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Effect of Soil Stabilization Using Cement, Cement Kiln Dust, and L.C.S.S. on Flexible Pavement Design

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Abstract: The main objective of this research is to study the effect of stabilizing the soil, which classified as A-2-4 according to AASHTO soil classification system, with Ordinary Portland Cement (OPC), Cement Kiln Dust (CKD) and a new Liquid Chemical Soil Stabilizer ($LCSS$) on the flexible pavement structural design for many classes of highways in Egypt. CKD contents were 2%, 4%, 8% and 12% by soil dry weight. Whereas OPC contents were 2%, 4%, 6%, 8%, and 10%. To study the effect of the $LCSS$, the same contents of OPC and CKD were used with adding the $LCSS$, whose concentration was 1:1000 by volume of water. The resilient moduli of the treated and untreated soil were determined. According to the Egyptian Code for Urban and Rural Highways, the required flexible pavement sections for many classes of highways have been determined. For each case of the treated and untreated soil, the construction cost of one square meter of pavement has been estimated to study the economic feasibility of using OPC, CKD and $LCSS$ as chemical soil stabilizers for flexible pavement construction purposes.

Keywords: Soil stabilization, Flexible pavement design, Cement kiln dust, Cement.

1. INTRODUCTION

Economic development of any country is controlled, to a great extent, by its highways network. Construction and maintenance cost of the highways network pavements is mainly affected by the subgrade soil properties [1, 2]. Therefore, improving soil properties through soil stabilization has been studied by several researchers [3, 4, 5, 6, 7, 8, 9, and 10].

Cement is the oldest stabilizing agent since the invention of soil stabilization technology in 1960's [11]. Its reaction is not dependent on the soil minerals, and the key role is its reaction with water that may be available in any soil [12]. Cement Kiln Dust (CKD) as cementitious material can be used as an effective stabilizer similar to cement but in much less cost as it is considered a waste. Soil stabilization using CKD increases the soil unconfined compressive strength, but this increase is inversely proportional to the untreated soil plasticity index [13, 14]. New soil stabilizers are developed continuously and its feasibility is mandatory before field application. This research introduces the use of a new Liquid Chemical Soil Stabilizer ($LCSS$).

The main objectives of this study are: investigating the effectiveness of the new $LCSS$ as a soil stabilizer; examining its impact beside traditional stabilizers (cement and CKD) on flexible pavement design; and finally investigating the economic feasibility of using the $LCSS$ and the traditional stabilizers in highways' pavement construction.

2. PROPERTIES OF THE STABILIZING AGENTS

Samples of Cement, CKD, and $LCSS$ were brought to the highway engineering laboratory at Shoubra Faculty of Engineering and stored in a moisture-proof containers at a dry place. The $LCSS$ is an environmental friendly biodegradable copolymer emulsion, whose properties are shown in Table 1. Properties of the used Ordinary Portland Cement (OPC) and CKD are provided in Table 2 and Table 3, respectively. The used CKD is an industrial waste of cement manufacturing at the Suez Cement Corporation, Helwan factory. It was collected in December 2020.

TABLE 1. $LCSS$ Properties

Base	Biodegradable organic compound
Physical Form	Liquid
Appearance/Color	Amber Black
Density (at 20°C)	1.4 ± 0.005 kg/Liter
Shelf life	24 months from date of production
pH	4.5 : 6
Boiling Point	> 180° c
Freezing Point	< 0° c
Specific Gravity	1.05 : 1.1
Solubility in Water	Completely (100%)

TABLE 2. Ordinary Portland Cement (CEM I 42.5N) Properties

Physical Properties				Mechanical Properties	
Setting Time		Soundness (mm)	Fineness (m^2/kg)	Compressive Strength (N/mm^2)	
Hour	Min.			2-Day	28-Day
2	15	1	351	17.9	43.2

TABLE 3. Cement Kiln Dust Properties

Specific gravity (G_s)	Chemical Composition							
	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Na_2O (%)	K_2O (%)
3.09	15.13	4.19	1.99	48.72	1.59	4.51	0.31	2.78

3. EXPERIMENTAL WORK

3.1. Properties of the Untreated Soil

Soil Samples were brought to the highway engineering laboratory at Shubhra Faculty of Engineering. Conforming to ASTM-D6913 [15], the soil gradation, shown in Fig. 1, was obtained. Liquid and plastic limit tests were conducted on soil passing sieve #40 conforming to ASTM-D4318 [16]. The soil was then classified based on ASTM-D3282 [17].

