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Effect of enhancing subgrade by additives on the structural pavement section.

M. S. Eisa [1*], M. E. Basiouny [2], A. Mohamady [3], M. Mira [4]

1- Civil Engineering Department, Benha Faculty of Engineering, Benha University, P.O. 13512, New Benha, Qalubiya Governorate, Benha, Egypt;
E-mail: mohamedeisa524@bhit.bu.edu.eg
ORCID: 0000-0002-4111-1829

2-Professor, Civil Engineering Department, Benha Faculty of Engineering, Benha University, Benha, Egypt; E-mail: mohamed.bassyoni@bhit.bu.edu.eg.

3-Professor, Construction Engineering and Utilities Department, Faculty of Engineering, Zagazig University, Zagazig, Egypt:
E-mail: dr_amohamady@yahoo.com

4-Ph.D. candidate, Benha Faculty of Engineering, Benha University, Benha, Egypt;
E-mail: Mahmira2010@gmail.com

الملخص العربى :

اهتمت مصر مؤخرا بسرعة تنفيذ مشروعات الطرق. لتحسين التقدم اقتصاديا لسهولة الحركة التجارية. إلا ان التحدي الذي يواجه معظم تلك المشاريع هي تأسيسها أحيانا على التربة الضعيفة مثل التربة الطينية المنتفشة. لذا فإن هذه الدراسة هي محاولة لتحسين خصائصها وزيادة قوتها كطبقة تأسيس لقطاع الرصف الإنشائي. وذلك باستخدام مزيج من التثبيت الحبيبي (بالإحلال) والكيميائي للتربة، حيث تم تطبيق التثبيت الحبيبي أولاً بخلط الرمل الطبيعي بنسب مختلفة 20٪، 35٪، و50٪ من الوزن الكلي لعينات التربة الطينية لإيجاد أقل نسبة لأضافتها اليها لتحسينها لتربة طينية رملية مقبولة كطبقة تأسيس وفقا للكود المصري للطرق. ثانياً التثبيت الكيميائي للتربة الطينية الرملية لزيادة قوة تحملها للأحمال العالية بإضافة (الجير المطفي، غبار الأسمنت) بنسب 2٪، 4٪و6٪ من الوزن الكلي لعينات التربة الطينية الرملية. تم إجراء برنامج عملي يتكون من اختبارات خصائص وقوام التربة، نسبة تحمل كاليفورنيا، بروكتور، معامل المرونة الرجوعي واختبار لوحة التحميل. أظهرت النتائج أن 50٪ من الرمل هي أقل نسبة يمكن خلطها بالتربة الطينية لتحسينها لتربة طينية رملية مقبولة كطبقة تأسيس، وان استخدام مزيج من التثبيت الحبيبي والكيميائي بإضافة 6٪ من الجير أو غبار الأسمنت من إجمالي وزن العينة أدى لزيادة قوة تحملها. في حين أن أفضل أداء حدث عند خلط 44٪ رمل و44٪ طين و6٪ جير و6٪ غبار اسمنت من إجمالي وزن عينة التربة. حيث انه يزيد من معامل المرونة الرجوعي لها وقدرتها على مقاومة الهبوط، فيؤدي إلى تقليل سمكات طبقات الرصف وبالتالي يعظم الفوائد الاقتصادية لتكلفة انشاؤه.

Abstract

The Egyptian government recently concerned to rapid implementation of highway projects. due to its directly reflected on pushing of economical and investment wheel according to the facility of trading movement. The main challenge facing most of highway engineers in such these projects is the weak subgrade soil such as swelling clayey soil. So, this study is a trial to improve the properties and increase the strength of weak clayey swelling soil for use as a subgrade for pavement structural sections. This trial was developed using a mix of granular and chemical stabilization for the soil. Granular stabilization was applied firstly by mixing natural sand at different percentages of 20%, 35%, and 50% of the total weight of clayey swelling soil samples to find the minimum percentage that could be added to improve it to sandy clayey soil which is acceptable as a subgrade according to the Egyptian highway specification code. Secondly, chemical stabilization was applied to enhance sandy clayey soil to increase its strength properties. This was performed by adding chemical additives (lime, cement kiln dust (CKD)) at different ratios of 2%, 4%, and 6% of the total weight of the samples of enhanced sandy clayey soil. An experimental program was conducted consisting of characteristics and consistency tests, the California bearing ratio (CBR) test, a proctor test, a modulus of resilience (MR) test and plate loading test. The results showed that 50% sand was the minimum percentage that could be mixed with swelling clayey soil for granular stabilization to be enhanced and become sandy clayey soil, which is accepted as a subgrade layer according to the Egyptian highway specification code. Furthermore, using a mix of granular and chemical stabilization increased the compressive strength of this enhanced subgrade by adding 6% lime or cement kiln dust (CKD) of the total sample weight. While the best performance occurred at sections contained a combination of 44% sand, 44% clay, 6% lime and 6% CKD by total weight of the soil sample. It increases MR and has the ability to resist deformation. So that it will lead to reduction in the required thickness of the pavement layers. accordingly, lead to economical cost benefits.

Keywords: Subgrade strength, Additives, Consistency tests, CBR test, modulus of resilience test – plate loading test

1. Introduction and background

The national road project that Egypt is implementing with a total length of 7000 km and at a cost of 175 billion Egyptian pounds is one of the most important axes of the comprehensive development plan for Egypt 2030 [1]. Because of its importance in linking housing communities safely together which led to reduce accidents, and maximizing the economic impact by linking industrial areas with airports, seaports and facilitating trade movement among them, which is the most important incentive for attracting investments. The national road network is the most important project undertaken recently by the Egyptian government. As The government needs to rapid completion of these projects in a very short time for achieving the desired goal. But sometimes the main challenge facing the highways engineers that some roads are required to be constructed in some places have soil with a weak subgrade of the pavement section. Like, very soft clay and/or swelling soil. As a result, it recently observed some defects in the wearing surface of the pavement section of these roads. Therefore, many studies were carried out to try and evaluate solutions to this problem in new methods. This study is one of them.

For centuries many researchers are carried out in this field used a granular and / or chemical stabilization. Granular stabilization was used by removing the poor soil (a portion of the poor soil) and replacement with a higher shear strength soil such as sand which is used in this study . However replacement is very costly and impractical in highway projects due to the huge volume of these projects as well as in some regions the unviability of the aggreagate or the shortage of the suitable fill materials makes replacement of weak subgrade soil uneconomical [2-4] . So all studies tended to get the optimum percentage of sand can be added to weak subgrade soil to improve its properties. Kollars and Athanasopoulou [5] found that adding up to 60% of sand by weight of the soil can be added to enhance swelling soil. While Nair and Salini [6] show that 50% can be added to enhance swelling clayey soil to be accepted as a subgrade. But as mentioned previously Sometimes needing for amount of sand depending on the type of soil to increase improving properties of weak swelling soil. This maybe not a suitable and uneconomical solution gives the desired characteristics. So, needing a mix of granular and chemical stabilization may be the most preferable solution to have the desired properties. On the contrary, with an economical view and for demanding larger strength resistance especially for large projects of highways, it is recommended to mix different additives to enhance clayey soil with sand. Kollars and Athanasopoulou [5] recommended that in their study.

Based on literature reviews, this study was carried out in two approaches. The first one is enhancing swelling clayey soil using granular stabilization by mixing different ratios of sand (20%, 35%, and 50%) of the sample total weight to accept as a subgrade. The second approach is chemical stabilization to increase the strength of enhanced subgrade soli. That by adding other additives (lime, cement kiln dust,) with different percentages (2%, 4%, and 6%) of the sample total weight to enhanced clayey soil with sand to get the optimum percentages can be added to improve and increase subgrade resistance to satisfy the desired characteristics. The basis for selecting the dosage of various modifiers is based on previous studies [6-8] which added higher dosages of additives to native soil directly (chemical stabilization only), while in this study additives were added with small amount to increase improvement characteristics of sandy clayey soil, also to have an advantage of economic viewpoint. So, this study try to evaluate of using mix of granular and chemical stabilization to have both benefits effect on the performance of structural pavement . Cementitious stabilization using lime and CKD stabilization have been studied extensively by many researchers [7-14]. Daipuria and Trivedi [15] and Ramteke et al. [16] found that adding 20% to 40% of sand mixed with 2% cement increased soil resistance strength. While other researchers added CKD only to swelling soil as Keerthi et al. [17] found that using up to 50% of CKD added only to swelling soil can increase its strength resistance. Also, Afaf et al. [18] proved that 16% of CKD improved stabilization of expansive soil in the Sohag region, Egypt. While Mosa et al. [19] exhibited that adding 20% of CKD with curing for 14 days improved properties of poor subgrade soil. Lime also was used in many studies to improve the characteristics of swelling clayey soil. Afaf et al. [18] showed that mixing of 6% lime of the soil total weight gave satisfactory results of swelling soil. Nair and Salini [6] showed in their study that adding 1% lime to problematic soil mixed with 50% sand gave good properties of soil. Cement stabilized subgrades have been extensively used to improve the engineering performance of pavement structures. Due to the effects of cementitious hydration, pozzolanic reaction, as well as, cation exchange, chemical bonding is generated between fine soil particles. Therefore, the geotechnical characteristics of difficult clay soils will be improved in terms of plasticity, strength, stiffness, and durability. The cement modified soils will then function as a new pavement layer which partially or totally preplaces the thickness of granular base layer as commonly found in traditional road constructions [20-21]. Other design agencies, including AASHTO (22), have recently shifted towards the resilient modulus (MR) for characterizing the strength of pavement materials. The immediate effects of lime treatment on the resilient modulus were studied by Thompson (*23*), McDonald (*24*), and Neubauer and Thompson (*25*). Their research shows that the *MR* of samples treated with 4 to 6 % lime (without curing) are 3 to 10 times the moduli of untreated samples. The long-term effects, on the other hand, often induce a 1,000 percent or more increase in *MR* or stiffness over that of the untreated soil according to Little (*26*).Adam et al [27] reported that adding lime to the subgrade decreased the required thickness of the pavement structure by about 50-60%. Moreover, adding lime significantly reduces the swelling potential (SP), liquid limit (LL), plasticity index (PI), and maximum dry density (MDD) of the subgrade soil, and increases the optimum moisture content (OMC), shrinkage limit (SL), and material strength [28-30].

2. Tested materials and experimental design

2.1. Tested materials

2.1.1. Natural soil

Very soft swelling clay is the natural soil used in this research as a subgrade. It was obtained from road construction in ELkasasin village in Ismailia governorate, Egypt. It was brought from excavation about 2m deep from the ground surface (foundation level according to geotechnical report). It was collected from different locations on the site. Table 1 shows the properties of the natural soil.

Table 1 Properties of tested materials

		Samples											
	symbol	**S0**	**Sos**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
% percent	**natural soil**	100		80	65	50	49	48	47	49	48	47	44
	sand	0	100	20	35	50	49	48	47	49	48	47	44
	lime						2	4	6				6
	cement kiln dust									2	4	6	6
properties	**L.L**	42	0	36.2	30.1	28	27.9	27	26	26.8	25.3	24.2	25
	PL	26.5	0	25.1	20.4	18.7	18.5	18	17.2	17.8	16.6	15.8	16.5
	P.I	15.5	0	11.1	9.7	9.3	9.4	9	8.8	9	8.7	8.4	8.5
	CBR	4.9	7.6	6.2	9.1	9.8	13.5	17.9	20.8	18.4	23	29.5	37.5
	γ_d(gm/cm3)	1.65	1.86	1.78	1.85	1.88	2.1	2.2	2.5	2.2	2.47	2.8	3.03
	%O.M.C	14.3	10.7	13	12.8	12.5	9.1	8	7.8	10	9.5	8.5	8.8
	%swelling	4.31	0.00	3.12	2.85	2.50	2.16	1.98	1.55	1.55	1.47	1.26	1.01
	AASHTO specification	A-7-6	A-3	A-6	A-6	A-2-4	A-2-4			A-2-4			A-2-4

2.1.2. Natural sand

The natural sand was used to enhance the undesired properties of the natural soil (very soft clay) by mixing it with different percentages of natural sand. The natural sand was mixed with different percentages (20%, 35%, and 50%) of the sample total weight. Table 1 shows the properties of the natural sand and the properties of mixes of natural soil enhanced with different percentages of natural sand.

