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The Chemical Role of Cement and Lime in the Stabilization Mechanisms of Lead Contaminated Iraqi Soils

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ABSTRACT

Unfortunately, Iraq has wide areas of heavy metals contaminated lands due to mismanagement of activities dealing with these pollutants. But, Iraq is one of the biggest countries in the Middle East in the production of cement and lime and both are of low prices and available in the local markets as building materials. This study is designed to investigate the use of (0.0, 3.0, 6.0 and 9.0% by weight) hydrated lime "locally known as Nora" and Portland cement in the treatment of many lead contaminated Iraqi soil samples and then studying their role in soil stabilization; as measured by a newly developed "mini" JET device and by the dispersion ratio method (DR, %) determined in 1:2 soil: water solutions. The results revealed that both lime and cement can significantly improve the stability of these soils and only 6% of both stabilizers were required to get the optimum soil stabilization. According to the "mini" JET calculations of the critical shear stress (τ_c, pa) and the erodibility coefficient (k_d), by using a linear model and the Blaisdell solution technique, both stabilizers have improved the soil engineering properties that are related to soil stabilization. Thus, stabilizers have reduced both the scouring depth (SD) and the erodibility coefficient (k_d) of treated soils. The DR values in both stabilizers were highly correlated with the (k_d) coefficients (R= 0.99 and 0.94 in lime and cement, respectively) and the soil solution chemistry, which is the main concern of this study, was of prime important in this respect. Chemically, both stabilizers have increased pH (from 7.18 to 9.20, R= 0.98 for lime; from 7.18 to 8.65, R= 0.97 for cement) but decreased both EC (from 3.50 to 1.40 mS/cm, R= -0.82 for lime; from 3.50 to 1.30 mS/cm, R= -0.85 for cement) and SAR (from 6.30 to 1.98, R= -0.96 for lime; from 6.3 to 2.8, R= -0.85 for cement) in treated soil solutions. Concerning the pH changes, lime has more impact than cement in increasing pH, especially in higher additions (i.e. 9%, pH 9.20 in lime, and 8.65 in cement), and this may make lime as being less efficient than cement as a stabilizer. However, both stabilizers have successfully decreased the erodibility coefficient (k_d, from 1090 to 170 cm^3/kN.s, R= -0.78 in lime, and from 1090 to 0.0 cm^3/kN.s, R= -0.85 in cement) and the dispersion ratio (DR, from 7.03 to 1.96%, R= -0.83 in lime, and from 7.03 to 1.33%, R= -0.96 in cement) and hence the lead solubility (Pb, from 48.8 to 19.5 ppm, R= -0.96 in lime, and from 48.8 to 12.2 ppm, R= -0.84 in cement) in the solutions of lead contaminated soil. Cement, with no doubt, was more efficient than lime in this respect.

Keywords: Hydrated lime, Cement, Soil Stabilization, Contamination, Lead, Iraq.