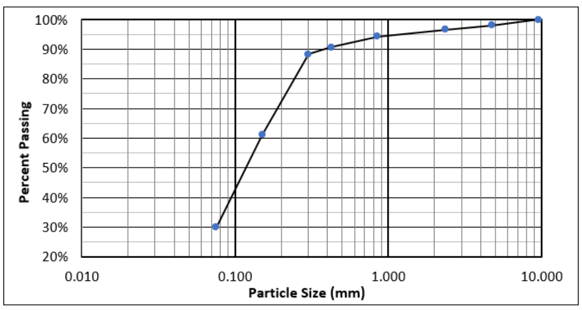

Fig 1. Grain Size Distribution Curve of the Untreated Soil

To determine the maximum dry density ($\gamma_{d\,max}$) and optimum moisture content (ω_{Opt}), the modified compaction test, conforming to ASTM-D1557 [18], was implemented. California bearing ratio (CBR) test was carried out to determine the soil CBR value, conforming to ASTM-D1883 [19]. CBR test was carried out in two cases; with and without submerging the CBR specimen in water for four days before the penetration test. Table 4 shows the untreated soil properties.

TABLE 4. Untreated Soil Properties

Percent Passing Sieve # 200	29.8%
Liquid Limit and Plasticity Index	Non-Plastic
Soil Classification	A-2-4
Maximum Dry Density	$1.97 gm/cm^3$
Optimum Moisture Content	12.38%
CBR (with submerging in water)	29.7%
CBR (without submerging in water)	27.9%

3.2. Properties of the Stabilized Soil

The natural soil was stabilized using $LCSS$, OPC, and CKD. The concentration of the $LCSS$ was constant in this research (1:1000 by volume of water) as recommended by the material manufacturer. The used OPC contents (by soil dry weight) were 2%, 4%, 6%, 8%, and 10% (with or without adding the $LCSS$). Whereas, CKD contents were 2%, 4%, 8%, and 12%.

Modified Compaction Test was carried out on soil stabilized with $LCSS$ and it was found that $\gamma_{d\,max}$ and ω_{Opt} are $1.998\ gm/cm^3$ and 12.3%, respectively. Figure 2 displays the effect of OPC content on the compaction characteristics of the soil.

It is observed that submerging specimen in water didn't affect the CBR value of the soil. Therefore, in case of the stabilized soil with only $LCSS$, soaking in water was considered unnecessary. The CBR value of the stabilized soil with only $LCSS$ is determined to be 29.8%.

Figure 2 shows that the differences in the values of $\gamma_{d\,max}$ and $\omega_{Opt.}$ are small. Therefore, the $\gamma_{d\,max}$ and $\omega_{Opt.}$ of the untreated soil were used as a target when preparing the specimens of the Unconfined Compressive Strength (UCS) Test, for all OPC and CKD contents (with or without adding the $LCSS$).