2.1.3. Lime

The used lime is one of the commercially hydrated lime $CaOH_2$ which produced by Tura company. Analysis supplied by the manufactures is indicated in table 2.

Table 2 Specifications of lime and cement dust

Chemical composition	lime	cement dust
% Ca $(OH)_2$	70-85	---
% SiO2	≥2%	11.9
% MgO	≥1%	1.7
% Fe_2O_3	≥0.5%	3.4
% Al_2O_3	≥0.5%	9.9
% $CaCO_3$	≥15%	---
% H_2O	0.5-1.05	---
% SO_3	---	1.48
% Na_2O	---	0.5
% K_2O	---	0.1
% CaO	---	55.06

2.1.4. Cement kiln dust (CKD):

Another additive used in this study is Ordinary cement kiln dust was produced and collected by the Tura factory. The chemical analysis of CKD is given in table 2. The CKD had a density of 3.08 g/cm3 and a bulk density of 1.17 g/cm3 and a porosity of 0.62.

2.2. Experimental design

The goal of this study is to evaluate effect of subgrade enhanced by using a combination of granular and chemical stabilization on structural pavement section. The granular stabilization was used firstly in this study by mixing a natural soil with different percentages of natural sand and hence finally chemical stabilization was carried out by adding different percentages of additives (lime – CKD) to natural soil enhanced by sand to increase improving properties of subgrade. To find the goal of the study, an experimental program was designed and described in the following steps:

1- The natural soil samples were air-dried and pulverized to pass sieve no. 4 (4.75 mm), hence enter the oven and leave it for 24 hrs. at the temperature of 110°c to control and check the humidity of the sample. Then take a sample S_0. The basic properties of the sample were determined using a group of tests including:

a. Free swelling test. Figure 1 shows the determination of free swelling ratio by Free swelling test apparatus

Figure 1. Free swelling test apparatus.

b. Grain size distribution according to AASHTO T-27 [31] and hydrometer analysis. The physical properties of the soil were studied and the soil was classified as A-7-6 according to the AASHTO classification system, while according to a unified classification system were classified as CL. Figure 2 shows the grading curve of natural soil, natural sand, and the treated soils with different percentages of sand.

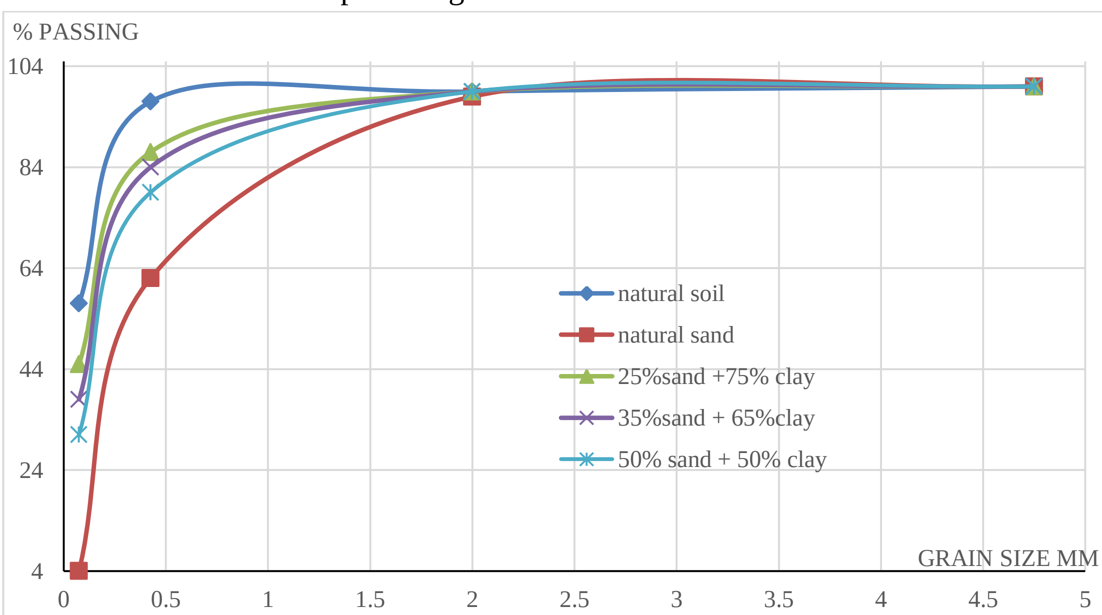


Figure 2. The grading curve of natural soil, natural sand, and the treated soils with different percentages of sand.

c. Liquid limit (L.L) and plastic limit (P.L) using the Casagrande method. Figure 3 shows the determination steps of L.L and P.L by the Casagrande apparatus.

Figure 3. Determination of L.L and P.L by Casagrand apparatus.

d. CBR test. Figure 4 shows the determination of CBR by CBR apparatus.

Figure 4. Determination of CBR by CBR apparatus

e. Procter test to determine optimum moisture content OMC and maximum dry density MDD of soil samples. Figure 5 shows the determination of OMC and MDD by proctor test.

Figure 5. Determination of OMC and MDD with a proctor test.

All tests were carried out according to the Egyptian specification code of soil mechanics. .[32]

2. Granular stabilization was carried out to Enhance the natural clayey soil. That by making samples containing mixes of natural clayey soil and different percentages of natural sand (20%, 35%, and 50%) of the total weight of the sample to make samples S1, S2, S3 respectively. as shown in table 1.
3. A Group of tests mentioned above repeated for samples S1, S2, and S3 to get the minimum percentage value of sand that can be mixed with natural soil to be enhanced and achieve the desired and acceptable properties to use as a subgrade according to Egyptian Highways specification code. [33]
4. Chemical stabilization was carried out based on the previous step. That by making samples containing natural clayey soil enhanced with a minimum percentage value of sand gained from the previous step and adding additives (CKD – lime) with different percentages 2%, 4%, and 6% respectively of the total weight of the sample to form samples S4:S9 respectively as shown in table.1
5. A Group of tests mentioned above was repeated and carried out for samples from S4: S9 to show the effect of additives on the properties of enhanced clayey soil with sand to improve and increase its strength and durability.
6. From step 5 we can get the most optimum percentages from lime or CKD that can be added to enhanced sandy clayey soil to improve its strength. Hence forming sample (S10) containing a mix of lime and CKD at their optimum percentages gained from step 5 .
6. A Group of tests mentioned above was repeated and carried out for sample S10 to show the effect of additives on the properties of enhanced sandy clayey soil to improve and increase its strength and durability.
7. Resilience Modulus test (MR test)

Determination of resilient modulus has important rule for characterizing materials in pavement design. So, MR test carried out in this study on samples representative the following:

a- Natural clayey soil only (S0),
b- Natural soil enhanced with optimum percentage of sand (sandy clayey) gained from step 3,
c- Sandy clayey soil containing optimum percentage of lime gained from step 5.
d- Sandy clayey soil containing optimum percentage of CKD gained from step 5.
e- and finally sandy clayey soil enhanced with a combination of lime and CKD at their optimum percentage gained from step 5.

The representative samples prepared at compaction mold with a dimension of 200mm high and 100 mm diameter, and compacted at their optimum moisture content and maximum dry density according to the modified Procter compaction effort in six layers accordance with

AASHTO T 180-20. Or by compressed statically at strain rate of 2.27mm/min in specialized molds and carefully extracted with the help of a sample extruder. as shown in figure 6 below:

a- mixing b- static compacting c- extraction of sample

Figure 6. preparing samples for MR test a- mixing, b- static compacting for sample and c- extraction of sample.

Samples were left one day for curing before de-molding and testing. the final height, diameter and weight of each specimen were recorded before testing. a rubber membrane was stretched around the specimen by the membrane expander and then the membrane was sealed to the top and bottom caps by means of O-ring as shown in figure 6. MR tests were conducted in accordance with the AASHTO T 307-99 standard test procedure using the universal test machine located at Arab Contractor company Laboratory, Egypt as shown in figure 7.

Figure 7. Repeated loading triaxial cell and soil specimen (universal test machine UTM).

The Repeated Load Triaxial Test (RLTT) to determine Mr, was conducted Results from duplicate tests at different confining and deviatoric stresses are presented in table 3.

Table 3 The resilient modulus values at different confining and deviatoric stress.

confining stress (psi)			deviotaric sress (psi)					Mr (psi)				
2	4	6	2	4	6	8	10	S0 (clay)	S3(clay +sand)	S6(clay +sand+lime)	S9 (clay +sand+CKD)	S10(clay sand+lime+CKD
2			2					7836.075192	22504.39583	31087.7801	33808.25107	42631.6666
2				4				6476.0952	18537.3936	24874.18769	28315.11815	38441.997
2					6			5834.32	15320.16	22583.351	23635.324	33721.05
2						8		5075.8584	13328.5392	19747.51537	20562.73188	26302.419
2							10	4974.341232	11995.68528	18682.76383	18506.45869	22041.9352
	4		2					9351.761516	23631.5	33835.04475	36457.72362	45452.61234
	4			4				7761.962058	20141.515	27216.38625	30530.75613	40576.616
	4				6			6908.146232	16747.5514	24783.45355	25443.37466	35718.22816
	4					8		6079.168684	14801.84523	22871.11912	22750.1697	28711.22306
	4						10	5288.876755	12521.66071	19984.00721	20775.15273	23440.10076
		6	2					10471.97598	24965.05428	36626.735	39794.56616	47902.20655
		6		4				9215.338858	22363.76385	31544.00188	32730.00945	42856.98289
		6			6			7556.577864	19735.54761	27837.12137	27702.9069	37715.59751
		6				8		6649.78852	17481.68854	24336.66681	25098.55807	30749.72581
		6					10	6018.058611	14484.61838	21402.80012	22042.78878	25269.76968

The test begins with a conditioning phase of 1000 cycles, and continues into the recorded test which is composed of 15 sequences. Each sequence consists of 100 cycles according to The AASHTO T307 protocol for subgrade soils. The specimen is constantly confined at stresses of (6 psi), (4 psi), and (2 psi). Additional deviatoric stresses of (10 psi), (8 psi), (6 psi), (4 psi), and (2 psi) are applied cyclically at each confining stress state, through the Haversine load pulse for 0.1 second duration and 0.9 second rest period. Two Linear Variable Differential Transducers (LVDTs) were mounted externally to the load cell in the UTM to measure deformations. The load shape was haversine with 0.1 second loading duration and 0.9 second as rest period for subgrade soils. The resilient modulus was calculated as the average of the last five cycles of each sequence. Resilient modulus test is a laboratory test that can be used to assess the behavioral response of stabilized subgrade under cyclic/repetitive loading. Also measured the dynamic stiffness values of pavement layer systems. At this test cylindrical specimens are subjected to a different low confining stress, with pulse applications of cyclic axial loads. The constant confining stresses of the specimen represent the lateral stresses caused by overburden pressures and applied wheel loads as mentioned George 2004 in his study [34]. Deviatoric stresses are additional stresses created when traffic is permitted on the roadway.

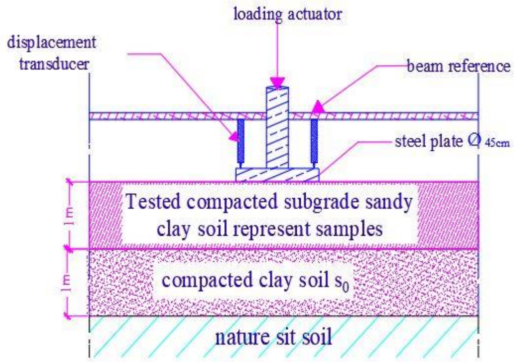
The resilient modulus test is an attempt to simulate actual field conditions, providing different stress states to represent vehicle loading over pavements and subgrades. The resilient modulus value is expressed as the ratio of applied deviator stress and the resilient axial strain recovered after removal of the deviator stress [35]. The resilient modulus at the different confining and deviatoric stresses shows in table 3.

