Influence of Soil Stabilizing Materials on Lead Polluted Soils using Jet Erosion Tests

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Abstract: Solidification or stabilization treatment is usually used to stabilize site of contaminated land. Several common binding materials, such as cement, hydrated lime, and bitumen, were usually utilized as stabilizer materials for contaminated soil and tested by conventional techniques (such as wet sieving and dispersion ratio methods). Recent studies have been proved that the high lead (Pb) concentration in soil causes an increase in soil erodibility, which is a major global environmental problem. An excess shear stress model is normally applied to measure soil erodibility based on two empirical soil parameters: critical shear stress (τc) and erodibility coefficient (kd). Jet Erosion Test (JET) is one of recent technique to measure the soil erodibility parameters (τc and kd) in the field as well as in the laboratory. The objective of this study was to investigate the influence of many stabilizer materials (cement, hydrated lime, and bitumen) on the stability of an artificially Pb-contaminated soil, using "mini" JET device as a function of measuring soil erodibility parameters (τc and kd). Hence, different percentages of three common Iraqi stabilizer materials (cement, hydrated lime, and bitumen) at different curing time were conducted to observe the effect of these materials on soil properties; such as Atterberg limits, dry density, optimum moisture content, and hardness as well as to soil erodibility parameters (τc and kd). The results showed a reduction in kd value with increasing in the percentage of stabilizer materials and curing time, while τc values were increased. The ideal mixing ratios of stabilizer materials showed that hardness degree increased by a ratio of 22% to 28.4%, while Atterberg limits either decreased or increased by a ratio of 5% to 28.5%. The results showed that all these materials can improve soil properties of Pb-contaminated soil and the cement was the best stabilizer. This study provides the benefit of using JET device in consume testing time and conserving energy, compared with other conventional techniques usually used for studying soil stabilization.

Keywords: Soil stabilization, stabilizer materials, contaminated soil, soil erodibility, JET

1. Introduction

The stabilization of soils has been performed for ages. For instance, the Mesopotamians and Romans separately discovered that it was possible to improve the ability of pathways to carry traffic by mixing weak soils with a stabilization agent like pulverized limestone or calcium [1]. Generally, soil stabilization aims to improve soil strength and increases resistance to softening by water through binding the soil particles together, water proofing the particles or combination of the two [2].

Soil erosion is one of the serious world problems that make the soil to become unstable. Soil erosion is a natural process that slough off and land transport material through the action of natural erosive agents such as: water, wind, gravity, or artificial processes caused by human activities. Recent researches showed that Pb-polluted soil is more erodible than clean soils [3]. Increasing the erodibility of cohesive soils indicated that there is a defect results from pollution in the environment. Soil erodibility is typically defined by excess shear stress model depend on two soil parameters: the critical shear stress (τ_c, Pa) and the erodibility coefficient (k_d, cm^3/kN.s). Currently, there is no widely accepted or reliable method to estimate these parameters for cohesive soils based on the soil properties. The best approach to determine these parameters is to measure them. One of the techniques to determine soil erodibility that is becoming more widely accepted in practice is the Jet Erosion Test, JET [4-6].

The accumulation of heavy metals in soil is an important issue because of the adverse effects that may have on food quality, soil usage, human health, and the environment [7, 8]. In response to these negative effects, there has been ongoing development of variety of technologies to remediate soil affected by heavy metal contamination. Solidification and stabilization immobilization techniques are the most commonly selected treatment options for metal-contaminated sites [9]. According to Wiles [10], chemical treatment of solidification and stabilization either binds the heavy metal and hazardous compound waste stream to a stable insoluble form (stabilization), or entraps the waste within a solid cementitious matrix (solidification). This technique is significant because it is relatively cheaper than most alternatives and resulted in well qualified long term physical and chemical stability, and also because

resultant products often possess superior mechanical and structural characteristics [9].

The most commonly-applied pozzolanic materials are Portland cement, lime, and/or fly ash [11-13]. Stabilization with cement and lime are common treatment technologies for the safe management, reuse, and treatment for disposal of contaminated waste. Portland cement is composed of calcium-silicates and calcium-aluminates that when combined with water, it will hydrate to form the cementing compounds of calcium-silicate-hydrate, and calcium-aluminates-hydrate, as well as excess calcium hydroxide [14]. Because of the cementation materials formed with the cement, and with the calcium hydroxide (lime), the stabilizing may be successful in both granular and fine-grained clay soils. The mechanism of treatment with bituminous material consists of adding cohesive strength and reducing water penetration by the physical presence of bitumen. There is no chemical interaction in this process. Bitumen stabilization includes both water proofing and cementation actions [15].