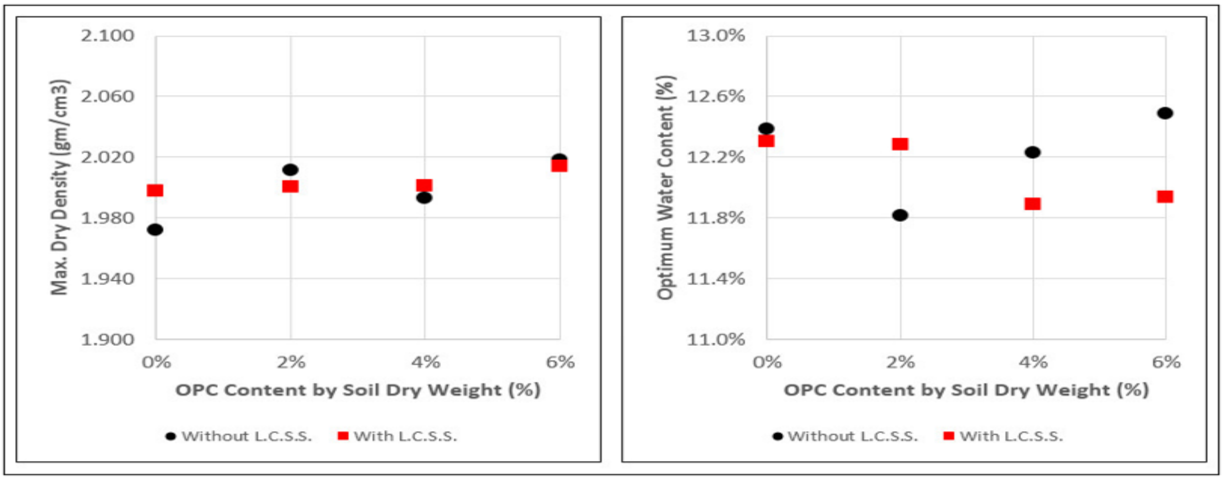

Fig2. Effect of OPC Content on the Compaction Characteristics of the Soil

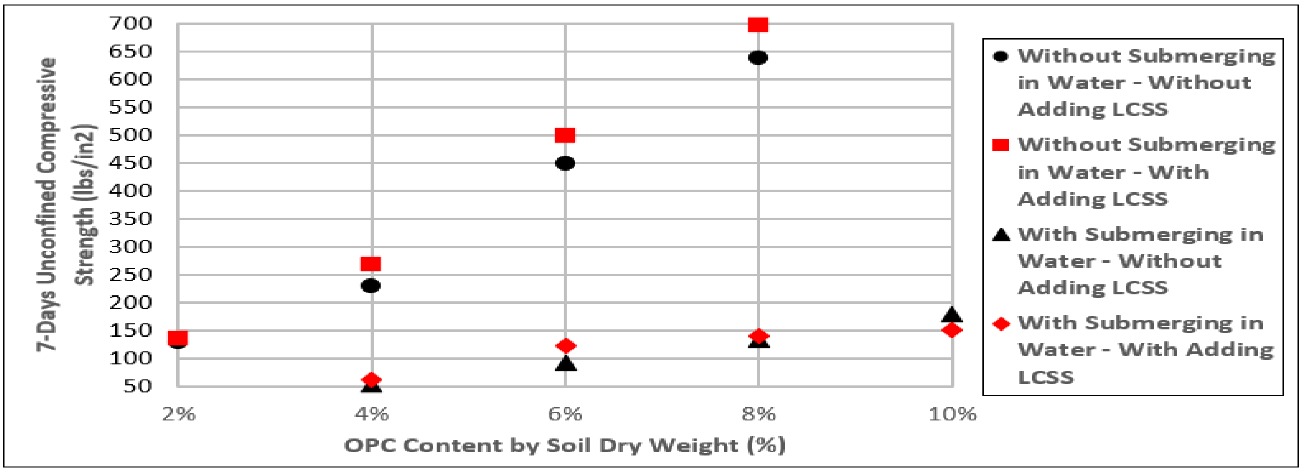

Fig 3. Effect of OPC Content on the 7-Days UCS

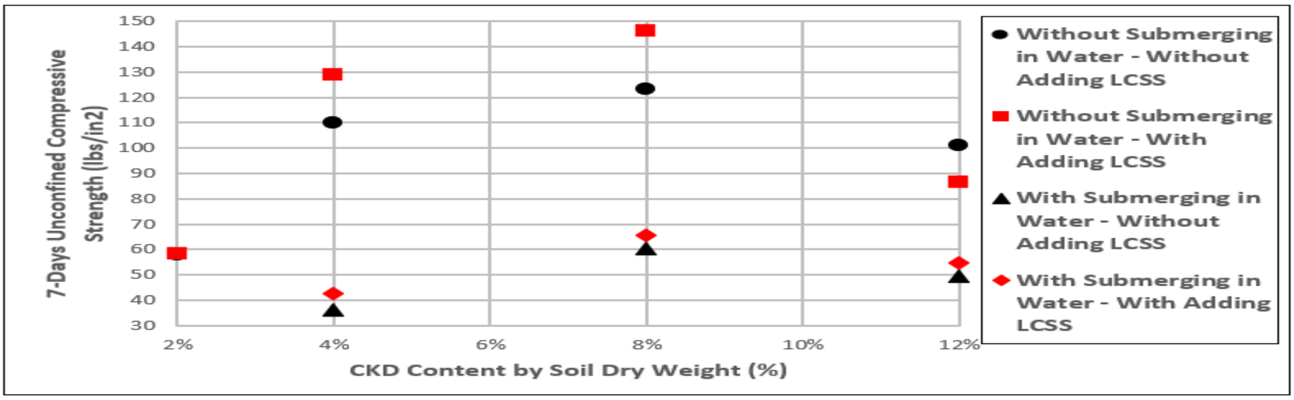

Fig4. Effect of CKD Content on the 7-Days UCS

According to ASTM-D1632 and ASTM-D1633 [20 and 21], UCS Tests were carried out in two cases; with and without submerging the specimens in water for four hours after the end of the curing period. The specimens with 2% CKD content were disintegrated when submerged in water for 4 hours. Figures 3 and 4 show the effect of OPC and CKD contents respectively on the 7-days UCS.