I. INTRODUCTION

Lead soil contamination becomes as a serious problem in Iraq; due to increasing in the population, wars, human activity and as a result of increasing of car usage; especially after 2003 when about one million used cars entered Iraq from the neighbouring countries. The increasing of used cars led to the increase of lead concentration; because the oil ministry in Iraq is still adding the tetra alkyl lead additive as a chemical agent in the benzene production. For example, lead concentration in Al-Dora region south of Baghdad, the place of Al-Dora refinery, was very high (more than the minimum range, 2 ppm, but less than the maximum, 300 ppm; Landon, 1991) due to the lead additives in Al-Dora refinery. Additionally, the presence of Babil car batteries factory in Al-Waziryah (north east of Baghdad) and Al-Noor batteries factory in Abu-Ghraib (west of Baghdad), which are still using old techniques, have no emission control devices and no waste water treatment plants. All these lead emissions can be deposited and adsorbed by soil. Immobilization or Solidification/Stabilization (S/S) technologies are designed to reduce the mobility of contaminants by changing the physical or leaching characteristics of the contaminated matrix. Contaminant mobility is usually decreased by physically restricting its contact with the surrounding waters, or by chemically fixing to make it more stable with respect to dissolution in water. The S/S treatments are the most commonly used in heavy metals-contaminated sites [1]. The general approach for S/S treatment processes involves mixing or injecting treatment agents to the contaminated soils. The most commonly-applied pozzolanic stabilizers are Portland cement, lime and/or fly ash [2-3]. Inorganic binders, such as cement, lime, fly ash, or blast furnace slag, and organic binders such as bitumen are also used to form a crystalline, glassy or polymeric framework around the waste [4]. The S/S is achieved by mixing the contaminated material with appropriate amounts of binder/stabilizer and water. The mixture sets and cures to form a solidified matrix and contain the waste. Soil stabilization studies have started in the early years of the 20th century. Middleton (1930) [5], for example, was found that many soil chemical properties may inhibit clay flocculation and stabilization sometimes despite the existence of other favourable conditions. The dominant cation in soil solutions as well as its concentration, for example, can play a major part in soil stabilization. Enough divalent cations, usually Ca^{+2} and Mg^{+2}, in soil solution are required to prevent clay dispersion and improve soil aggregation [6-7]. Emersion (1967) [8] suggests that at least 0.6 to 2.0 meq/l divalent cation concentration is required in soil solution to prevent clay dispersion. In sodium affected soils, aggregates may be stable only if the salt concentration (EC) of the soil solution is large enough to cause flocculation [9]. Soil pH and SAR have significant links with clay dispersion and aggregation. According to Emersion model (1959) [10], the increase in soil pH causes the charge at the edges of the clay minerals to change from positive to negative and hence both the soil cation capacity and flocculation value increase. Abu-Sharar *et al*. (1987) [11] noted that the extent of soil aggregates slaking is dependent upon the level of SAR and EC. The soil electrical conductivity (EC) is also important. Clay particles become closer and form more stable suspensions when salt concentration is low [12]. Therefore, huge efforts were used in recent years to overcome the weakness of soil stability against erosion agents.

Iraq is one of the biggest countries in in the Middle East in the production of hydrated lime “locally known as Nora” and cement building materials and they are of low cost and very available in the local market to be utilized in the stabilization of soils against erosion and heavy metals movement. The main objective of this study is to evaluate the chemical effect of lime and cement, as soil stabilizers, on soil properties that have an impact on the aggregate stability of an artificially lead contaminated soil. The procedures also include the shaking of 1:2 soil: water mixture to determine both the dispersion ratio (DR, %) and the soluble (i.e. unstable or mobile) Pb in soil solution. The DR was measured by the gravimetric method to be related later to the chemistry properties of soil solution (EC, pH, and SAR).

II. COMPONENTS OF SOIL STABILIZATION

Soil stabilization means the use of stabilizing agents as binding materials in weak soils to improve their properties; such as permeability, strength, compressibility, and durability and hence the stability against erosion agents. The components of stabilization technology include soils and or soil minerals and stabilizing cementing agents or binders.

A. Soils

Most of stabilization has to be used in weak and vulnerable soils in order to achieve desirable properties. According to Sherwood (1993) [13], fine-grained granular materials are the easiest to stabilize due to their large surface area in relation to their particle diameter. A clay soil compared to others has a large surface area due to flat and elongated particle shapes. On the other hand, silty materials can be sensitive to small change in moisture and, therefore, may be difficult to improve during stabilization.

B. Cement

Cement is the oldest binding agent since the start of soil stabilization technology. It may be considered as a primary stabilizing agent because it can be used alone to achieve the stabilizing action required [13]. Cement reaction is not dependent from soil minerals, and the key role is its reaction with water that may be available in any soil [14]. This can be the reason why cement is used to stabilize a wide range of soils. Many types of cement are available in the market; like ordinary Portland cement, blast furnace cement, sulphate resistant cement and high alumina cement. Compared with other remediation technologies, cement-based S/S has many advantages; like its low cost long-term stability, good impact and compressive strength, relatively low water permeability, and non-toxic and highly resistant to biodegradation [15-16].