Several researches were utilized building materials to stabilize polluted soils [16-18]. Al-Layla *et al.* [16] investigated the tensile stress properties of natural and stabilized clayey soil. The tensile strengths were obtained using the flexural test. The compressive strength on a portion of the beam was determined for both soils after curing time of 7 and 30 days. The results revealed that both the tensile and compressive strengths increased with the addition of lime and with increasing curing time. Shubber *et al.* [17] studied the effect of bituminous materials on gypseous sandy soil using different percentages of bitumen. The results revealed that the addition of cutback bitumen with different soaking periods of (0, 4, 7, and 21) days would improve its strength and stiffness characteristics and enhance its waterproofing characteristics. Saeed *et al.* [18] performed experimental studies to evaluate strength development in cement-lime stabilized/solidified soils contaminated with either copper or zinc. Their results confirmed the interference of heavy metals in the process of cement and lime hydration as a direct reflection of varied strength developments in tested soil samples with 200 days curing time selected.

All the pervious techniques were required more time and conservation to test soil stabilization. This research was investigated a new technique to reduce time consuming and energy conservation to investigate the influence of Iraqi local building materials (cement, lime, and bitumen) on Pb-contaminated soil using JET device by measuring soil erodibility parameters (τ_c and k_d). The original JET device was first developed by Hanson [4]. Hanson and Cook [5, 6] developed the analytical method of JET to measure τ_c and k_d immediately using Excel spreadsheet depending on the diffusion principles. Al-Madhhachi *et al.* [19, 20] developed a new miniature version of JET, refers as to "mini" JET device. Al-Madhhachi *et al.* [19] compared the performance of the origin and "mini" JET devices under controlled laboratory setting to investigate the performance of

"mini" JET versus original JET. They found equivalent results between the two JET devices. The "mini" JET device has several benefits over the original JET device; such as, the small size of the "mini" JET, more converted to use in many setting, consume less water, and could be used in situ as well as in the laboratory in comparison to the original JET.

Al-Madhhachi *et al.* [20] verified the results of the origin and "mini" JET devices with the results of flume tests. Khanal *et al.* [21] conducted 20 "mini" JETs under control laboratory condition on two soil types of contrasting texture to investigate the variability of "mini" JET device on estimating soil erodibility parameters. They recommended that at high pressure head, the initial time interval should be taken at least 30 s and a termination time interval should be at least 300 s for less erodible soils. Salah and Al-Madhhachi [3] investigated the influenced of lead (Pb) pollution on the erodibility of cohesive soil using "mini" JET device. Their results showed that the high lead concentration in soil causing an increase in soil erodibility. They found that polluted soil is more unstable than clean soils.

The objectives of this study were 1) to investigate the influence of different percentage of building materials (cement, hydrated lime, and bitumen) on the stability of an artificially Pb-contaminated soil using "mini" JET device as a function of measuring soil erodibility parameters (τ_c and k_d) at different curing times, and 2) to developed relationships between soil erodibility parameters (τ_c and k_d) and other soil properties; such as Atterberg limits, and hardness.

2. Materials and Methods

2.1 Materials

Lean clay soil samples were used as a model in this study to carry out the experiments, acquired from Al-Taji region, North of Baghdad city. Table (1) shows the physical properties and the chemical composition of lean clay soil used in this study. Soil texture, liquid limit, plastic limit, plasticity limit, maximum dry density, optimum water content, soil PH, in addition to chemical composite were reported in Table (1). The soil samples were tested and analyzed according to ASTM standards [22]. The soil sample was classified according to the Unified Soil Classification System (USCS). Soil analyses were carried out in the soil laboratory of the Civil Engineering Department, Al-Mustansiriya University.

Chemical analyses were tested at sanitary laboratory of the Environmental Engineering Department, Engineering College, Al-Mustansiriya University. Other chemical tests were carried out by the State Company of Geological Survey and Mining, Ministry of Industry and Minerals. Three stabilizers were employed in this study; cement, lime, and bitumen. The type of cement, lime, and bitumen used in this study were the ordinary Portland cement, Hydrated lime $Ca(OH)_2$, and bitumen emulsion, respectively. The chemical analysis of cement, hydrated lime, and bitumen utilized in this study are shown in Table (2).

Table 1 Physical properties and chemical composition of soil used in this study.

Site	USCS classification	Soil texture			Atterberg limits			Standard Compaction		Specific gravity	PH
		Sand (%)	Silt (%)	Clay (%)	Liquid limit	Plastic limit	Plasticity index	Maximum Density	Optimum water content (%)		
Al-Taji, North Baghdad	Lean Clay	13	57	30	39	25	14	1.77	18	2.48	7.53

Chemical composition, (%)									
Fe_2O_3	P_2O_5	SO_3^{-2}	CL^{-1}	CO_3^{-2}	OM	T.D.S	$CaSO_4$	SO_4^{-2}	
4.09	0.74	0.28	0.11	0.2	1.09	0.66	0.6	0.34	

Table 2 Chemical composition of stabilizers (cement, lime, and bitumen) used in this study.