4. RESILIENT MODULUS DETERMINATION

Repeated load tri-axial tests are used to measure the resilient modulus (M_r) of pavement materials. However, they are rather expensive and not available in Egypt except at limited places, besides it takes much time to be done, and requires very efficient people to obtain reliable results [22 and 23]. In addition, the Egyptian code for urban and rural highways [1] and the AASHTO guide for design of pavement structures [2] have connected the M_r values with other strength parameters (CBR for untreated and granular materials and UCS for stabilized materials).

For untreated soil and stabilized soil with only $LCSS$, equation 1 [1] was used to determine the M_r values. Whereas, for the stabilized soil with OPC and CKD (with or without adding the $LCSS$), equations 2 and 3 [24] were used to determine the M_r values. Table 5 displays the M_r values of both treated and untreated soil.

TABLE 5. Resilient Modulus of the Treated and Untreated Soil

Content by Soil Dry Weight (%)	Without Adding $LCSS$			With Adding $LCSS$		
	7-Days UCS (lbs/in^2)	One-Day UCS (lbs/in^2)	M_r (lbs/in^2)	7-Days UCS (lbs/in^2)	One-Day UCS (lbs/in^2)	M_r (lbs/in^2)
Stabilized SoilOPC						
0%	- - - - - -	- - - - - -	24,313.93	- - - - - -	- - - - - -	25,095.10
4%	52.60	36.46	47,428.49	61.48	42.69	60,942.82
6%	92.82	65.29	128,668.65	123.48	87.02	209,757.18
8%	132.85	95.28	250,731.41	139.49	100.15	273,048.19
10%	178.93	129.10	437,266.42	150.35	109.02	323,986.76
Stabilized SoilCKD						
0%	- - - - - -	- - - - - -	24,313.93	- - - - - -	- - - - - -	25,095.10
4%	36.27	24.42	26,419.24	42.48	28.68	33,546.57
8%	60.20	41.21	66,796.03	65.76	45.16	76,710.35
12%	49.44	33.31	56,152.07	54.62	37.03	64,953.27

$$M_r = 4920 * (CBR)^{0.48} \quad (1)$$

$$M_r = m_0 * UCS \quad (2)$$

$$m_0 = 50{,}230 * \left(\frac{1}{F}\right) + 27.540 * PI + 34.931 * AC + 211.38 * \left(\frac{UCS_1}{P_a}\right) - 1448.1 \quad (3)$$

Where:

- CBR is the California Bearing Ratio of the untreated soil and the treated soil with only $LCSS$.
- UCS is the 7-days unconfined compressive strength of the stabilized soil with OPC or CKD, with soaking the specimens in water for four hours before the test.
- F and PI are the percent passing sieve # 200 and the plasticity index, respectively, of the untreated soil. F is 29.8% and PI is 0 because the soil is non-plastic.
- AC is the additive content as a percent of soil dry weight.
- UCS_1 is the unconfined compressive strength of the stabilized soil after one day of curing.
- P_a is the atmospheric pressure (14.696 lbs/in^2)

5. PAVEMENT STRUCTURAL DESIGN

Tables 6 and 7 show the design inputs and general calculations which were used to design the required flexible pavement for many classes of highways in Egypt, according to the Egyptian code for urban and rural highways [1].

TABLE 6. Pavement Design Inputs

Parameter	Arterial Highway	Collector Highway	Local Highway
Annual average daily traffic, $AADT$, (veh/day)	15,000	6,000	4,500
Percent of trucks, $\%T$, (%)	32.5%	35%	20%
Truck factor, TF, $(standard\ axle/truck)$	3.54	3.54	3.54
Directional distribution factor, $D.D.$	0.5	0.5	0.5
Lane distribution factor, $L.D.$	0.8	0.8	0.9
Analysis period, n, $(years)$	15	15	15
Traffic annual growth rate, r, (%)	2%	2%	2%
Design reliability, R, (%)	90%	90%	80%
Overall standard deviation, S_0.	0.45	0.45	0.45
Initial present serviceability index, P_i.	4.2	4.2	4.2
Terminal present serviceability index, P_t.	2.5	2	1.5
Granular base CBR (%)	90%		
Granular base layer coefficient, a_{GB}.	0.138		
Granular base drainage coefficient, m_{GB}.	1		
Drainage coefficients of the treated soil layers, m_{TSL}.	1		
Layer coefficient of asphalt layers, $a_{Asphalt}$.	0.46		

TABLE 7. General Calculations of Pavement Design

Parameter	Arterial Highway	Collector Highway	Local Highway
Traffic annual growth factor, $G.F.$	17.293		
Cumulative equivalent single axle load application, W_{18},	43,571,357	18,769,200	9,049,436
According to W_{18}, $t_{Asphalt\ min}$, (cm)	10		
According to W_{18}, $t_{Base\ min}$, (cm)	15		
The standard normal deviate, Z_R	-1.282	-1.282	-0.841
Present serviceability loss, Δpsi	1.7	2.2	2.7
Granular base M_r, $M_{r\ GB}$, (lbs/in^2)*	42,658.10		

* the granular base M_r was calculated by using equation 1

5.1. Pavement Design in Case of Using the Granular Base Layer

5.1.1. Case of the Untreated Soil

Figure 5 displays the design inputs which were used to design the required flexible pavement of an arterial highway, that will be constructed above the untreated soil. By using these design inputs and the AASHTO equation for flexible pavement design, the required structural numbers ($SN_1 = 3.33$ and $SN_{total} = 4.108$) were calculated.