7. plate loading test

An extensive field static plate loading testing was conducted according to ASTMD1196 to evaluate the in situ bearing characteristics of four different subgrade soils represent the following samples:

a- Natural soil enhanced with optimum percentage of sand (sandy clayey) gained from step 3,
b- Sandy clayey soil containing optimum percentage of lime gained from step 5.
c- Sandy clayey soil containing optimum percentage of CKD gained from step 5.
d- and finally sandy clayey soil enhanced with a combination of lime and CKD at their optimum percentage gained from step 5.

So four different experimental sections prepared in situ represent the four samples with a dimension of 2m depth , 2.15 m width and 2.8 m length as shown in figure 8 (a through d) .Each experimental section prepared and formed from 1m depth of compacted nature clayey soil, over it the other 1m depth contained the subgrade soil tested , which placed at layers of 15 cm each , and mixed homogenously by manual laborer , and compacted using rollers at its O.M.C and maximum dry density for each layer up till 1m depth to the surface of the section . Then sand cone test carried out to check the achieved density. Plate loading device was set up. the strain gages were installed on the top of the subgrade. The footing was loaded with a hydraulic jack actuator to apply an incremental static load on a circular steel plate of 45 cm diameter placed on a subgrade soil section. 1 cm thick rubber pad was attached to the bottom of the loading plate to ensure full contact and minimize stress concentrations at the edge of the plate. The peak load was selected to simulate a single wheel load of 40KN (equivalent to an axial load of 80KN and a tire contact pressure of 80 psi) then all corresponding values of settlements are measured and modulus of elasticity of subgrade soil for each section as shown in table 4.



a – Typical experimental cross sections

b – Digging and measuring experimental sections

C – Mixing and preparing of different subgrade soil phases

D– Compacting and plate loading test carried out of different subgrade soil

Figure 8 – plate loading test carried out for different experimental subgrade

Table 4 Average Elastic modulus values and displacements for subgrade soil samples at different loading plate stresses.

Stress ρ (Kg/cm²)	Average settlement Δ(mm)			
	S3	S6	S9	S10
0	0.000	0.000	0.000	0.000
0.4	0.150	0.125	0.066	0.062
0.8	0.233	0.199	0.148	0.104
1.2	0.348	0.287	0.206	0.160
1.6	0.495	0.362	0.268	0.204
2	0.685	0.428	0.331	0.279
2.4	0.848	0.498	0.411	0.348
2.8	0.984	0.602	0.485	0.407
3.2	1.200	0.698	0.563	0.468
3.6	1.376	0.800	0.629	0.538
4	1.459	0.891	0.698	0.617
4.4	1.625	0.978	0.759	0.690
4.8	1.750	1.031	0.810	0.724
5.2	1.868	1.133	0.884	0.791
5.6	1.957	1.208	0.970	0.829
6	2.062	1.289	1.029	0.865
Average Es (kg/cm²)=1.18*ρ*a/Δ	768.196	1178.376	1544.224	2823.867

3. Results and discussion

This section presents the results of the study program tests. Analyzing these results will be presented in the following subsections:

3.1. Evaluation of grain size distribution.

Grain size analysis was carried out for the soil according to AASHTO T-27 [31] and hydrometer analysis. The natural clayey soil is classified as A-7-6 and natural sand used is classified as A-3.

Natural soil mixed with 20% and 35% natural sand to form samples (S1, S2) is classified as A-6, which means still poor for use as a subgrade according to Egyptian Highways specification code [33]. While the natural soil mixed with 50% natural sand of the total weight of the sample was classified as A-2-4 that is acceptable for use as a subgrade according to Egyptian Highways specification code. Figure 2 shows the grading curve of natural soil, natural sand, and the treated soils with different percentages of sand. Also, the samples from S4: S10 contained 50% of natural soil and 50% of natural sand when mixed with different percentages by additives (lime – CKD). They were classified as A-2-4 for all samples.

3.2. Effect of granular stabilization on soil properties

Granular stabilization is carried out by mixing natural sand with different percentages (20%, 35%, and 50%) of the total weight of the samples with natural clayey soil. It enhances the properties of natural clayey soil as shown below:

3.2.1. Effect of granular stabilization on free swelling ratio.

Table 1 results show that the free swelling ratio decreased by increasing percentages of sand (20%, 35%, and 50%) mixing with natural clayey soil of the total weight of the sample. Fig. 9 shows the relation between the free swelling ratio and sand percentages. It shows free swelling ratio decreased from 4.31% to its optimum value of 2.5% when mixing 50% sand at sample S3. That behaves may be due to the reduction of percentage clay in the sample, also the fine particles of clay fill the voids between particles of sand, leading to a reduction in swelling.

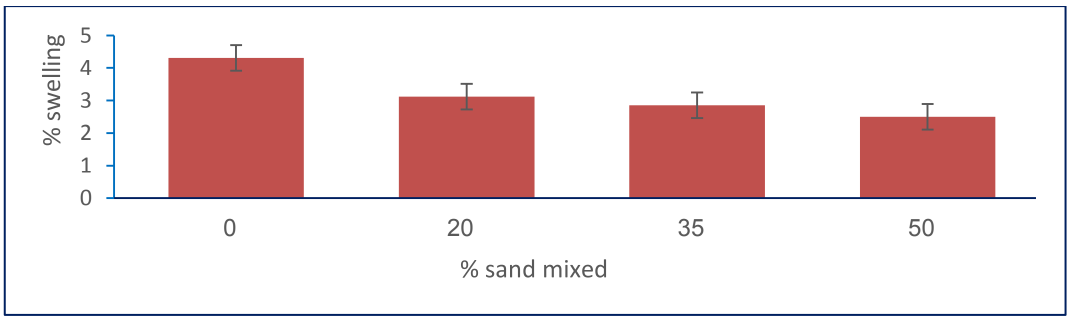


Figure 9. Effect of sand on % swelling.

3.2.2. Effect of granular stabilization on L.L

Table 1 results show that the liquid limit of the natural soil decreased by increasing percentages of natural sand mixed with it. L.L decreased from 42 to its min value of 28 at the percentage of 50 % of natural sand added to natural clay soil of the total weight of the sample. As shown in the sample (S3). Fig. 10 shows the relation between liquid limit and sand percentages.

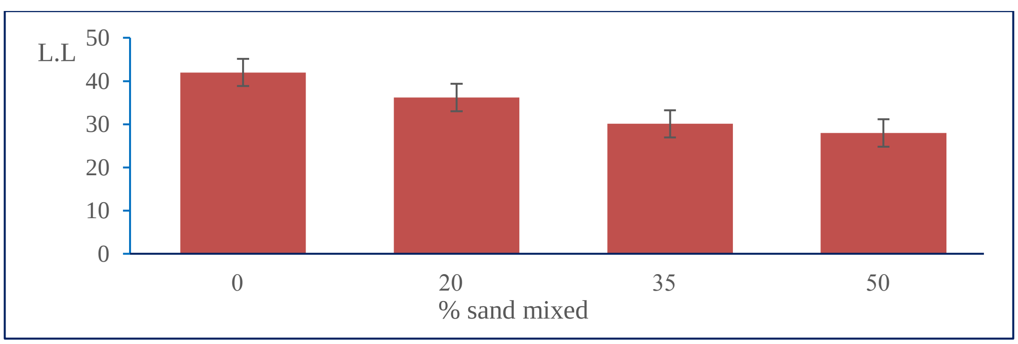


Figure 10. Effect of sand on L.L.

3.2.3. Effect of granular stabilization on P.L.

Table 1 results show that the plastic limit of the natural soil is decreased by increasing percentages of natural sand mixed with it. Fig. 11 shows the relation between plastic limit and sand percentages. It shows P.L decreased from 26.5 to its minimum value of 18.7 at the percentage of 50 % of natural sand mixed with natural clay soil of the total weight of the sample (S3).

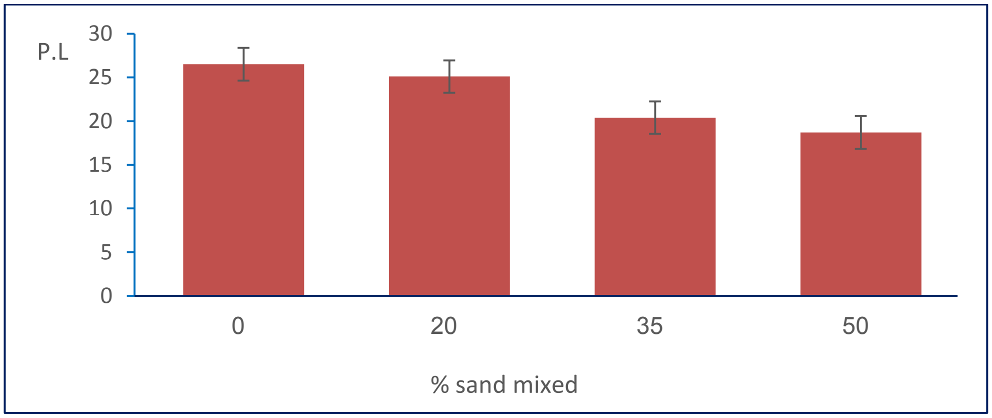


Figure 11. Effect of sand on P.L.

3.2.4. Effect of granular stabilization on P.I

Table 1 results show that the plastic index of the natural soil is 15.5 and decreased by increasing percentages of natural sand mixed with it. Fig. 12 shows the relation between plasticity index and sand percentages. It shows P.I decreased from 15.5 to its min value of 9.3 at the percentage of 50 % of natural sand mixed with natural clay soil of the total eight of the sample (S3).

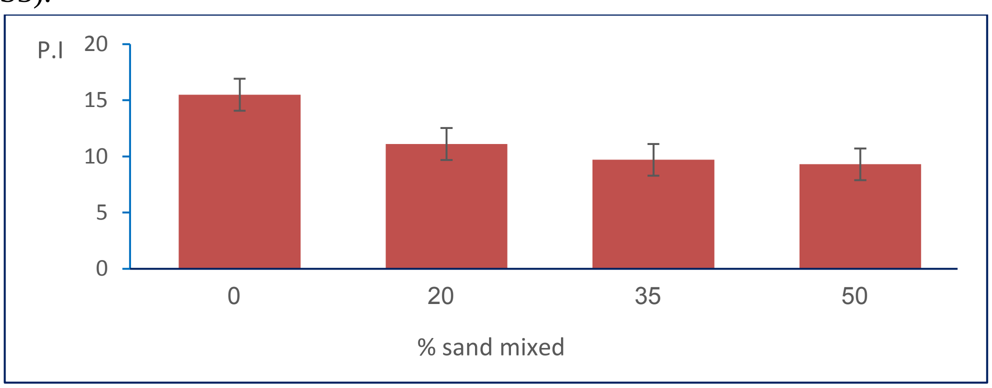


Figure 12. Effect of sand on P.I.

3.2.5. Effect of granular stabilization on CBR

From table 1 results show *CBR* of the natural soil is 4.9 and increased by increasing percentages of natural sand mixed with it. CBR increased from 4.9 to its maximum value of 9.8 at the percentage of 50 % of natural sand mixed with natural clay soil of the total weight of the sample (S3). Figure 13 shows the relation between California bearing ratio CBR and sand percentages.

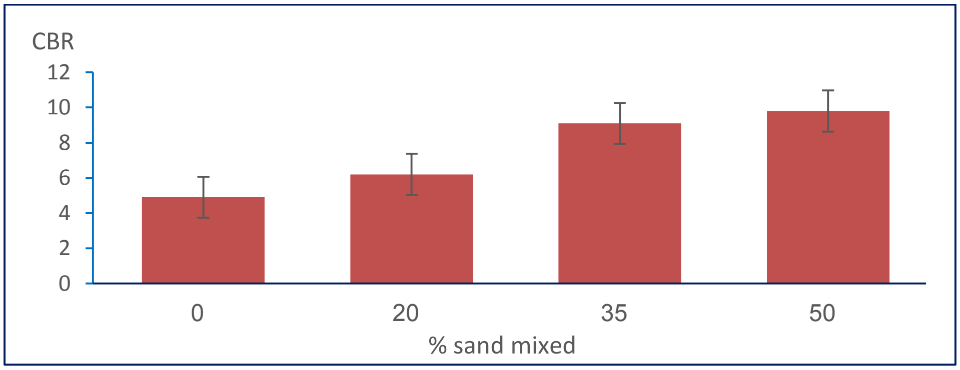


Figure 13. Effect of sand on CBR.