Chemical composition (%)	MgO + CaO	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	L.O.I	Total
Cement	-	62.37	20.81	3.57	4.62	1.2	0.64	0.29	2.36	3.64	99.5
Lime	71.50	-	0.98	0.21	0.17	1.28	-	-	0.13	25.73	100

Bitumen						
Properties	Form	Color	Density, g/cm^3	Penetration at 25 C$^\circ$	Solid Content%	Service Temp, C$^\circ$	Setting time, hrs.
Values	Thick viscose liquid	Dark brown		1.03 ±0.02	40 ±5	6 to 47	8 touch dry to 24 firm set
Test standard	visible	visible		ASTM D2939	ASTM D5	ASTM D2939	ASTM D2939

2.2 Experimental procedure

The soil samples were air-dried, broken into smaller pieces size, and sieved through a 4.75 mm sieve according to ASTM standard [22]. The sieving was performed to ensure that the soil was of uniform grade. Several groups were tested in this study. Each group contained 8 samples with a total of 96 samples. Two of them are prepared without stabilizer and the other six were prepared with stabilizer.

For samples without stabilizer, the artificial Pb-contaminated soil samples were prepared by mixing lead nitrate, as the source of lead (Pb), to produce lead concentration of 4000 mg/kg into the natural soil of 2000 g in weight of each sample. The mixture was mixed by hands for (5-10) min until the mixture has a homogenous and uniform appearance and left for 24 hrs. with required water content in a closed bucket to allow moisture equilibrium, then soil moisture content (ω) of the samples was determined.

For samples with stabilizer, the soil samples were contaminated with lead (Pb) as explained previously. Then different percentages of (3%, 6%, and 9%) stabilizers (cement, hydrated lime, and bitumen) were added to the contaminated soil (the percentage added according to the weight of dry soil). The required optimum moisture content added to the soil in the case of bitumen was based on fluid content of the mixture (water + bitumen). After that, the contaminated soil and stabilizer were mixed for (5-10) min until the

mixture has a homogenous and uniform appearance and left for 24 hrs. in a closed bucket to allow moisture equilibrium, then soil moisture content (ω) of the samples was determined.

Eight soil samples of each group with a total of 96 samples were prepared for testing after 24 hrs. by mixing in standard mold, using proctor compaction test which is consists of a standard mold with standard compaction energy according to ASTM standard. The standard mold was a 101.6 mm in diameter and the soils were compacted at three separate layers using 25 blowing in each layer by a 2.5 kg hammer falling of 305 mm in height according to ASTM standard [22].

The "mini" JET device (Figure 1) was performed to derive excess shear stress model parameters (τ_c and k_d). The description, dimension, and functions of this device were defined in Al-Madhhachi et al. [19]. In this study, the "mini" JET was calibrated according to Al-Madhhachi et al. [19] and the coefficient of discharge (C) was found to be 0.65. The sample without stabilizer was tested using "mini" JET directly after compaction while the sample with stabilizer were tested after (1, 3, and 7) days after compaction, in order to investigate the stabilizer effect on soil stabilization using "mini" JET device. Every two soil samples from each group were prepared for testing with the "mini JET device at the same time and in the same manner. The soil specimen was place in the center of the submergence tank directly below the jet nozzle. The adjustable head tank was then set at the desire constant head (70 cm for all experiment) and hoses (including water source) were connected to the JET device (Figure 1). Tests were repeated twice for each curing time of one additive. The procedure of running JET and collecting data were followed Al-Madhhachi et al. [19, 20] and Khanal et al. [21] with test length of 120 minutes.
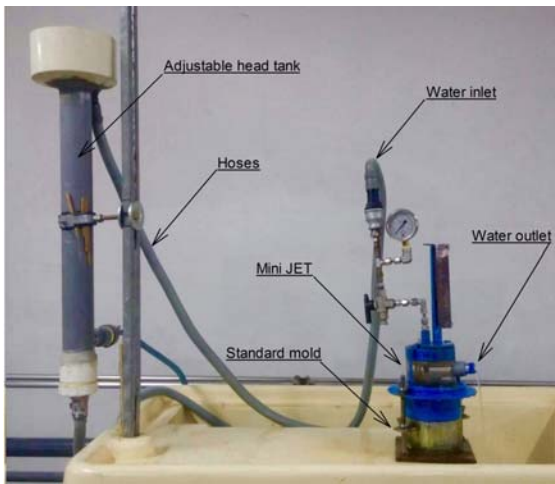

Fig. 1 Laboratory setup of the "mini" JET device.

Digital Shore-D durometer, which is usually used to measure the hardness of rubber according to ASTM, was performed for measuring the hardness of soil-stabilizer mixture [23] to determine the hardness of 26 soil samples tested in this study after 7 days of curing time. Two samples of each percent of addition of the three stabilizers were tested to increase the accuracy of the tests.

2.3 Analysis method of JETs

The excess shear stress model is the most commonly used model to predict soil erodibility depends on two empirical soil parameters: k_d and τ_c. It is expressed as [24, 4]:

$$\varepsilon_r = k_d \left(\tau - \tau_c \right)^a \tag{1}$$

where ε_r is the detachment rate (cm/s), τ is the average hydraulic boundary shear stress (Pa), and a is an empirical exponent assumed to be unity according to Hanson [4] and Al-Madhhachi et al. [19, 20].