The asphalt layers' thickness ($t_{Asphalt} = 19cm$) and the granular base layer thickness ($t_{GB} = 15cm$) were calculated by using equations 4 and 5, in which: $a_{Asphalt}$ is 0.46; a_{GB} is 0.138; and m_{GB} is 1.

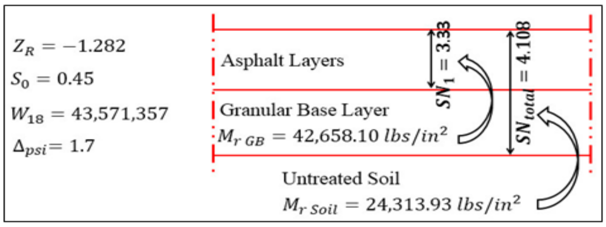

Fig 5. Design Inputs for Pavement Design of an Arterial Highway in Case of the Untreated Soil

$$SN_1 = a_{Asphalt} * t_{Asphalt} \quad (4)$$

$$SN_{total} = a_{Asphalt} * t_{Asphalt} + a_{GB} * t_{GB} * m_{GB} \quad (5)$$

5.1.2. Case of the Stabilized Soil

In case of the stabilized soil with only $LCSS$ or with 4% CKD content (with or without adding the $LCSS$), the M_r

values of the stabilized soil are lower than the granular base M_r. Therefore, in these cases, the stabilized soil layer was assumed to be a subbase layer. Using the minimum thickness ($15cm$) of the granular base layer leads to obtain negative values for the subbase layer thickness. Hence, the same pavement section ($t_{Asphalt} = 19cm$ and $t_{GB} = 15cm$) was obtained.

In the same manner, the structural design calculations - in case of collector and local highways – have been implemented. Table 8 displays the pavement sections in case of using the granular base layer.

TABLE 8. Pavement Sections in Case of Using the Granular Base Layer

Highway Classification	$t_{Asphalt}$ (cm)	t_{GB} (cm)
Arterial	19	15
Collector	16	15
Local	13	15

5.2. Pavement Design in Case of Using the Stabilized Soil as a Base Layer

In case of the stabilized soil with OPC or with 8% and 12% CKD (with or without adding the $LCSS$), the M_r values of the stabilized soil are greater than the granular base M_r. Therefore, in these cases, the pavement section was designed considering utilizing the stabilized soil as a base layer.

For example, Fig. 6 displays the design inputs which were used to design the required flexible pavement of an arterial highway, that will be constructed above the stabilized soil with 6% OPC and the $LCSS$. By using these design inputs and the AASHTO equation for flexible pavement design, the required structural numbers ($SN_1 = 1.793$ and $SN_{total} = 4.108$) were calculated.

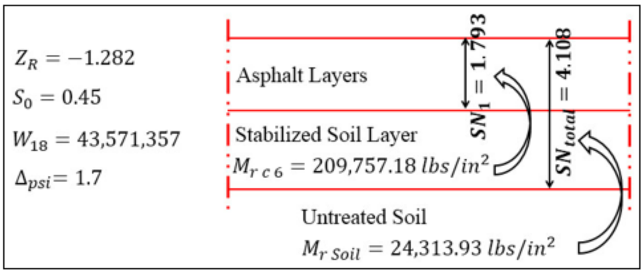

Fig 6. Design Inputs for Pavement Design of an Arterial Highway in Case of the Stabilized Soil with 6% OPC and $LCSS$

For the stabilized soil layer, the layer coefficient ($a_{TSL} = 0.0898$) was calculated using equation 6 [25]. In which, a_{Ref} and $M_{r\,Ref}$ are the layer coefficient and the resilient modulus respectively of a known reference material. The reference material is the cement treated base whose modulus and layer coefficient are 500,000 lbs/in^2 and 0.12 respectively, according to the Egyptian code for urban and rural highways [1].

$$a_{TSL} = a_{Ref} * \left(\frac{M_{r\,TSL}}{M_{r\,Ref}}\right)^{1/3} \tag{6}$$

The asphalt layers' thickness ($t_{Asphalt} = 10cm$) and the treated soil layer thickness ($t_{TSL} = 65cm$) were calculated by using equations 4 and 7, in which: $a_{Asphalt}$ is 0.46; a_{TSL} is 0.0898; and m_{TSL} is 1.

$$SN_{total} = a_{Asphalt} * t_{Asphalt} + a_{TSL} * t_{TSL} * m_{TSL} \tag{7}$$

In the same manner, the structural design calculations - in case of collector and local highways - were implemented. Tables 9 and 10 display the required pavement sections in case of using the stabilized soil with CKD and OPC respectively as a base layer.