3.2.6. Effect of granular stabilization on OMC.

Table 1 results show OMC of the natural soil is 14.3 and decreased by increasing percentages of natural sand mixed with it. OMC decreased from 14.3 to its minimum value of 12.5 at the percentage of 50 % of natural sand mixed with natural clay soil of the total weight of the sample (S3). Figure 14 shows the relation between optimum moisture content OMC and sand percentages.

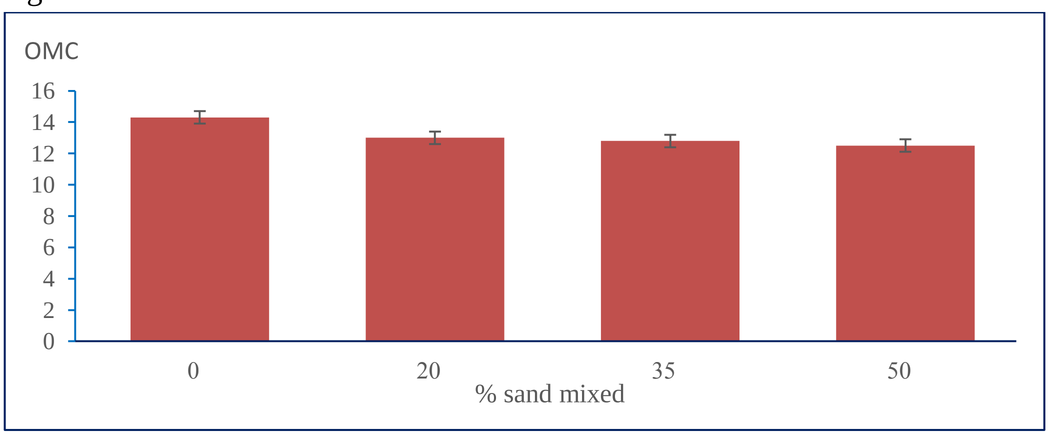


Figure 14. Effect of sand on optimum moisture content OMC.

3.2.7. Effect of granular stabilization on MDD

Table 1 results show MDD of the natural soil is 1.65 and increased by increasing percentages of natural sand mixed with it. MDD increased from 1.65 to its maximum value of 1.86 at the percentage of 50 % of natural sand added only to natural clay soil of the total weight of the sample (S3). Fig. 15 shows the relation between maximum dry density and sand percentages.

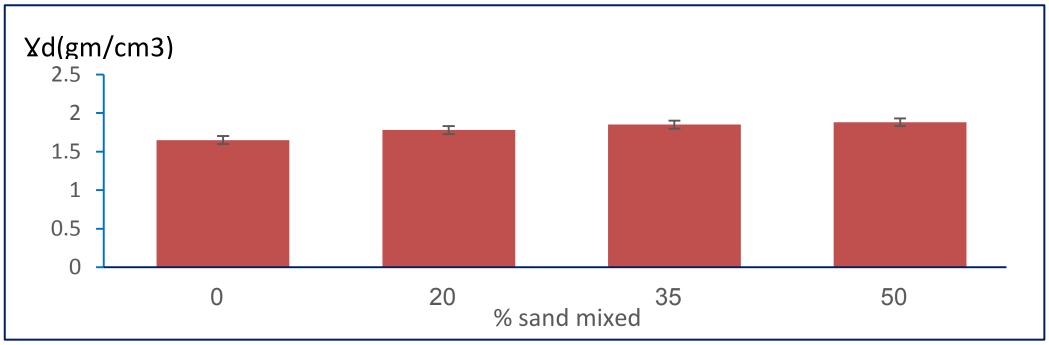


Figure 15. Effect of sand on maximum dry density.

3.3. Effect of chemical and granular stabilization on soil properties.

Based on previous results obtained in this study mentioned above. It was shown that sample S3 a sandy clayey that consists of 50% sand and 50% clay has the most enhanced properties of the soil. So, the minimum percentage of sand that can be mixed with the natural clayey soil is 50%. It can enhance the soil properties to accept as a subgrade in the pavement structural section according to the Egyptian Highways specification code [33] as shown in sample s3. Hence chemical stabilization was carried out for sample S3. That by adding additives (CKD - lime) with different percentages 2%, 4%, and 6% respectively of the total weight of the sample to form samples S4:S9. The following sub-sections show the effect of a combination of granular and chemical stabilization on soil properties.

3.3.1. Effect of chemical and granular stabilization on free swelling ratio.

In Table1 and Fig. 16 results showed that the swelling ratio decreased and reached to 1.55 and 1.26 at 6% lime or CKD was added to sandy clayey samples enhanced respectively at samples (S6, S9) which contain 6% lime or CKD respectively. Where reached to its optimum minimum value of 1.01 at sample S10 when a combination of 6% lime and CKD were added to sandy clayey samples.

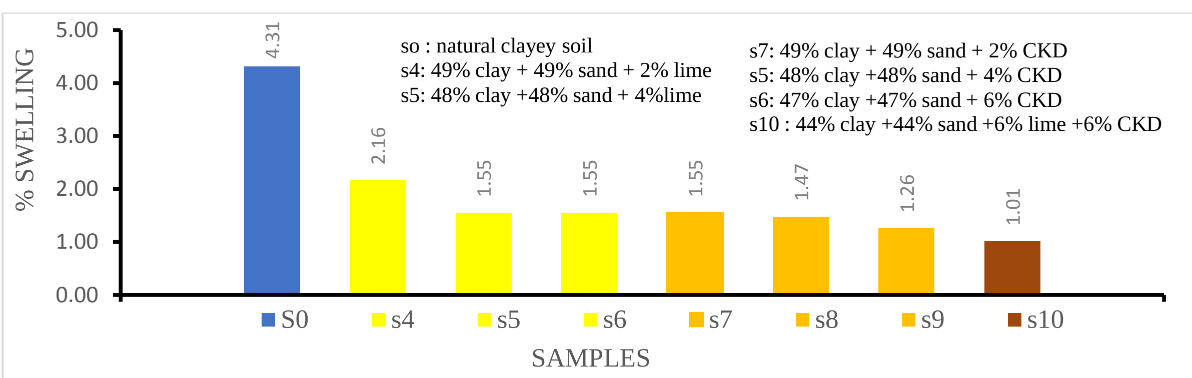


Figure 16. Effect of additives on % swelling

3.3.2. Effect of chemical and granular stabilization on L.L

In Table 1 and Fig. 17 results show that the L.L decreased with increasing percentages for both additives. But the higher decrease was remarked for adding CKD than lime. The L.L decreased from 42 to 26 and 24.2 in the case of adding 6% lime or CKD respectively. As shown in samples S6 and S9. Where the highest decrease noticed when adding a combination of 6% lime and CKD as shown in sample S10. Fig. 17 shows the relationship between additives percentages added to enhanced sandy clayey soil and L.L. It was shown that the L.L decreased with increasing of percentages content for both kind of additives.

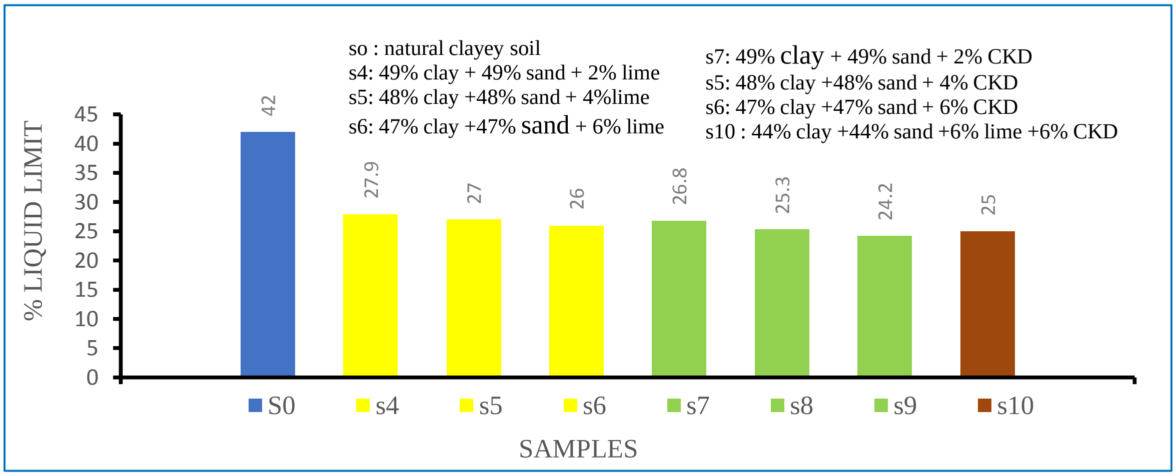


Figure17. Effect of additives on liquid limit

3.3.3. Effect of chemical and granular stabilization on P.L.

In Table 1 and Fig. 18 results show that the P.L decreased with increasing percentages for both additives. But the higher decrease was remarked for adding CKD than lime. The P.L decreased from 26.5 to 17.2 and 15.8 in the case of adding 6% lime or CKD respectively. As shown in samples S6 and S9. Where the highest decrease noticed when adding a combination of 6% lime and CKD as shown in sample S10. Fig. 18 shows the relationship between additives percentages added to enhanced sandy clayey soil and P.L.

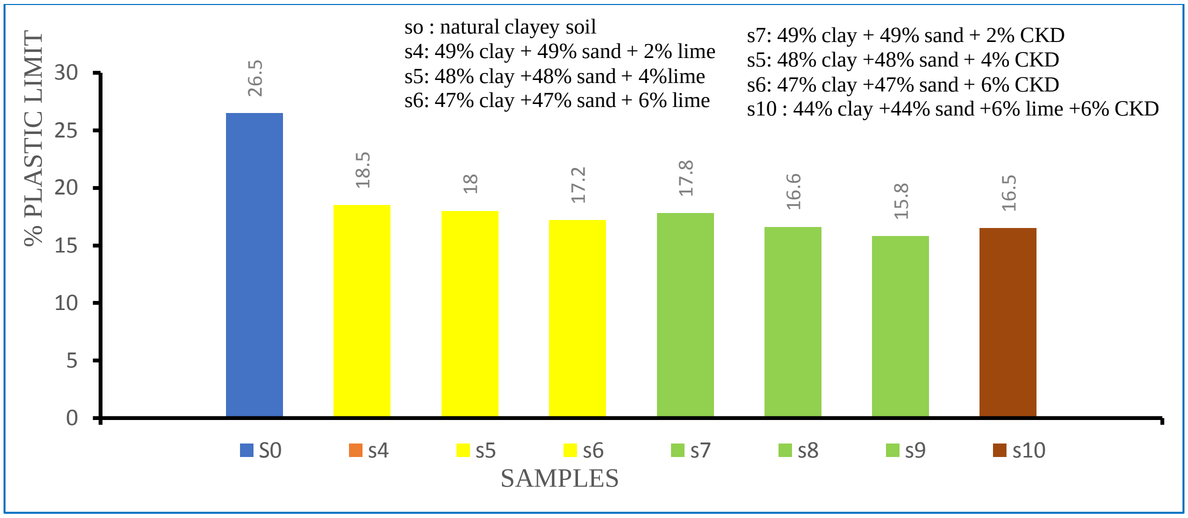


Figure 18. Effect of additives on the plastic limit.

3.3.4. Effect of chemical and granular stabilization on P.I

In Table 1 and Fig. 19 results show that the P.I decreased with increasing percentages for both additives. But the higher decrease was remarked for adding CKD than lime. The P.I decreased from 15.5 to 8.8 and 8.4 in the case of adding 6% lime and CKD respectively. Where the highest decrease noticed when adding a combination of 6% lime and CKD as shown in sample S10. Fig. 19 shows the relationship between additives percentages added to enhanced sandy clayey soil and P.I. It was shown that the P.I decreased with increasing of additives percentages content.