The solution method of excess shear stress model parameters was based on principles of fluid diffusion presented by Stein and Nett [25] and a hyperbolic function modeling the depth progression of the scour hole developed by Blaisdell et al. [26]. The equilibrium depth (J_e) is defined as the maximum depth of the scour hole beyond which the water jet cannot erode further. This solution method predetermines the τ_c parameter based on J_e of scour hole as predicted by the Blaisdell's function as following [5, 6]:

$$\tau_c = \tau_o \left(\frac{J_p}{J_e} \right)^2 \tag{2}$$

where $\tau_o = C_f \rho_w U_o^2$ is the maximum shear stress due to the jet velocity at the nozzle (Pa); $C_f = 0.00416$ is the coefficient of friction; ρ_w is water density (kg/m^3); $U_o = C\sqrt{2gh}$ is the velocity of jet at the orifice (cm/s); C is discharge coefficient (ranged from 0.6 to 0.8 for "mini" JET according to Al-Madhhachi et al. [19]); h is the pressure head (cm); $J_p = C_d d_o$ is the potential core length from jet origin (cm); d_o is the nozzle diameter (cm); and $C_d = 6.3$ is the diffusion constant. The k_d is then determined by solving for the least squared deviation between the observed scour time and predicted time of the following equation [5]:

$$T^* - T_p^{\,*} = -J^* + 0.5\ln\left(\frac{1+J^*}{1-J^*} \right) + J_p^{\,*}$$
$$- 0.5\ln\left(\frac{1+J_p^{\,*}}{1-J_p^{\,*}} \right) \tag{3}$$

where $T^* = t / T_r$ is the dimensional time, t is the time of a scour depth measurement, $T_r = J_e /(k_d \tau_c)$ is the

reference time according to Stein and Nett [25], $J^* = J/J_e$; J is the scour depth (cm), and $J_p^* = J_p /J_e$. The parameters of the excess shear stress model were derived using equations 1 through 3 for JET data using Spreadsheet Tool, Version 2.1.1 that developed by Daly *et al*. [27]. The above procedure is referred to Blaisdell solution.

3. Results and Discussion

A total of 96 soil samples were tested using "mini" JETs to drive the erodibility parameters (k_d and τ_c) of excess shear stress model. Figure (2) shows the relationships between excess shear stress parameters (k_d and τ_c) and curing time (0, 1, 3, and 7) days after adding different percentage (0%, 3%, 6%, and 9%) of stabilizers (cement, hydrated lime, and bitumen) to the Pb-contaminated soil. The zero percentage indicated to soil samples tested without adding any stabilizers.
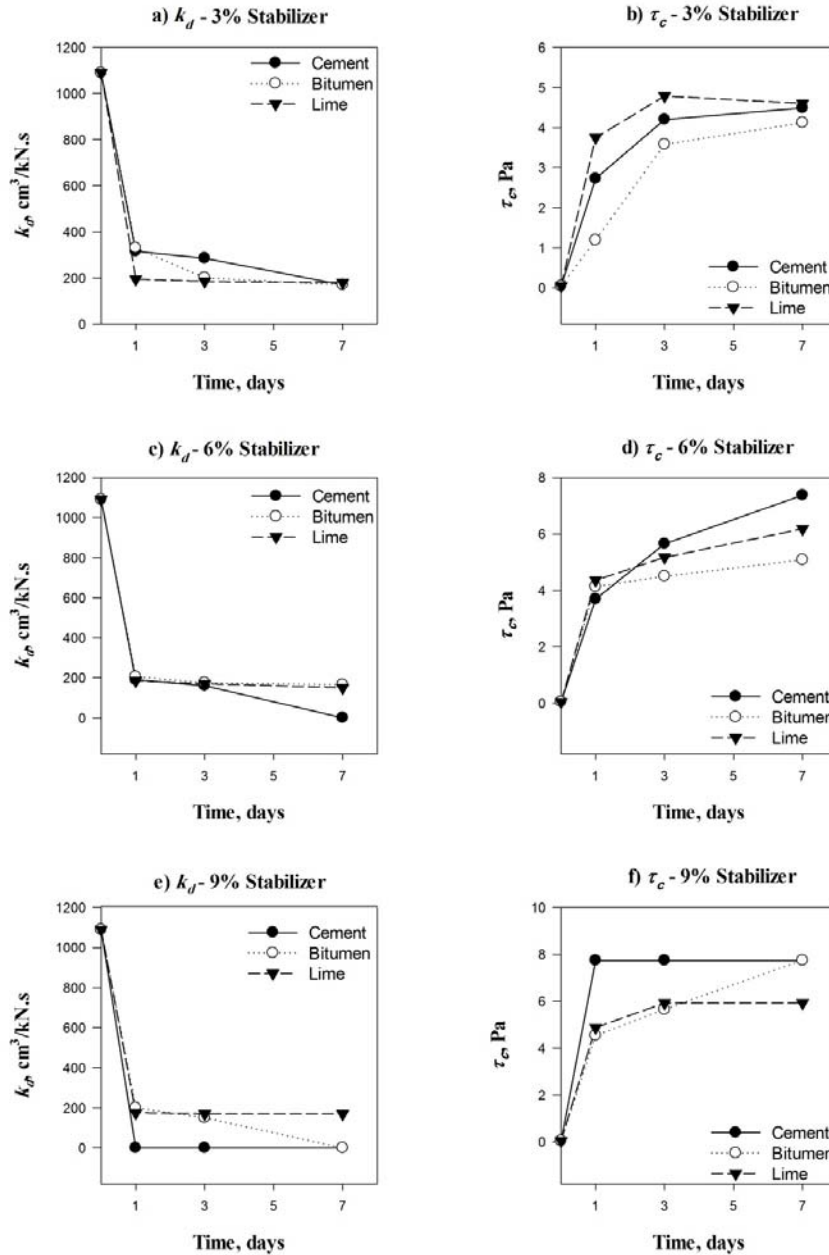

