength increased due to lime stabilization from 89.4 k-Pascal of natural compacted shale to 214.54, 402.47, and 189.84, after curing 7, 28, and 90 days, respectively.

While using optimum CKD content the strength increased to 675.58, 1450.1, and 715.94 after curing for 7, 28, and 90 days, respectively. However, in case of using a mixture of both lime and CKD at their optimum contents, it is found that the strength increased to 552.84, 1214.03, and 471.35 after curing for 7, 28, and 90 days, respectively. The results of DQ are not very different from those of DB and the values have the same development direction, see Table 6.

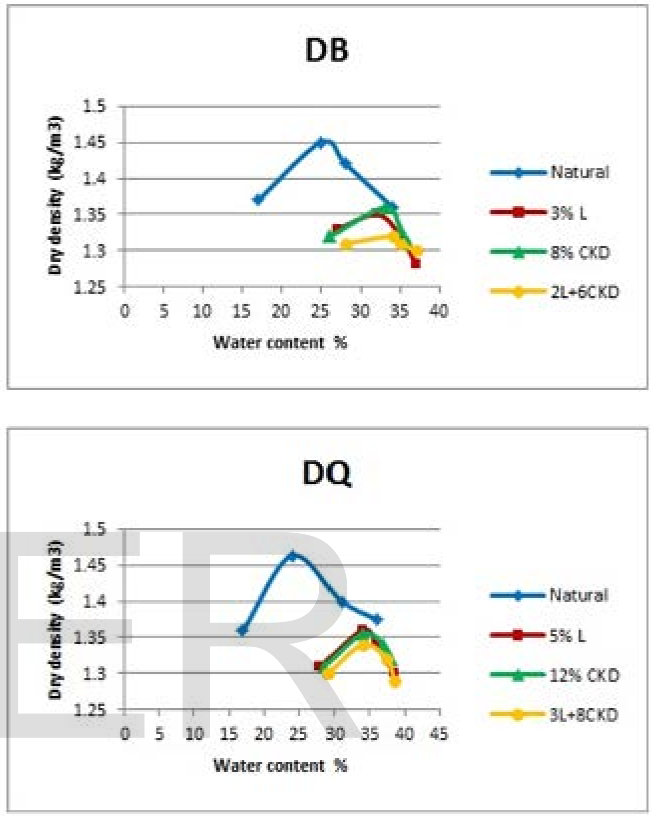

Fig.3. Proctor compaction curves.

3.5 Free Swelling Test Results

Free swelling test was applied for both natural and treated samples (Table 6). The free swelling percent of the natural shale samples was 80% (in case of DB) and 104% (in case of DQ), and classified as moderately swelling shale according to [23]. Free swelling percent decreased to its lowest values for treated samples cured for 90 days. In case of DB, the lowest free swelling values (zero% swelling) resulted from treating with mixture of 2% lime with 6% CKD and curing for 90 days. However; free swelling of DQ treated shale samples decreased to its lowest values (4% swelling) when treated with 12% CKD and cured for 90 days.

3.6 Ultrasonic Velocity Test (Vp) Results

Ultrasonic velocity test was performed to measure longitudinal waves (p-waves or Vp) as indication for porosity and the formation of cementitious materials (pozzolans) resulted for pozzolanic reactions. Table (6) shows the values of Vp for nat-

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ural and treated soils.

Figure (4) illustrates the development of treated shale samples from ductile behavior to brittle behavior.

TABLE 6

UNCONFINED COMPRESSIVE STRENGTH, FREE SWELLING, AND ULTRASONIC VELOCITY RESULTS

Sample	Additives	Curing time	qu-value (k-Pascal)	Free swelling	Vp (m/sec)
DB	Natural compacted	0	89.38	80%	640
	3% lime	7 days	214.54	65%	649
		28 days	402.47	68.33%	456
		90 days	189.84	2.67%	287.5
	8% CKD	7 days	675.58	35%	962
		28 days	1450.1	19.33%	1373
		90 days	715.94	3.33%	511
	2L + 6CKD	7 days	552.84	15%	837
		28 days	1214.03	20.67%	1167
		90 days	471.35	0%	500
DQ	Natural compacted	0	215.94	104.17%	696.5
	5% lime	7 days	490.2	70%	577
		28 days	351.03	60%	402
		90 days	231.22	23.33%	575
	12% CKD	7 days	1271.46	30%	686
		28 days	1290.56	23.33%	1629
		90 days	1212.12	4%	1000
	3L + 8CKD	7 days	777.9	20%	396
		28 days	1301.9	26.67%	1414
		90 days	914.57	25.67%	1416

Fig.4. The development of shale samples behavior from ductile (for untreated compacted samples) to brittle (for stabilized samples): a) DB; a1) Natural compacted DB; a2) DB+CKD 7days; a3) DB+CKD 28days; a4) DB+CKD 90days; a5) DB+L/CKD 7days; a6) DB+L/CKD 28days; a7) DB+L/CKD 90days; b) DQ; b1) Natural compacted DQ; b2) DQ+CKD 7days; b3) DQ+CKD 28days; b4) DQ+CKD 90days; b5) DQ+L/CKD 7days; b6) DQ+L/CKD 28days; b7) DQ+L/CKD 90days.