TABLE 9. Pavement Sections in Case of Using the Stabilized Soil with CKD as a Base Layer

Highway Classification / CKD Content (%)		Arterial		Collector		Local	
		$t_{Asphalt}$ (cm)	t_{TSL} (cm)	$t_{Asphalt}$ (cm)	t_{TSL} (cm)	$t_{Asphalt}$ (cm)	t_{TSL} (cm)
Without Adding $LCSS$	8%	16	51	14	37	11	34
	12%	17	46	15	32	12	28
With Adding $LCSS$	8%	15	56	13	43	11	33
	12%	16	51	14	38	11	34

TABLE 10. Pavement Sections in Case of Using the Stabilized Soil with OPC as a Base Layer

Highway Classification / OPC Content (%)		Arterial		Collector		Local	
		$t_{Asphalt}$ (cm)	t_{TSL} (cm)	$t_{Asphalt}$ (cm)	t_{TSL} (cm)	$t_{Asphalt}$ (cm)	t_{TSL} (cm)
Without Adding $LCSS$	4%	18	40	15	33	13	21
	6%	13	59	11	48	10	34
	8%	10	62	10	43	10	27
	10%	10	51	10	36	10	22
With Adding $LCSS$	4%	17	44	14	38	12	27
	6%	10	65	10	46	10	29
	8%	10	60	10	42	10	26
	10%	10	57	10	40	10	25

6. ECONOMIC FEASIBILITY OF SOIL STABILIZATION

To evaluate the economic feasibility of soil stabilization with OPC, CKD and $LCSS$, the construction cost of one square meter of pavement ($OSMPC$) has been calculated, in each case of treated and untreated soil. Table 11 displays the costing items [26, 27], which were used to calculate the $OSMPC$.

In case of using the granular base layer, equations 8, 9, 10, and 11 were used to calculate the $OSMPC$. Whereas in case of using the stabilized soil as a base layer instead of the granular base layer, equations 8, 9, 12, 13, 14, 15, 16, 17, and 18 were used.

TABLE 11. Costing Items for the Calculation of $OSMPC$

Costing Item	Unit	Unit Cost (EGP)
Hot mix asphalt	m^3	2,250
Prime coat	m^2	25
Tack coat	m^2	9
Granular Base	m^3	200
Earth works (Mixing, Compaction, etc.) for Treated Soil Layer	m^3	40
CKD	ton	150
OPC	ton	1,250
$LCSS$	m^3	100,000

$$ALC = (t_{Asphalt} * 1 * 1) * ALUC + n_1 * TCUC + PCUC \quad (8)$$

$$n_1 = \frac{t_{Asphalt}}{0.07} - 1 \quad (9)$$

$$GBLC = (t_{GB} * 1 * 1) * GBLUC \quad (10)$$

$$OSMPC = ALC + GBLC \quad (11)$$

Where:

- → $t_{Asphalt}$ and t_{GB} are the thicknesses (m) of both the asphalt layers and the granular base layer respectively.
- → ALC and $GBLC$ are the construction costs (EGP) of one square meter of both the asphalt layers and the granular base layer respectively.
- → $ALUC$, $TCUC$, $PCUC$, and $GBLUC$ are the unit costs (EGP) of the asphalt layers, the tack coat, the prime coat, and the granular base layer respectively.
- → n_1 is the number of tack coat layers, rounded to a nearest whole number.

$$W_s = (0.95 * \gamma_{d\,max}) * (t_{TSL} * 1 * 1) \quad (12)$$

$$AC = AP * W_s * AUC \quad (13)$$

$$LCSSV = LCSSP * (W_s * O.M.C.) \quad (14)$$

$$LCSSC = LCSSV * LCSSUC \quad (15)$$

$$EWC = EWUC * (t_{TSL} * 1 * 1) \quad (16)$$

$$TSLC = AC + LCSSC + EWC \quad (17)$$

$$OSMPC = ALC + TSLC \quad (18)$$

Where:

- → W_s is the dry weight (ton) of one square meter of the treated soil layer before adding the traditional additive (OPC or CKD).
- → $(0.95 * \gamma_{d\,max})$ is the field dry weight (ton) of one cubic meter of soil that is compacted to a dry density equals 95% of the maximum dry density ($\gamma_{d\,max} = 1.972\ ton/m^3$).
- → t_{TSL} is the thickness (m) of the treated soil layer.