Fig. 2 Effect of different percentage of stabilizers (cement, hydrated lime, and bitumen) on excess shear stress parameters at different curing times: (a) k_d − 3% stabilizer, (b) τ_c − 3% stabilizer, (c) k_d − 6% stabilizer, (d) τ_c − 6% stabilizer, (e) k_d − 9% stabilizer, and (f) τ_c − 9% stabilizer.

Table 3 Excess shear stress parameters (k_d and τ_c) values at different percentage of stabilizers (cement, hydrated lime, and bitumen) after 7 days of curing time.

Cement			Hydrated lime			Bitumen		
Percentage, %	k_d, cm^3/kN.s	$\tau_{c,}$ pa	Percentage, %	k_d, cm^3/kN.s	$\tau_{c,}$ pa	Percentage, %	k_d, cm^3/kN.s	$\tau_{c,}$ pa
0	1090	0.045	0	1090	0.045	0	1090	0.045
3	170	4.49	3	180	4.605	3	170	4.125
6	0.1	7.37	6	150	6.18	6	165	5.085
9	1.0000e^{-3}	7.74	9	170	5.925	9	0.1	7.74

It can be observed that the erodibility coefficient k_d decreased with increased curing time for the same percentage of stabilizers and k_d decreased with increased stabilizer percentages, while the critical shear stress τ_c increased with increased curing time for the same percentage of stabilizer and with increasing stabilizer percentages. The decreased in k_d values with cement was due to the chemical compositions of cement contributed to adhesive and cohesive property of the cement which make it capable of binding fragments of minerals into whole compacted soil. The contested area between chemical components of cement and chemical components of soil produced more stable soils [28]. The decreasing in k_d values with hydrated lime was due to the cementitious products of the lime which obtained strengths to lime-stabilized soil layers [29]. Note that the chemical reactions with lime required more time compared with cement [30]. The decreasing in k_d values with bitumen was due to increase in the cohesive and load bearing capacity of the soil particles which is increased the resistant to the action of water. The soil particles were covered with bitumen that prevents or slows the penetration of water [28]. The entire samples in this study after stabilization were converted to very resistant and more stable soils. Hanson and Simon [31] reported that the very erodible soils had low τ_c and high k_d, while the very resistant soils had high τ_c and low k_d.

The results of excess shear stress parameters (τ_c and k_d) with different percentages (0%, 3%, 6%, and 9%) of stabilizers (cement, hydrated lime, and bitumen) after 7 days of curing time were reported in Table (3). This curing time was enough to obtain the desired results compared with other old techniques that required a long time ranged from 21 to 200 days for testing soil stabilization. This proved the beneficial of JET device in consume testing time and conserving energy when compared with other conventional techniques. Table (3) showed that the ideal mixing ratios of stabilizers were 6% for cement, 6% for hydrated lime, and 9% for bitumen to obtain the significant values of excess shear parameters values (τ_c and k_d) after 7 days of curing time.

In order to investigate the influence of some soil properties on soil erodibility parameters (k_d and τ_c); Atterberg limits, dry density, moisture content, and hardness were reported in this study. The Atterberg limits reflect to the physical response of a soil to water, and hence are significant as indices of behavior of clay soils. The relationships between Atterberg limits (liquid limit, plastic limit, and plasticity index) and different percentages (0%, 3%, 6%, and 9%) of stabilizers (cement, hydrated lime, and bitumen) are shown in Figure 3.
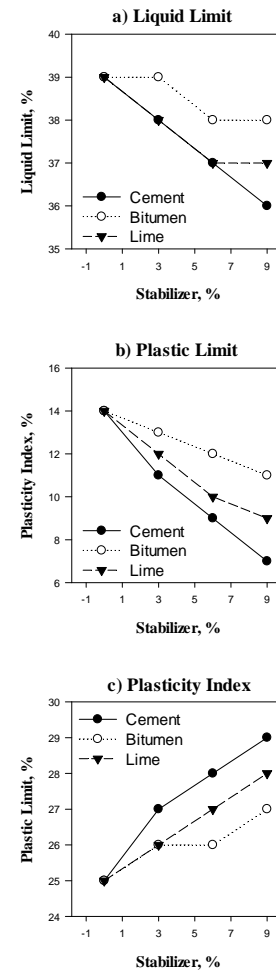

Fig. 3 Relationships of Atterberg limits with different percentage of stabilizers (cement, hydrated lime, and bitumen) for: a) Liquid limit, b) Plastic limit, and c) Plasticity index.