3.7 Scanning Electron Microscope (SEM) Results

Figure (5) shows the micrographs of natural and treated samples. Figure (5a) represents the natural DB sample; it can be easily to discriminate the plates (sheet structure) of clay minerals. Figure (5b) illustrates the formation of floccules due to flocculation process which lead to increase of pores diameter (DB sample treated with 8% CKD and after curing for 7 days). Figure (5c) demonstrates the formation of ettringite mineral having prismatic crystals (DB sample treated with 8% CKD after curing of 90 days). When comparing between the micrograph of Figure (5b) with this of Figure (5d) it is indicated that the size of pores decreased with increasing curing time from more than 300µm for 7 days (Figure 5b) to about 40µm for 90 days (Figure 5d).

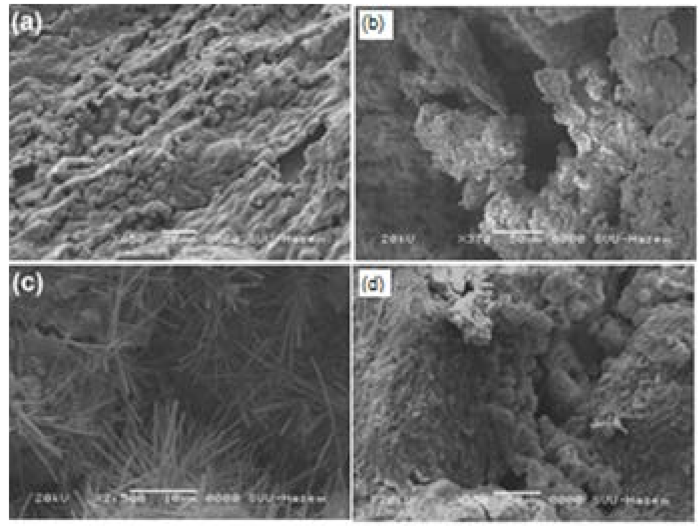

Figure 5. Micrographs of a) DB Natural soil. b) Floccules of DB treated with 8% CKD and cured for 7 days. c) Ettringite mineral of DB treated with 8% CKD and cured for 90 days. d) Size of pores of DB treated with 8% CKD and cured for 90 days.

4 CONCLUSIONS

Form the results it can be concluded that; Dakhla Formation is expansive shale (≥ 90% free swelling) due to its high content of expansive clay minerals and need to be stabilized. Based on pH-test it was founded that the optimum contents of additives used for stabilization of Dakhla Formation were as follow; 4% if using lime, 10% if using CKD, and 2% lime with 8% CKD in the case of using a mixture of them.

Unconfined compressive strength values and ultrasonic velocities of the treated samples (qu- and Vp-values) revealed that using CKD alone can increase the strength and the velocity of the treated samples more than that using lime, or than using a mixture of lime and CKD. Also the compressive strength and the ultrasonic velocity increased with increasing curing time to about 28 days. As with increasing curing time from 28 to 90 days, the strength began to decrease, that due to formation of ettringite mineral in elongated fibrous crystals form which its growth stress lead to formation of micro-cracks resulting in a decrease of compressive strength and ultrasonic velocity of the treated samples.

In general, the treatment program of the stabilized samples lead to decrease the free swelling percent but the high percent of free swelling for some treated samples proved the formation of ettringite mineral which considered as expansive mineral. Ettringite result from the hydration of calcium sulfate, which present in the shale samples, lime and CKD. Its prismatic crystals (Figure 5c) leading to increase the volume of the treated samples.

Increasing Vp-values with increasing curing time proves the decreasing of pore size in treated samples. For DB sample the Vp reaches its higher velocities (1373 m/sec) when treated with 8% CKD and cured for 28 days. According to DQ Vp increased to its maximum then stabilized with 12% CKD and cured for 28 days.

The treatment program results indicate that Dakhla shale is moderately swelling shale which needs to be stabilized when used as sub-base or sub-grade. It is best stabilized with optimum CKD content which ranges between (8-12%) at optimum water content ranges between (32-33%). Its geotechnical properties will also enhanced with increasing curing time; if there is enough water, CKD, and clay minerals content which are needed for pozzolanic reactions. Increasing curing time of the treated shale from 28 to 90 days lead to decrease of its geotechnical properties that due to formation of ettringite crystals which resulting in formation of micr-cracks as discussed above. To avoid the problems of ettringite crystals, must be emphases the following: In case of, sulfate (Gypsum) bearing sample treated with lime and CKD requires to special technical methods in situ. National Lime Association [24] reported that these technical methods in situ include "two applications of lime (and/or CKD), the first before the first mixing and the second after the mellowing period. The moisture content of the soil is raised to 5% over the optimum during a multi-day mellowing period to soluble as many as sulfate as possible and to force ettringite to form before compaction. Once formed, ettringte is relatively stable and is unlikely to cause further problems. After the mellowing period, additional lime (and/or CKD) is added to the soil and construction proceeds normally.

The use of ultrasonic p-wave velocity method is a simple and practical (non-destructive) tool to evaluate the stabilized soils using lime, cement kiln dust, and lime/cement kiln dust and would need many studies to establish a guideline and standard specification.

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