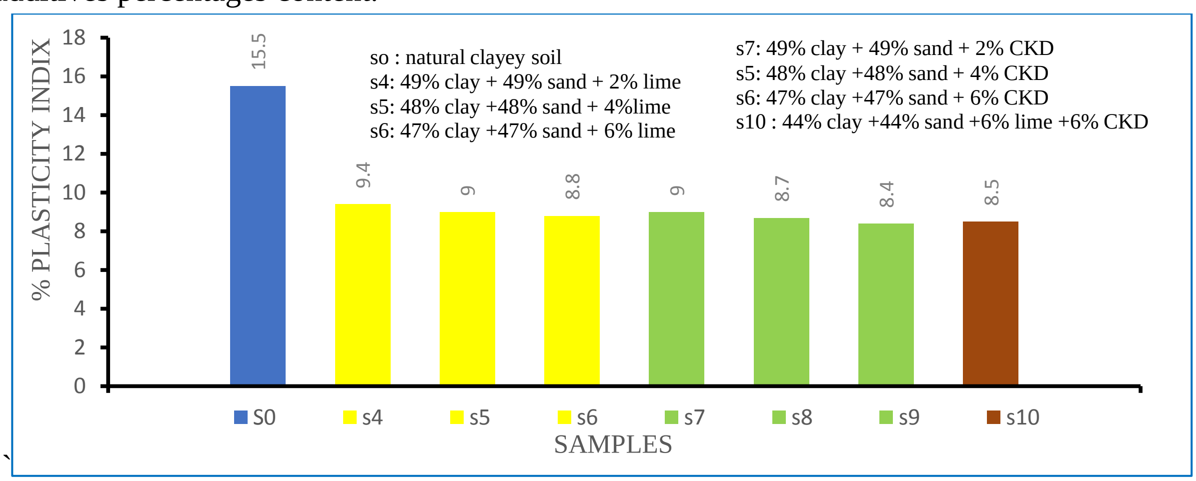


Figure 19. Effect of additives on plasticity index.

3.3.5. Effect of chemical and granular stabilization on CBR

In Table 1 and Fig. 20 results show that the CBR increased with increasing percentages content for both additives. But the higher decrease was remarked for adding CKD than lime. The CBR increased from 4.9 to 20.8 and 29.5 in the case of adding 6% lime or CKD respectively. Where the highest increase noticed when adding a combination of 6% lime and CKD as shown in sample S10. This behavior is suggested due to the chemical bond produced by the reaction of CKD or lime with components of the soil. Increasing the dose increases the bond leading to an increase of strength and consequently increase in CBR. Fig. 20 shows the relationship between additives percentages added to enhanced sandy clayey soil and CBR. It shows CBR was increased with increasing percentages content for both additives lime and/ or CKD.

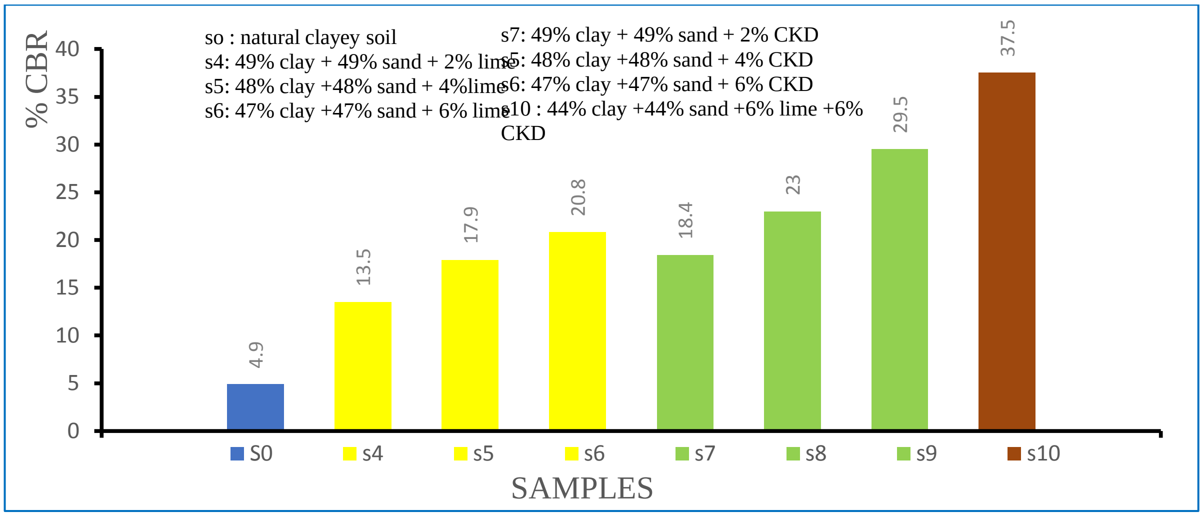


Fig. 20. Effect of additives on CBR

3.3.6. Effect of chemical and granular stabilization on MDD.

In Table 1 and Fig. 21 results show that with an increase in percentages of additives, the MDD of soil increased for both additives. A higher increase was remarked for adding CKD than lime. It is increased from 1.65 to 2.5 and 2.8 in the case of adding 6% lime or C.D respectively. Where the highest increase noticed when adding a combination of 6% lime and CKD as shown in sample S10. Fig. 21 shows the relationship between additives percentages added to enhanced sandy clayey soil and MDD. It was shown that the MDD increased with increasing of percentages content for both additives

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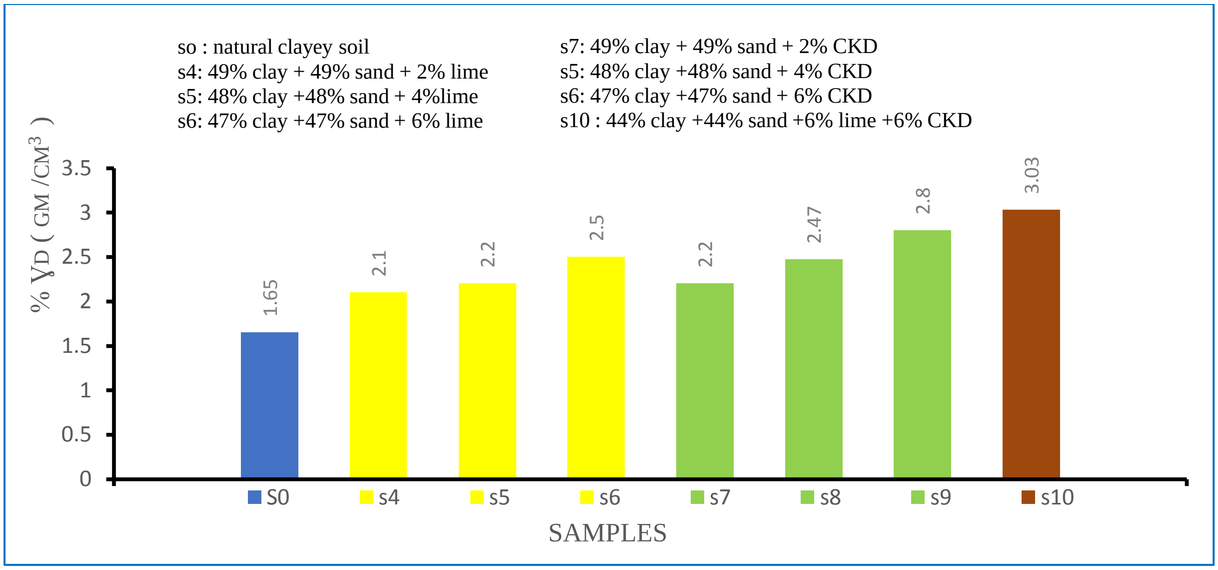

Figure 21. Effect of additives on maximum dry density.

3.3.7. Effect of chemical and granular stabilization on OMC.

In Table 1 and Fig. 22 results show that with an increase in percentages of additives, the OMC of soil goes on decreasing for both kinds of additives. A higher decrease was remarked for adding lime than CKD. It is decreased from 14.3% to 7.8% and 8.5% in the case of adding 6% lime or C.D respectively. Where the highest decrease noticed when adding a combination of 6% lime and CKD as shown in sample S10. Fig. 22 shows the relationship between additives percentages added to enhanced sandy clayey soil and OMC. It was shown that OMC was decreased with increasing of percentages content for both additives,

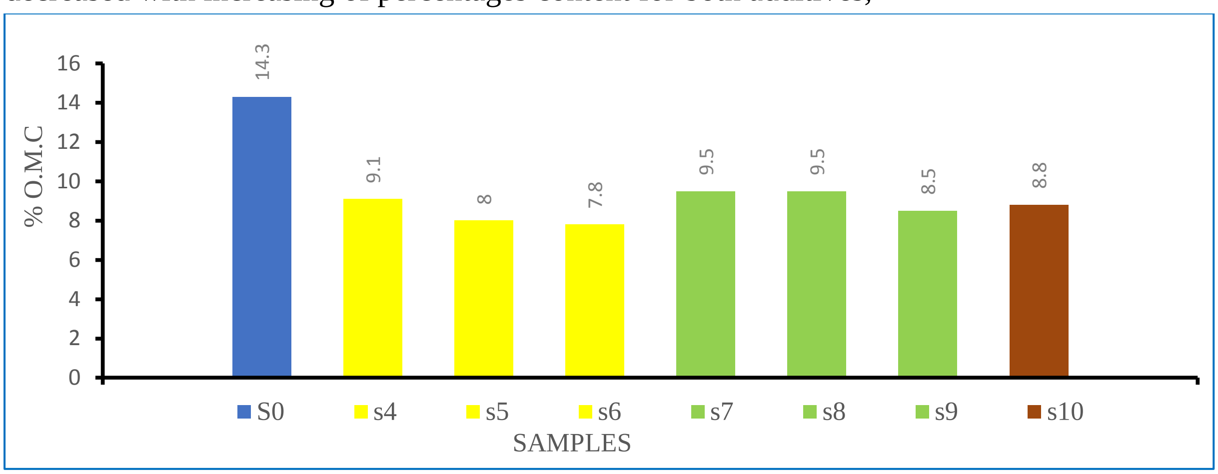

Figure 22. Effect of additives on optimum moisture content.

3.4. Evaluation of resilient modulus testing

Based on previous results obtained in this study mentioned above. Results shown that the optimum percentage of sand can be added to natural clayey soil to form granular stabilization of soil is 50% this represented in sample S3. Also, samples S6 and S9 represented of sandy clayey soil enhanced and mixed of 6% lime and CKD respectively. That represent the best percentages can be added to make a combination of granular and chemical stabilization of soil. So, to try to get the most advantages of using lime and CKD in a combination of granular and chemical stabilization of soil. sample S10 prepared containing of combination of 6% lime, 6% CKD, 44 % clay and 44% sand in this section. All routine tests mentioned above repeated and carried out on sample S10 to be evaluated and compared with other samples. Which shown that the best performance of results tests given at these percentages.

Modulus of resilience (MR) test carried out in accordance with the AASHTO T 307-99 on sample of natural soil S0, a sample of clayey soil enhanced with sand S3, samples of sandy clayey soil enhanced and mixed with 6% lime or CKD respectively S6 and S9, and sample S10 of sandy clayey soil enhanced and contained a combination of 6% lime and 6 % CKD. Table 3 and figures 23 through 27 show values of MR and the applied deviator stress under different confining pressures for the samples S0, S6, S9 and S10.