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The liquid limit decreased gradually with increasing percentages of cement and hydrated lime, but showed less reduction with bitumen percentage (Figure 3a). This reduction in liquid limit was 5%, 5%, and 2.5%, for the ideal mixing ratios of cement, hydrated lime, and bitumen, respectively. This could be as a result of the pores in the clay soil being occupied by the particles of the three stabilizers and hence less vulnerable with increasing water content. Similar results were reported in Kadhim [32].

Increasing in plastic limits was observed as percentage of stabilizers increased as shown in Figure 3b. The increasing in plastic limit was 12%, 8%, and 8% for ideal mixing ratios of cement, hydrated lime, and bitumen, respectively. This was due to the phenomenon of flocculation and agglomeration that obtained after the addition of stabilizing agents which leads to decrease in the thickness of the water layer (electric double layer). Therefore, the clay becomes less affected by the addition of water. Similar results were observed by Locat et $al.$ [33]. As a result of differences between liquid limit and plastic limit, the reduction in plasticity index was 35.7%, 28.5%, and 21.4% for ideal mixing ratios of cement, hydrated lime, and bitumen (Figure 3c), respectively. These differences were also observed by other researches [34].

A comparison of dry density and optimum moisture content at different percentage (0%, 3%, 6% and 9%) of stabilizers (cement, hydrated lime and bitumen) added to the Pb-contaminated soil using Proctor compaction test is shown in Figure 4. The dry density of soil decreased with increased in percentage of cement and lime. The increasing of 8.5% and 10% at the ideal mixing ratios was due to flocculation and agglomeration of fine grained soil particles which occupied larger space and lead to a corresponding drop in dry density. Sherwood [2] and Al-Qaisee [35] reported similar results.

The dry density of compacted soil increased with increased bitumen percentage by 1.1% for the ideal ratio was due to that the pore spaces were filled with bitumen that could move through the soil particles and link them together (Figure 4a). Similar behaviors were found by Ogundipe [36]. The increasing in moisture content of soil with cement and lime was 5.5% and 2.7% for the ideal mixing ratios because cement and lime powders are finer than the soil particles (Figure 4b). The finer particles resulted in more surface area; therefore, more water is required to provide better lubrication. The increasing was also attributed by the pozzolanic reaction of these materials with the soil [37]. The increasing in moisture content with bitumen was 11% for the ideal ratio (Figure 4b). This was probably due to lubricating effect and fluid content of bitumen, as observed in Kadhim [32].
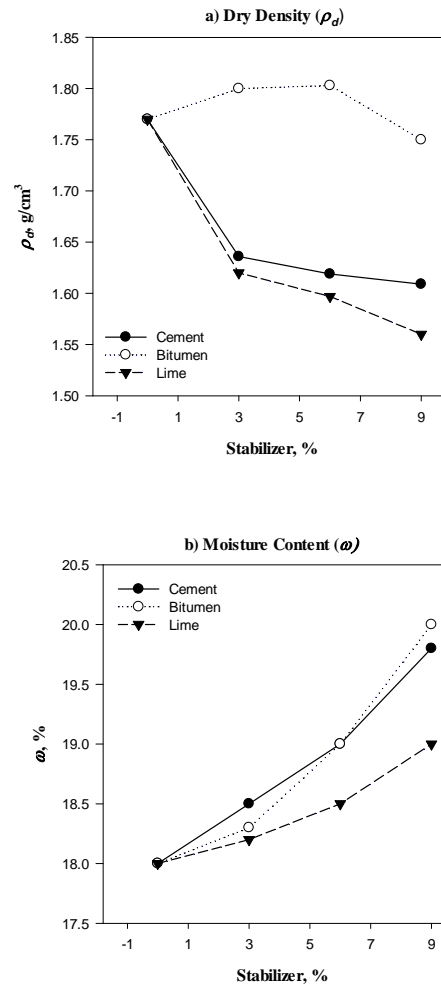

Fig. 4 Relationships between different percentage of stabilizers (cement, hydrated lime, and bitumen) with: a) Dry density, and b) Moisture content.
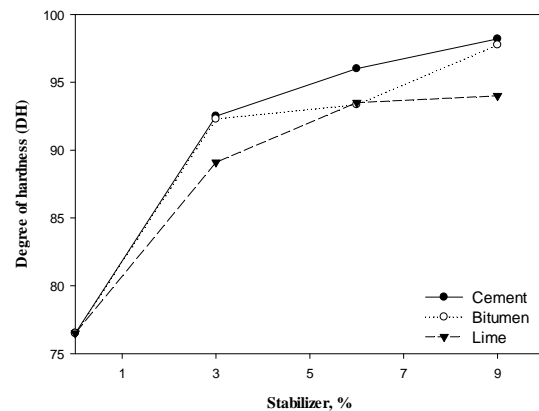

Fig. 5 The variation of average degree of hardness on different percentage of stabilizers (cement, hydrated lime, and bitumen).