- AC is the cost (EGP) of the required weight of the additive (OPC or CKD) for stabilizing one square meter of the treated soil layer. Whereas AUC is the additive (OPC or CKD) unit cost (EGP).
- AP is the additive (OPC or CKD) percent by soil dry weight.
- $LCSSV$ is the required volume of the $LCSS$ (m^3) for stabilizing one square meter of the treated soil layer.
- $LCSSP$ is the $LCSS$ concentration with respect to water volume (0.001 m^3 of $LCSS$ for 1 m^3 of water).
- $O.M.C.$ is the optimum moisture content of the treated soil layer (12.38%).
- $LCSSC$ is the cost (EGP) of the required volume of the $LCSS$ for constructing one square meter of the treated soil layer. Whereas $LCSSUC$ is the unit cost (EGP) of the $LCSS$.
- EWC is the cost (EGP) of mixing, compacting, etc. of one square meter of the treated soil layer. While $EWUC$ is the unit cost (EGP) of earth works.
- $TSLC$ is the construction cost (EGP) of one square meter of the treated soil layer.

Figures 7 and 8 show the effect of soil stabilization with CKD and OPC respectively on the $OSMPC$. Table 12 displays a comparison between savings in $OSMPC$, which result from using the stabilized soil with OPC and CKD as a base layer instead of the traditional granular base layer.

TABLE 12. Savings in $OSMPC$ As a Result of Soil Stabilization with OPC and CKD

Highway Classification	CKD		OPC	
	Optimum Content (%)	Saving in $OSMPC$ (EGP)	Optimum Content (%)	Saving in $OSMPC$ (EGP)
Arterial	8% + $LCSS$	72.02	6% + $LCSS$	110.93
Collector	8% + $LCSS$	69.66	6% + $LCSS$	81.60
Local	8%	53.76	6% + $LCSS$	39.25