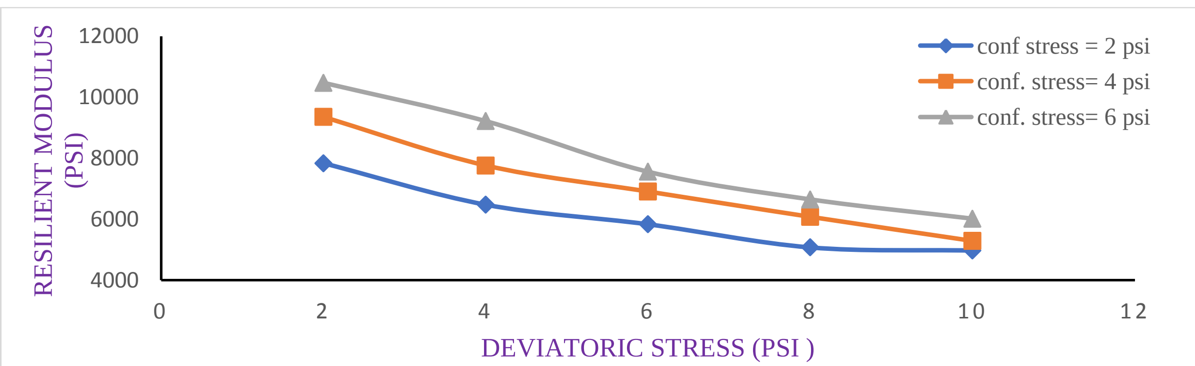

Figure 23. MR values for natural clayey soil S0.

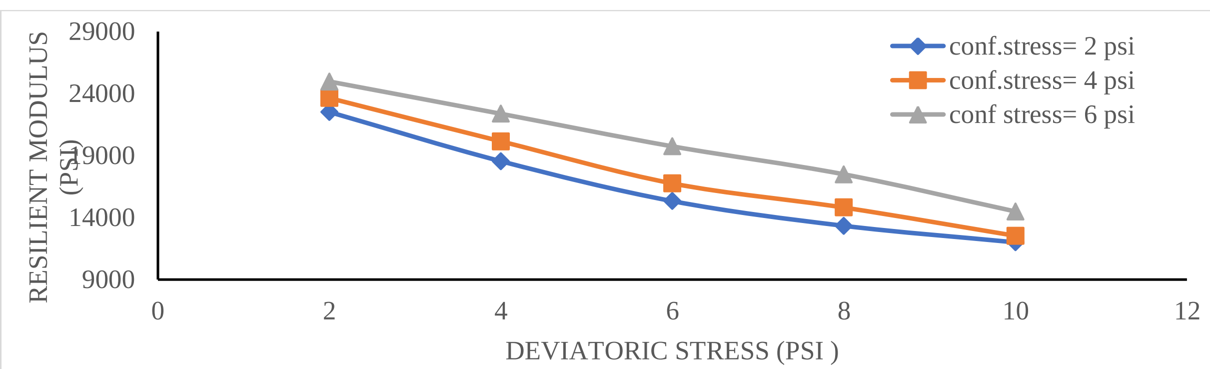

Figure 24. MR values for sandy clayey soil S3.

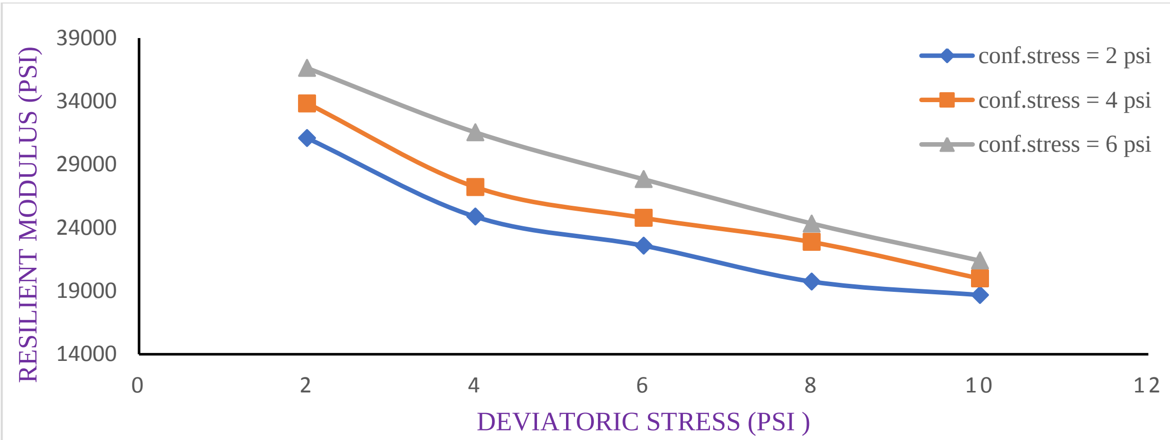

Figure 25. MR values for sandy clayey soil mixed with 6% lime S6.

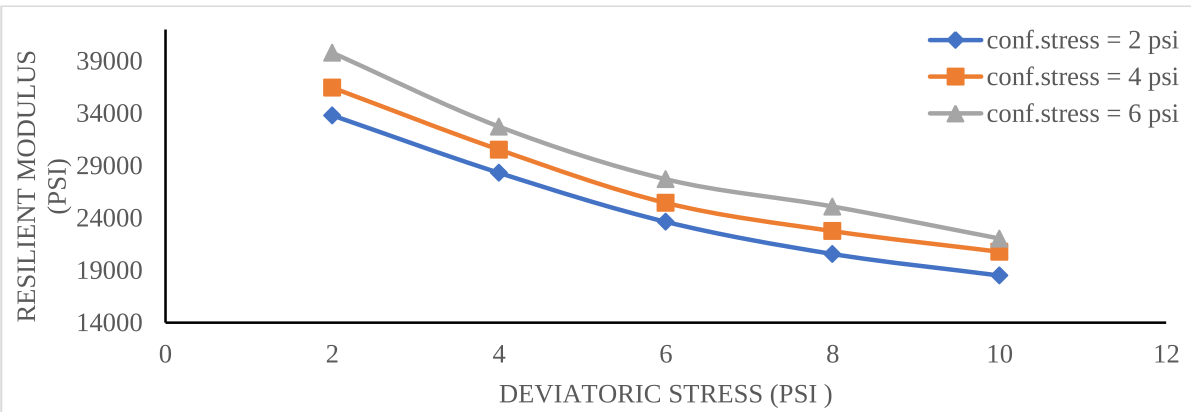

Figure 26. MR values for sandy clayey soil mixed with 6% CKD S9.

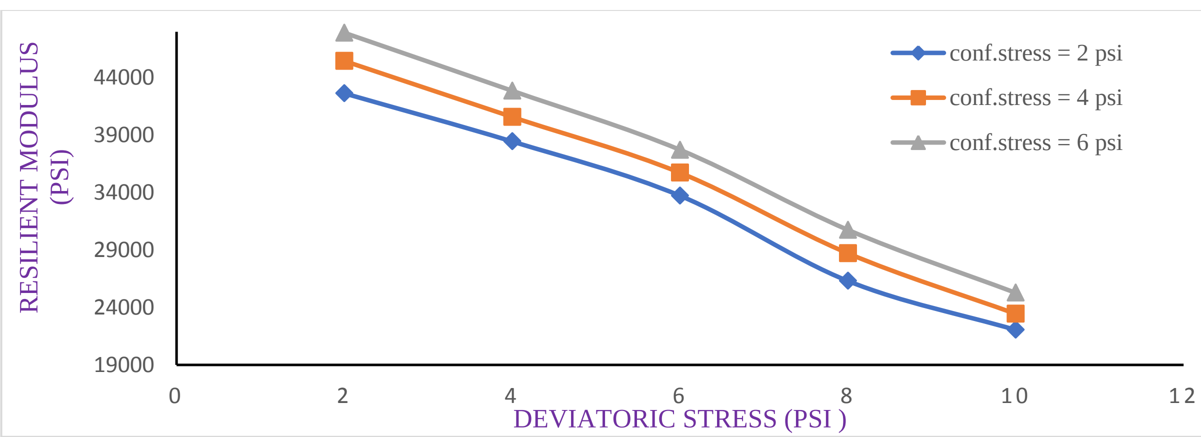

Figure 27. MR values for sandy clayey soil mixed with 6% lime + 6% CKD S10.

The MR test results show that with an increase in deviatoric stress the MR value increased considerably at different confining stresses. It is clear that MR values increased because of stabilization. This improvement is begun at natural clayey soil enhanced with sand and increased respectively by adding lime and CKD respectively while best maximum performance occurred at adding combination of lime and CKD.

The design MR values to be adopted shall correspond to the stress states anticipated in the field. The anticipated field stress configuration for the subgrade material is (6 to 7 psi) for the deviator stress and a confining pressure of (1 to2 psi) (Ji et al. 2014; Mousa et al. 2017) [36,37]. This is in accordance with most of the researches carried out with recommendations for design MR values pertaining to confining pressure of (2 psi) and deviator stress of (6 psi) (Jones and Witczak 1977; Ping et al. 2001) [38,39]. Hence in this

study MR values at deviatoric stress 6 psi and confining stress of 2 psi considered in pavement design parameters according to AASHTO 1993 design method. figure 28 shows MR values at confining pressure of (2 psi) and deviator stress of (6 psi) for samples S0, S6, S9 and S10.

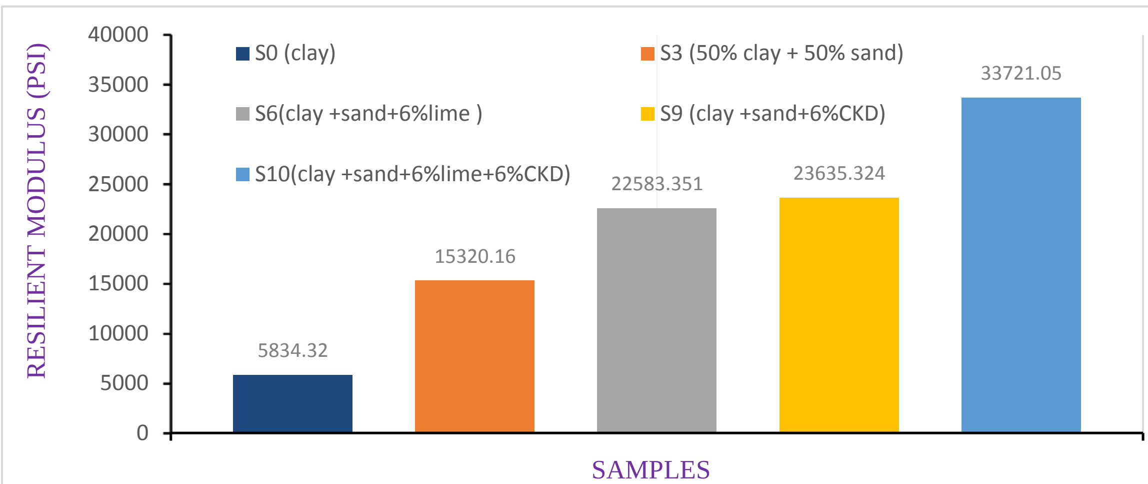

Figure 28. MR values at confining pressure of (2 psi) and deviator stress of (6 psi).

3.5. Evaluation of plate loading test.

Based on previous results obtained in this study mentioned above. Results shown that the optimum percentage of sand can be added to natural clayey soil to form granular stabilization of soil is 50% represented in sample S3. Also, samples S6, S9 represented the sandy clayey soil enhanced and mixed of 6% lime and CKD respectively. That represent the best percentages can be added to make a combination of granular and chemical stabilization of soil. finally, S10 which represent the best performance of a combination of granular and chemical stabilization of soil. So, four experimental sections prepared from subgrade soil represent four samples S3, S6, S9 and S10 respectively. The sections are carried out in situ as shown in figure 8 (from a to d) and applied plate loading test for them to show the modification effect of granular and chemical stabilization on modulus of elasticity Es and resistance displacement deflection Δ of subgrade soil . These sections established on four cases of subgrade stabilizations as follow: -Section 1: granular stabilization of subgrade soil represents sample s3. subgrade soil established from 50 % sand and 50% clay.

Section 2: mix of granular and chemical stabilization of subgrade soil represent sample s6. subgrade soil established from 47 % sand, 47% clay and 6% lime.

Section 3: mix of granular and chemical stabilization of subgrade soil represent sample s9. subgrade soil established from 47 % sand, 47% clay and 6% CKD.

Section 4: mix of granular and chemical stabilization of subgrade soil represent sample s10. subgrade soil established from 44 % sand, 44% clay, 6% lime and 6% CKD.