As expected, increased in average degree of hardness (DH) was observed as stabilizer percentages (0%, 3%, 6% and 9%) of cement, hydrated lime, and bitumen, increased (Figure 5). The increased in hardness was 28.4%, 22%, and 27.7% at the ideal mixing ratios of cement, hydrated lime, and bitumen, respectively. The higher hardness with cement was due to the pozzolanic reactions which produced a cementitious bond between soil mineral substances that increased the cohesion of soil particles [38]. The lower hardness was with hydrated lime, because the pozzolanic reactions required several months or years to be stabilized [33]. The hardness with bitumen includes both waterproofing of soil and cementation actions which bind the particles together [15].
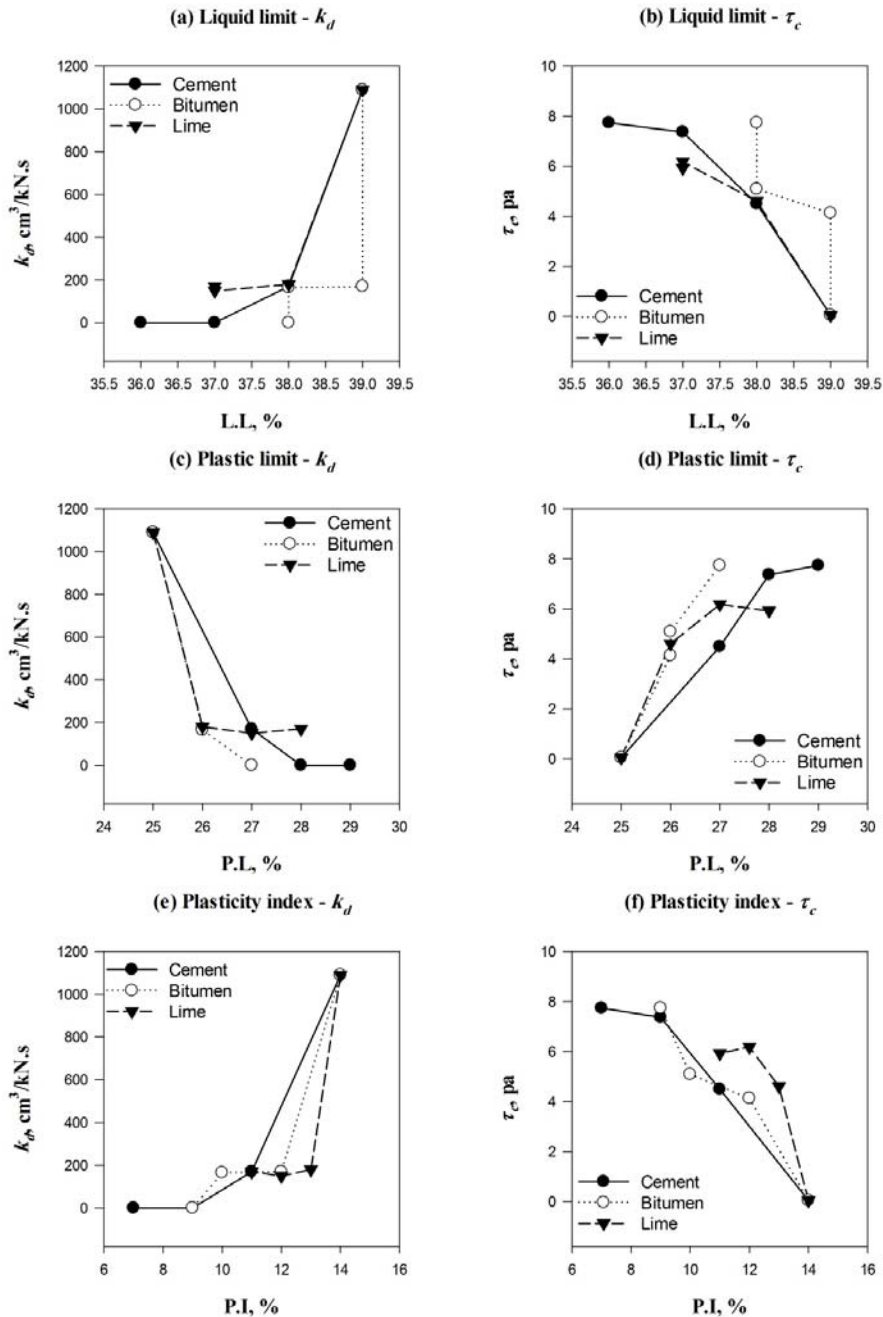

Fig. 6 Relationship between excess shear stress parameters and Atterberg limits for different stabilizer materials (cement, hydrated lime, and bitumen):   a) Liquid limit–k_d, b) Liquid limit–τ_c, c) Plastic limit–k_d, d) Plastic limit–τ_c, e) Plasticity index–k_d, and f) Plasticity index–τ_c.