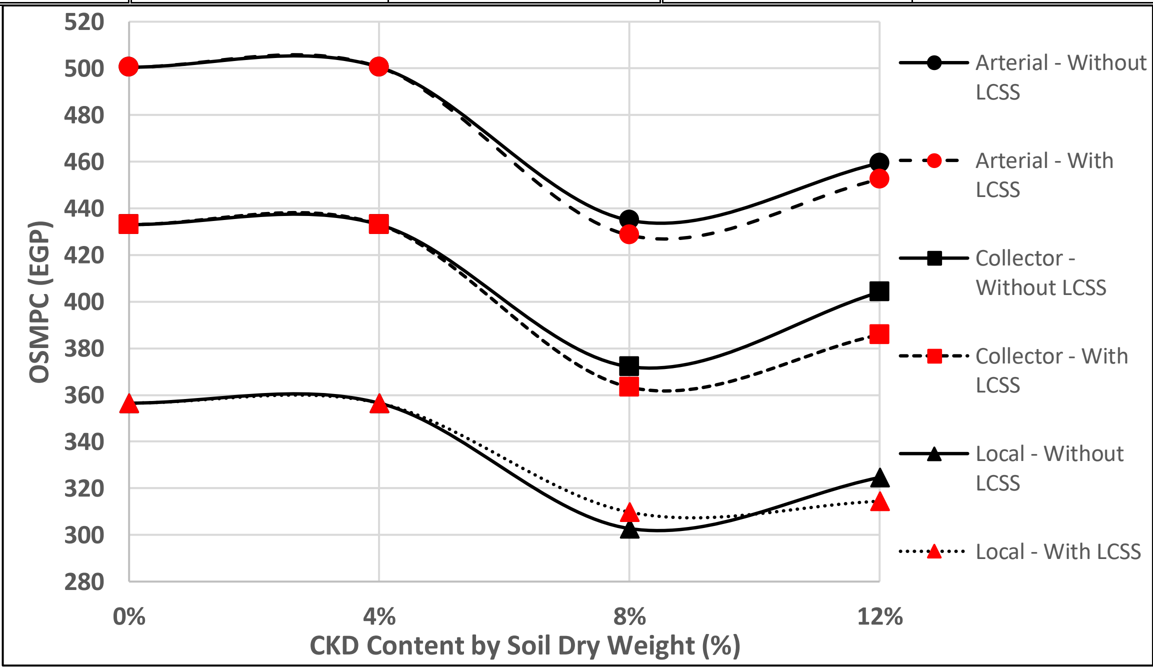

Fig 7. Effect of CKD Content on the $OSMPC$

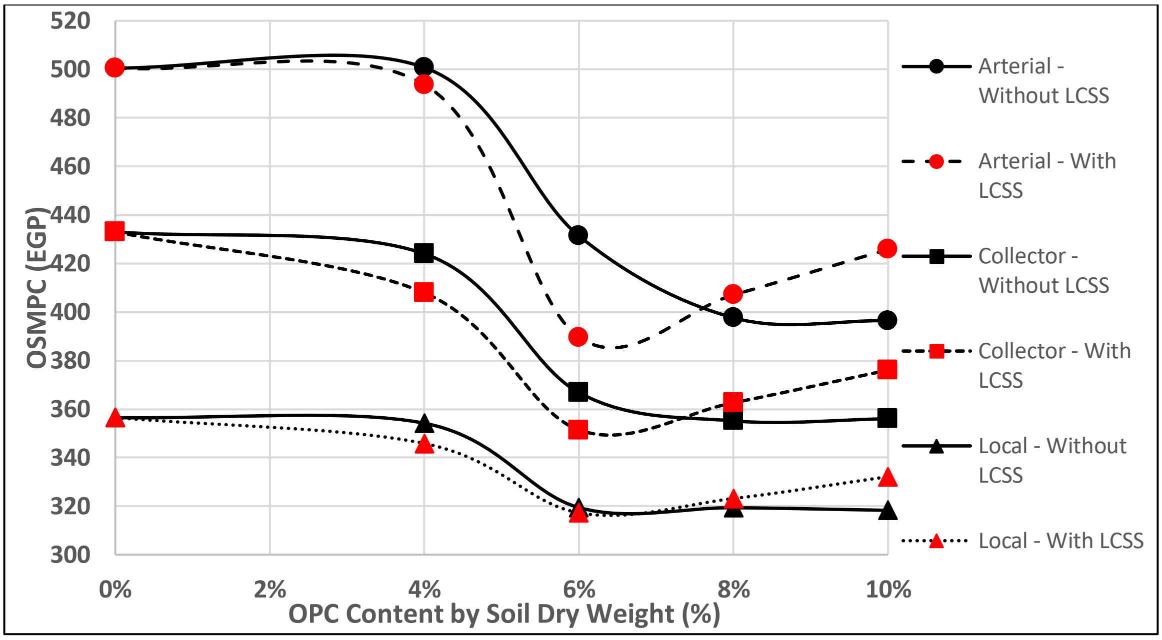

Fig8. Effect of OPC Content on the $OSMPC$

7. CONCLUSIONS

- The addition of the $LCSS$ enhances the soil compact ability.
- The addition of the $LCSS$, without OPC or CKD, did not cause a considerable increase in the CBR value.
- In regard to 7-days UCS:
  - The relation between the OPC content and the 7-days UCS is always a direct relationship whether the $LCSS$ is added or not. Whereas in case of CKD, it is a direct relationship up to the optimum content (8%) only.
  - Submerging the specimens in water for 4 hours before the test resulted in a decrease of the 7-days UCS values.
  - Addition of the $LCSS$ leads to an increase in the 7-days UCS, except in case of 10% OPC content (for submerged specimens) and 12% CKD content (for dry specimens).
- In regard to M_r:
  - Addition of the $LCSS$ leads to the improvement of soil M_r except for 10% OPC content.
  - The optimum CKD content is 8% (whether the $LCSS$ is added or not).
  - The best effect for adding the $LCSS$ is at 6% OPC content.
- In regard to the economic feasibility:
  - For arterial and collector highways, using the stabilized soil with 6% OPC (with adding the $LCSS$) as a base layer is the more economical solution.
  - For local highways, the more economical solution is using the stabilized soil with 8% CKD as a base layer.

8. RECOMMENDATIONS

Based on the discussion presented in this research, the following suggestions for further research may be stated:

- Implementing the resilient modulus test to measure the resilient modulus values of the untreated and treated soil. Measuring of resilient modulus to verify the used values is planned to be carried out and published as appendix to this research work.
- Investigating the effect of using the $LCSS$, beside the selected traditional stabilizers, on the stabilized soil durability.
- Investigating the effects of using the $LCSS$, beside the selected traditional stabilizers, for stabilizing the subbase and base materials on the thickness of both base and asphalt layers.
- Constructing test sections, in case of using the stabilized soil as a base layer, to investigate both the

long-term performance of the pavement sections and the asphalt layers' cracking.

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