They mixed and compacted at their O.M.C and maximum dry density for each one. Then sand cone test carried out to check the achieved density. Hence plate loading test carried out according to ASTMD1196 for each experimental section. modulus of elasticity Es which calculated according to Boussinesq's formula .$E_s = 1.18\rho a/\Delta$; (where ρ : loading plat stress (kg/cm^2) , a: radius of plate loading (22.5cm used in sthis study) , Δ : deflection within subgrade layer . From table 4 and figures 29 and 30 results show that for Es subgrade soil increasing from 768.196 kg/cm^2 at sandy clayey soil to 1178.376 kg/cm^2 and 1544.224 kg/cm^2 at sandy clayey soil mixed with 6% lime and CKD respectively. While best performance of increasing 2823.867kg/cm^2 occurred at sandy clayey soil mixed with a combination of 6% lime and 6% CKD. figure 29 shows the average elastic modulus of subgrade soil samples. Also, the displacement measured at peak load of 40 KN (equivalent to an axle load of 80 KN and contact tire pressure of 80 PSI almost (6 kg/cm^2)) shows the displacement decrease with increasing of additives. It decreases from 2.062 mm at sandy clayey soil to 1.289 mm and 1.029 mm at sandy clayey soil mixed with 6% lime or CKD respectively. While best performance also at sandy clayey soil mixed with a combination of 6% lime and 6% CKD, it decreased to 0.865 mm. Figure 30 shows the displacement of subgrade soil samples at different loading. The results show that the additives improve the ability of sand clayey subgrade soil to resist deformation.

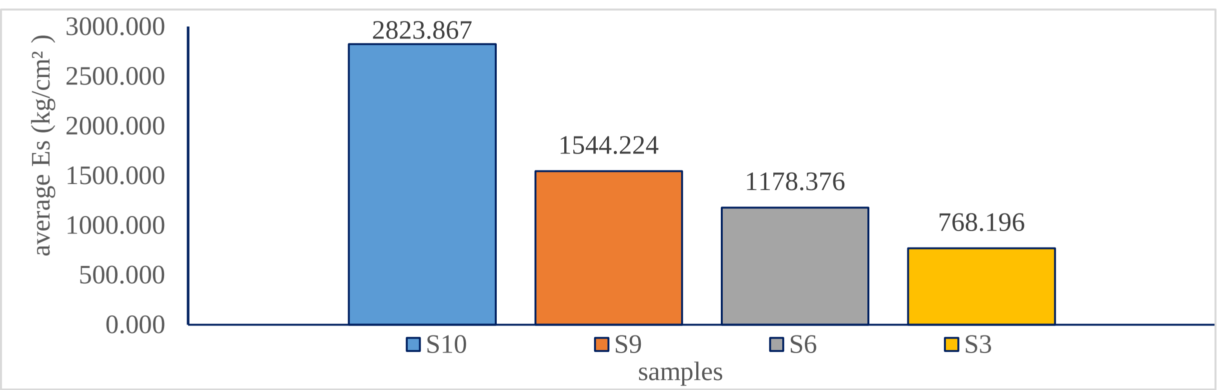

Figure 29. Elastic modulus average values for subgrade soil samples

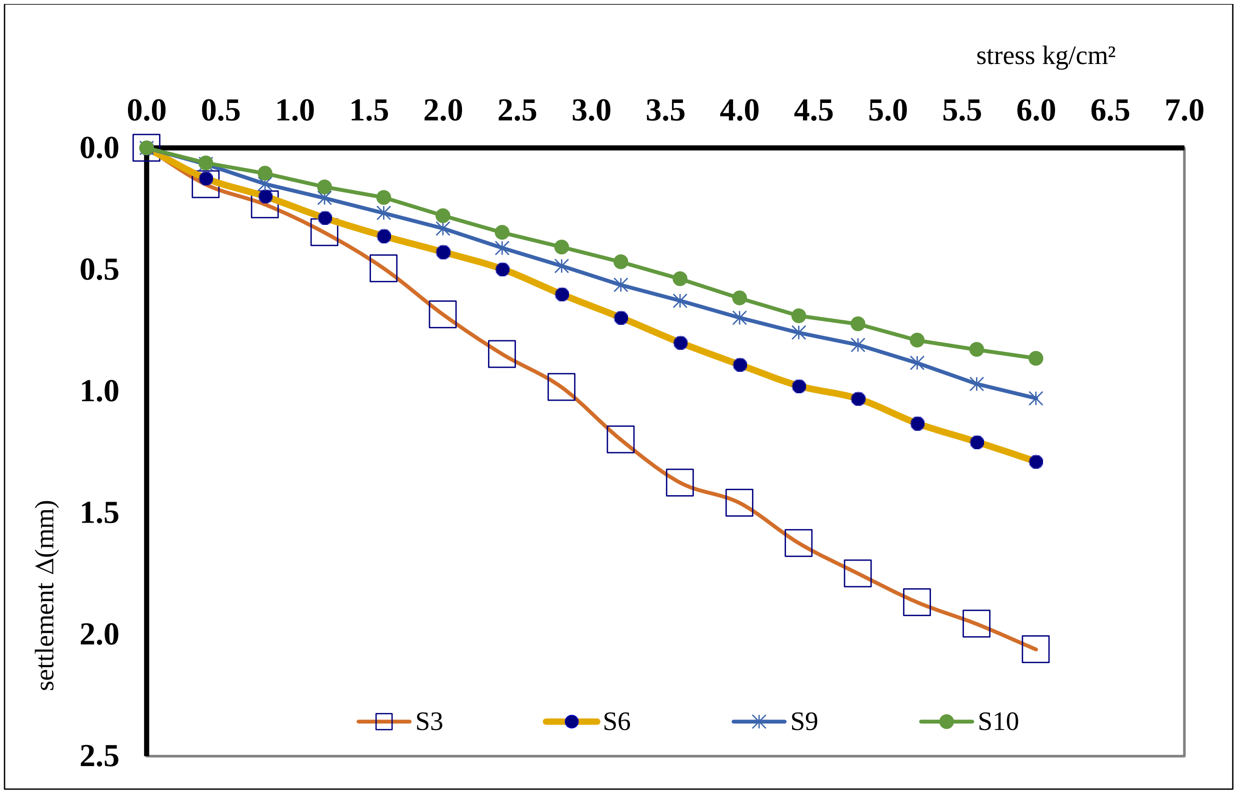

Figure 30. Displacement values for subgrade soil samples at different loading pressures.

3.5. effective of enhancing subgrade by granular or/ and chemical stabilization on pavement design section.

Based on previous studies a structural design section adopted for different subgrade soil represent samples (S1, S3, S6, S9, S10). Structural design of this highway pavements sections based on the AASHTO 1993 design method. In this method each layer thickness is determined based on the strength of the underneath layer as determined by the structural layer (SN). This design is adopted as a basis for comparison to determine the technical and economic benefits of structural design of this highway pavements sections. The design basically involved calculations of the thickness of three main layers in the pavement system (granular subbase, granular base, and surface asphalt cement layer) based on equation (1) and AASHTO flexible pavement thickness design nomograph) [15] and predetermined conditions.

$SN = a1 \times D1 + a2 \times D2 \times m2 + a3 \times D3 \times m3$ ………. (1)

This design applied based on the following assumptions of design parameters:

- ESALs = 40×10^6 pound
- Reliability, R (95%)
- Over all standard deviation, $S_o = 45\%$
- Δ PSI = 2 (the difference between the initial and final design serviceability index)

- m2= 0.8 (drainage coefficient base layer) and m3 = 0.7 (drainage coefficient of subbase layer).
- a1= 0.42 (assumed for E= 400000psi of asphalt cement layer) , a2= 0.12 (assumed for base layer with MR=2500 psi) and ,
- a3 = 0.1 (assumed for subbase layer with MR = 13800 psi (resilient modulus of subbase layer).
- MR_0 = 5834.32 psi (resilient modulus of clayey subgrade soil for structural pavement design section 0) obtained from previous results at this study and represent sample S3.
- MR_1= 15320.16 psi (resilient modulus of sandy clayey subgrade soil for structural pavement design section 1) obtained from previous results at this study and represent sample S6.
- MR_2= 22583.351 psi (resilient modulus of sandy clayey subgrade soil enhanced with 6% lime for structural pavement design section 2) obtained from previous results at this study and represent sample S9.
- MR_3= 23635.324 psi (resilient modulus of sandy clayey subgrade soil enhanced with 6% CKD for structural pavement design section 3) obtained from previous results at this study and represent sample S9.
- MR_4= 33721.05 psi (resilient modulus of sandy clayey subgrade soil enhanced with 6% lime and 6% CKD for structural pavement design section 4) obtained from previous results at this study and represent sample S10.
- So based on these praters assumptions and calculated of MR for different subgrade soil sections. the design sections can be obtained as shown in the following figures 31 a through 31 e.

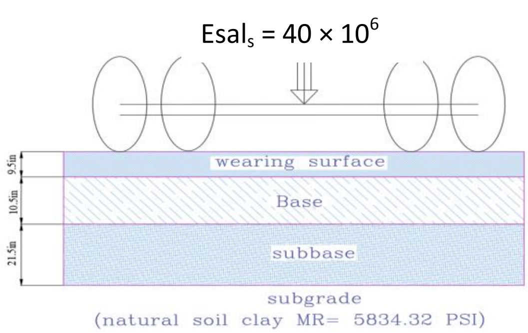

Figure 31a.

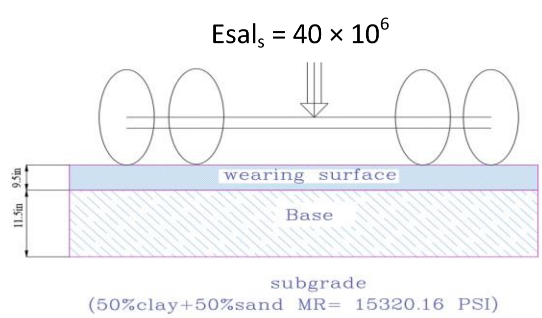

Figure 31b.

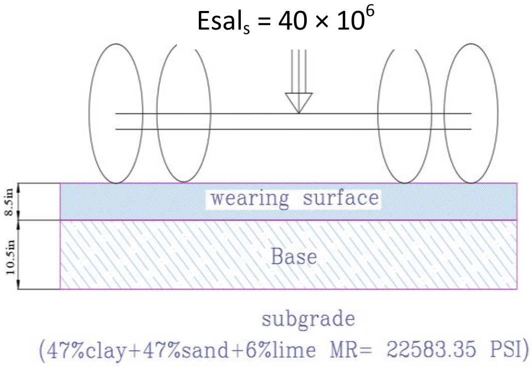

Figure 31c.

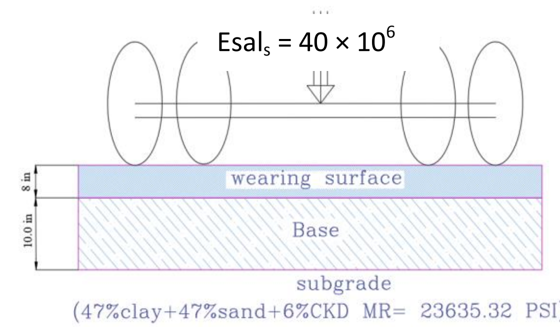

Figure 31d.

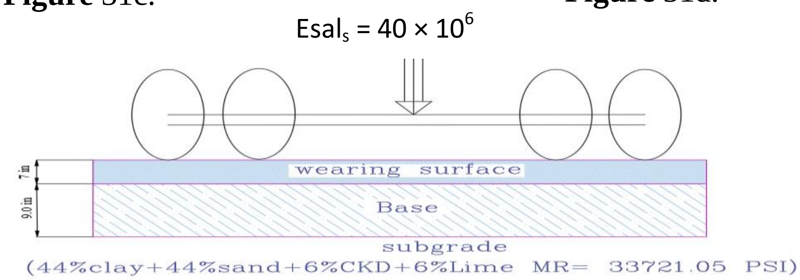

Figure 31e.

From this experimental design sections, it was shown that enhancements in MR values will lead to reduction in the required thickness of the pavement layers. This will lead to economical cost benefits.