The relationships between excess shear stress parameters (τ_c and k_d) and Atterberg limits of different percentage (0%, 3%, 6%, and 9%) of stabilizers (cement, hydrated lime, and bitumen) added to the Pb-contaminated soil were reported (Figure 6). The results showed that there were increasing in erodibility coefficient k_d associated with increasing in liquid limit, with correlation coefficient (R^2) of 0.47 to 0.77 and with increasing in plasticity index, with R^2 of 0.61 to 0.81 (Figures 6a and 6e). While there was a reduction in k_d as plastic limit increased, with R^2 of 0.61 to 0.87 (Figure 6c). As expected, the critical shear stress τ_c followed opposite behavior to k_d in relation to the Atterberg limits, with R^2 of 0.62 to 0.97 (Figures 6b, 6d, and 6f).
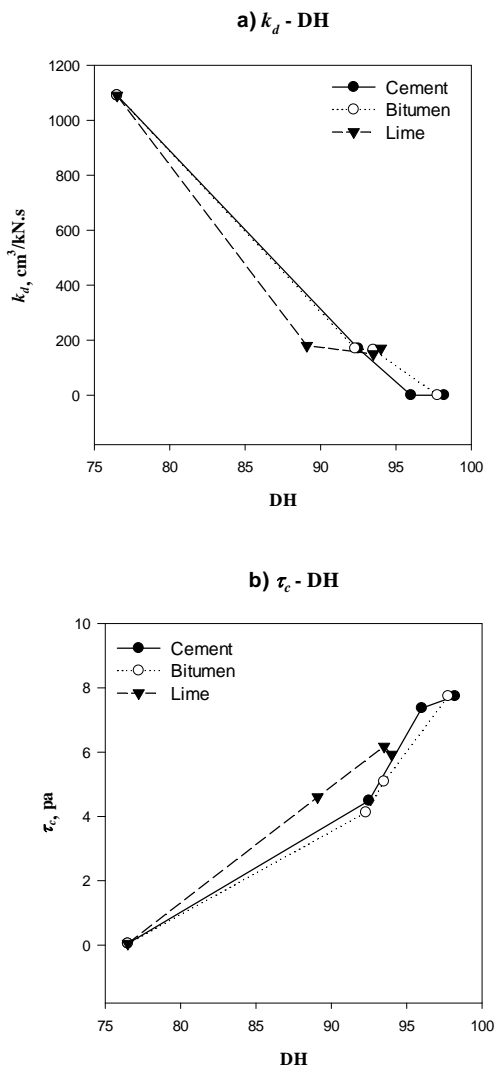

Fig. 7 Relationship between excess shear stress parameters (k_d and τ_c) and the degree of hardness (DH) after 7 days for different stabilizer materials (cement, hydrated lime, and bitumen) where; a) k_d-DH, and b) τ_c-DH.

Figure (7) shows the relationships between excess shear stress parameters (τ_c and k_d) and the degree of hardness (DH) at different percentages (0%, 3%, 6%, and 9%) of stabilizers (cement, hydrated lime, and bitumen) added to the Pb-contaminated soil. As expected, an inverse relationship between k_d and the degree of hardness, with R^2 of 0.94 to 0.99, while the critical shear stress τ_c followed a direct correlation versus the degree of hardness, with R^2 of 0.94 to 0.99. Low k_d values indicted to more stable soils.

4. Conclusion

Cement, lime, and bitumen are considered as stabilizers of contaminated land, since they can reduce the mobility of contaminant soils. Ninety-six tests were performed using "mini" JET device to investigate the influence of these stabilizers on the resistance of Pb-contaminated cohesive soil erodibility by measuring the excess shear stress parameters (τ_c and k_d). The data obtained from the "mini" JETs were analyzed with the linear model using Blaisdell solution technique to derive τ_c and k_d. Relationships between erodibility parameters (τ_c and k_d) and soil properties (Atterberg limits and soil hardness) were developed. The results indicated that the erodibility coefficient k_d of the soil decreased with increasing curing time for the same stabilizer percentage, and with increased stabilizer percentages. While the critical shear stress τ_c increased with increasing curing time for the same stabilizer percentage and with increasing stabilizer percentages.

An inverse relationship between τ_c and k_d were observed as developed in previous studies. The results showed that the ideal mixing ratios to stabilize Pb-contaminated soil was at 7 days of curing time with 6% cement, 6% hydrated lime, and 9% bitumen. At ideal mixing ratios of these stabilizers, the value of k_d decreased from 1090 to 0.1 cm^3/kN.s, soil hardness increased from 22% to 28.4%, and the Atterberg limits either decreased or increased from 5% to 28.5%. As expected, a strong inverse relationship between k_d and the degree of hardness with R^2 of 0.94 to 0.99 was observed, while the critical shear stress τ_c followed a direct correlation with the degree of hardness, R^2 of 0.94 to 0.99. The results indicated that low k_d values referred to more stable soils and the cement was superior in stabilizing contaminated soil among lime and bitumen. This study proved the beneficial of using JET device in consume testing time and conserving energy when compared with other conventional techniques used for testing soil stabilization.

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