4. Conclusions and recommendations

4.1. Conclusions

Based on the methodology and the analysis of the results of this study, the following conclusions were drawn:

1. Using granular stabilization by mixing 50% of natural sand of the sample total weight with natural clay swelling soil enhances it to use as a sandy clayey subgrade layer in pavement construction section.
2. Using mix of chemical and granular stabilization increasing the enhancing strength properties of subgrade soil. That by mixing 47% sand, 47% clay and 6% lime or CKD by total weight of the soil sample.
3. The percentage of 6% CKD shows better results for enhancing strength properties of sandy clayey subgrade soil than 6% lime. That when using mix of chemical and granular stabilization technique. It increases the enhancing of maximum dry density and CBR, and reducing of swelling properties for sandy clayey subgrade soil.

4. L.L of swelling clayey soil enhanced with mixing of 50% natural sand of the total weight of the sample. It decreases by almost 20% of its original value. Also adding 6% lime and CKD increasing this Improvement by decreasing L.L by 38% and 42% respectively of its original value. Also, P.L of swelling clay soil enhanced with mixing of 50% natural sand of the sample total weight. It decreases by almost 29.43% of its original value. Adding 6% lime and C.D increasing this Improvement by decreasing P.L by 35.1% and 40.4% respectively of its original value. And so on, P.I of swelling clay soil enhanced with the mixing of 50% natural sand. It decreases by almost 40% of its original value. While Adding 6% lime and CKD increasing this Improvement by decreasing P.L by 43.2% and 45.8% respectively of its original value.
5. CBR of swelling clay soil enhanced with the mixing of 50% natural sand It increases by almost 100% of its original value. Adding 6% lime and C.D increasing this Improvement by increasing CBR by 324.4% and 502% of its original value respectively.
6. The maximum dry density of swelling clay soil enhanced with mixing of 50% natural sand increased by 12.27% of its original value. Also, it goes to increase with increasing percentages up to its optimum values of 2.5 and 2.8 g/cm³ at 6% lime and CKD respectively.
7. The optimum moisture content of swelling clay soil enhanced with mixing of 50% natural sand of the sample total weight. It decreased by 12.5% of its original value. Also, it decreases from 55% to 60% of its original value with increasing percentages of lime and / or CKD up to 6% of the sample total weight.
8. The best performance for strength properties of sandy clayey soil using as a subgrade achieved when using mix of chemical and granular stabilization that by mixing a combination of 44% sand, 44% clay, 6% lime and 6% CKD by total weight of the soil sample.
9. Using granular stabilization increasing MR for swelling clayey soil by mixing of 50% natural sand of the sample total weight. It increases by 2.6 times almost of its original value. This improvement increased when adding 6% lime or CKD of the sample total weight to sandy clayey subgrade it reaches to 3.87 and 4.05 times almost of its original value respectively.
10. The best performance for MR of sandy clayey subgrade soil achieved when using a using mix of chemical and granular stabilization that by mixing a combination of 44% sand, 44% clay, 6% lime and 6% CKD by total weight of the soil sample. This enhancements in MR values will lead to reduction in the required thickness of the pavement layers. This will lead to economical cost benefits.
11. The modulus of elasticity of swelling clayey soil enhanced Using granular stabilization by mixing 50% of natural sand of the sample total weight. And therefore, it improves its ability to resist deformation. This improvement increased by adding 6% lime or / and CKD of the sample total weight respectively. The best performance for the ability of

resist deformation of subgrade section containing 44% clay ,44% sand, 6% lime and 6% CKD.

12. Granular stabilization of subgrade swelling clayey soil by mixing of 50% natural sand of the sample total weight reduced the pavement design thickness to its 50% of its original value. while using combination of chemical and granular by adding 6% lime or CKD of the sample total weight to sandy clayey subgrade it increases the reduction to 54% and55% almost of its original value respectively. while the best result of reduction of pavement design thickness achieved at subgrade section containing of 44% clay, 44% sand, 6% lime and 6% CKD. It reaches to 60 % almost of its original value.

4.2. Recommendations

Based on previous conclusions the following recommendations can be drawn:

1. Evaluate more percentages of lime and CKD or other additives to show its effect on the performance of sandy clayey soil
2. Study the effect of using combination of granular and chemical stabilization of sandy clayey soil at the optimum percentages of additives mentioned in this study on the performance of pavement structural section related to different conditions such as climate or traffic loads .
3. Making an economical evaluation for using other additives with different percentages can be added to sandy clayey soil to get the most useful additives improve the performance of pavement section from an economical viewpoint.
4. Carry out more studies in situ at different traffic loads on the pavement structural sections mentioned in this study to evaluate their performance with respect to fatigue or rutting problems.

References :

1- https://mot.gov.eg/#/Home/Achievements/Achievement-Details/4031.
2- Terrel, R. L., J. A. Epps, E. J. Barenberg, J.K. Mitchell, and M. R. Thompson, " Soil Stabilization in pavementStructures - A User Manual." FHWA Research Report No. FHWA-IP-80-2, WA (**1979**).
3- "Guidelines for Modification and Stabilization of Soils and Base for Use in Pavement Structures." (March2008).
4- United Facilities Criteria (3-250-11). "Soil Stabilization for Pavements, TM 5-822-14/AFJMAN 32/1019."(**2004)**
5- G. Kollaros, A. Athanasopoulou, Sand as a Soil Stabilizer. Bulletin of the Geological Society of Greece 50 (2) (2016) 770-777.
6- L. N. Nair, U. Salini, Lime Stabilization of Subgrade with Waste Sand as Partial Soil Replacement. In-Ground Improvement Techniques and Geosynthetics, vol 14, pp. 125-133, Singapore, 2019.
7- McManis, K. L. and Arman, A. (1989). "Class C Fly Ash as a Full or Partial Replacement
8- for Portland Cement or Lime." Transportation Research Record, 1219, 68 – 81
9- Baghdadi, Z.A. (1990). "Utilization of kiln dust in clay stabilization." J. King Abdulaziz Univ.: Eng Sci, 2, 53 – 163.
10- Zaman M., Laguros J.G. and Sayah A.I. (1992). "Soil stabilization using cement kiln dust," Proceedings of 7th Int. Conf. on Expansive Soils, Dallas, Texas, 1 -5.
11- Little, D.L. (2000). "Evaluation of Structural Properties of Lime Stabilized Soils and Aggregates." Mixture Design and Testing Protocol for Lime Stabilized Soils, 3, National Lime Association report, (http://www.lime.org/SOIL3.PDF).
12- Miller, G.A. and Zaman, M. (2000). "Field and laboratory evaluation of cement kiln dust as a soil stabilizer," Transportation Research Record, 1714, Transportation Research Board, National Research Council, Washington D. C., 25-32.
13- Parsons, R.L., Kneebone, E. and Milburn, J.P. (2004). "Use of Cement Kiln Dust for Subgrade Stabilization." Final Report No. KS-04-03, Kansas Department of Transportation, Topeka, KS.
14- Kim, D., and Siddiki, N. (2004). "Lime Kiln Dust and Lime – A Comparative Study in Indiana." Transportation Research Board 2004 Annual Meeting, CD-ROM Publication, Paper No. 04-4147.
15- P. Daipuria, M. K. Trivedi, Improvement Of Swelling Properties Of Expansive Soil Blending With Sand And Cement, International Journal of Science, Engineering and Technology Research (IJSETR) 5 (6) (2016) 2009-2014.
16- M. N. B. Ramteke, A. Saxena, T. R. Arora, Stabilization of black cotton soil with sand and cement as a subgrade for pavement, International Journal of Engineering Sciences and Research Technology 3 (6) (2014) 688-692.

17- Y. Keerthi, P. D. Kanthi, N. Tejaswi, K. S. Chamberlin, B. Satyanarayana, Stabilization of clayey soil using cement kiln waste, International Journal of Advanced Structures and Geotechnical Engineering 2 (2) (2013) 77-81.
18- A. H. M. Afaf, A. H. I Hesham, A.Elh. M. Atef, Improvement Of Expansive Subgrade By Lime Addition, Journal of Engineering Sciences, Assiut University, Faculty of Engineering 41 (5) (2013) 1778-1795.
19- A. M. Mosa, A. H. Taher, L. A. Al-Jaberi, Improvement of poor subgrade soils using cement kiln dust, Case Studies in Construction Materials 7 (2017) 138-143.
20- Petry, T.M. and Little, D.N., 2002. Review of stabilization of clays and expansive soils in pavements and lightly loaded structures—history, practice, and future. Journal of Materials in Civil Engineering, 14(6), pp.447-460.
21- Prusinski, J. and Bhattacharja, S., 1999. Effectiveness of Portland cement and lime in stabilizing clay soils. Transportation Research Record: Journal of the Transportation Research Board, (1652), pp.215-227.
22- AASHTO Guide for Design of Pavement Structures. AASHTO, Washington, D.C., 1993
23- Thompson, M. R. Lime Reactivity of Illinois Soils. Journal of Soil Mechanics and Foundations Division, Vol. 92, No. SM5, 1966, pp. 67–92.
24- . McDonald, E. B. Lime Research Study—South Dakota Interstate Routes (Sixteen Projects). South Dakota Department of Highways, 1969.
25- Neubauer, C. H., Jr., and M. R. Thompson. Stability Properties of UncuredLime-Treated Fine-Grained Soils. In Highway Research Record 381,HRB, National Research Council, Washington, D.C., 1972, pp. 20–26.
26- Little, D. N. Evaluation of Structural Properties of Lime Stabilized Soils and Aggregates, Volume 1: Summary of Findings. Report prepared for National Lime Association, Arlington, Va., 1999.
27- A. Adam, I. Ibrahim, A. Alhardllo, A. Hadi, M. Ibrahim, Effect of Hydrated Lime on Behavior of Expansive Soil as Subgrade of Flexible Pavement Structural System, Second International Conference on Sustainable Construction Materials: Design, Performance, Application, Wuhan, China,2012.
28- J.B. Croft, The Influence of Soil Mineralogical Composition on Cement Stabilization, Geotechnique 17 (2) (1967) 119-135.
29- R. Alzubaidi, K. AlRawi, A. AlFalahi, Using Cement Dust to Reduce Swelling of Expansive Soil, Geomech. Eng. 5 (6)(2013) 565-574.
30- A. Almurshedi, J. Thajeel, H. Dekhn, Swelling Control of Expansive Soils Using Cement Dust, IOP Conference Series:Mater. Sci. Eng. 584 (1) (2019) https://doi.org/10.1088/1757-899X/584/1/012021.
31- American Association of State Highway and Transportation Officials. Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates; T-27; AASHTO: Washington, DC, USA, 2020.

32- Egyptian Code (2001): Egyptian Code of Soil Mechanics, Foundations Carrying out and Designation. In Part 2, Laboratory Tests, 6th ed.; Ministry of Housing, Utilities Urban Communities; Cairo; Egypt; 2001.
33- Egyptian Highways specification code (2008): The Egyptian code for the design principles and requirements for the implementation of urban and rural roads. In Part 6, Structural Highways Design, 6th ed.; Ministry of Housing, Utilities Urban Communities; Cairo; Egypt; 2008.
34- George, K. P., (2004). "Prediction of resilient modulus from soil index properties." University of Mississippi, University, Miss.
35- Hopkins, T. C., University of Kentucky Transportation, KTC., and United States. Federal Highway, A. (2004). "Resilient modulus of Kentucky soils.".
36- Ji R, Siddiki N, Nantung T, Kim D (2014) Evaluation of resilient modulus of subgrade and base materials in Indiana and its implementation in MEPDG. Sci World J. https://doi.org/10.1155/2014/372838.
37- Mousa E, Azam A, El-Shabrawy M, El-Badawy SM (2017) Laboratory characterization of reclaimed asphalt pavement for road construction in Egypt. Can J Civil Eng.44:417–425. https://doi.org/10.1139/cjce-2016-0435.
38- Jones MP, Witczak MW (1977) Subgrade modulus on the San Diego test road. Transp Res Rec 641:1–6.
39- Ping WV, Yang Z, Liu C, Dietrich B (2001) Measuring resilient modulus of granular materials in flexible pavements. Transp Res Rec 1778:81–90. https://doi.org/10.3141/1778-10.