C. Lime

Lime provides an inexpensive method of soil stabilization. Lime stabilizations technology is widely applied in geotechnical, environmental and foundation improvement; such as in use of lime pile or lime-stabilized soil columns [17]. There are three types of lime: dry hydrated lime, dry quick lime, and sulrry lime [14].

Lime can increase the strength brought by the cation exchange capacity rather than cementing effect brought by pozzolanic reaction [13]. In soil modification, clay soils turn drier and less susceptible to water content changes [18].

III. STABILIZATION REACTIONS

A. Soil-Cement Reaction

Adding Portland cement to a soil body results in a primary hydration reaction in the cement, followed by a secondary pozzolanic reaction. The former happens in any mixture of cement and water, but the latter only occurs in the vicinity of soil particles between calcium hydroxide supplied by the cement, and silica and alumina from the soil [19]. The production of cementitious bonds between soil mineral substances creates a matrix that encloses the unbounded particles and aggregates and results in an apparent cohesion in the soil material, making its engineering behavior more complicated [20]. The reaction of cement with water and decomposition can be indicated by following equations [21]:

$$3CaO.SiO_2 \xrightarrow{H_2O} 2CaO.SiO.XH_2O + Ca(OH)_2$$

$$2CaO.SiO \xrightarrow[\text{Slow}]{\overset{\text{Moderate}}{H_2O}} \underset{\text{(Microcrystalline)}}{\overset{\text{(Microcrystalline)}}{2CaO.SiO.XH_2O}}$$

$$3CaO.Al_2O_3 \xrightarrow[\text{Immediate}]{H_2O} \underset{\text{Crystalline}}{3CaO.Al_2O_3.6H_2O}$$

$$3CaO.Al_2O_3 \xrightarrow[\text{Moderate}]{CaSO_4+H_2O} \underset{\text{Crystalline}}{2CaO.Al_2O_3.3CaSO_4.3H_2O}$$

$$4CaO.Al_2O_3.Fe_2O_3 \xrightarrow{H_2O} \underset{\text{Crystalline}}{3CaO.Al_2O_3.6H_2O}+\underset{\text{compound Amorphous}}{\text{undetermined}}$$

B. Soil-Lime Reaction

The addition of lime to the soil water system produces (Ca^{+2}) and (OH^-) and the remaining anions (OH^-) in the solution are responsible for the increased in pH and alkalinity [22-23]. In the cation exchange process, divalent calcium ions (Ca^{+2}) may replace monovalent cations on clay surfaces. The Ca^{+2} ions link with the negatively charged soil minerals together and reduce the repulsion forces and the thickness of the diffused water layer. This layer encapsulates the soil particles and strengthens the bond between them. After the reduction in water layer thickness, the soil particles become closer to each other, causing the soil texture to change. This phenomenon is called flocculation-agglomeration [24]. Lime stabilization may refer to pozzolana reaction in which pozzolana materials reacts with lime in presence of water to produce cementitious compounds [25]. Pozzalanic reaction are time dependent and require long periods of time (years) because such reactions are functions of temperature, calcium quantity, pH value and the percentage of silica and alumina in the soil minerals [26]. In addition, the impurities present on the surface of clay minerals are inversely affected on lime stabilized soil [27]. However, these pozzolanic reactions can be described by the following chemical equations [28-29]:

$$Ca(OH)_2 + SiO_2 \longrightarrow CaO\text{-}SiO_2\text{-}H_2O$$

$$Ca(OH)_2 + Al_2O_3 \longrightarrow CaO\text{-}Al_2O_3\text{-}H_2O$$

IV. MATERIALS

The soil samples used in this study was acquired from Al-Taji region, north of Baghdad city. The soil is a Lean Clay CL according to the Unified Soil Classification System (USCS) and a Silt Clay Loam in the triangle of the USDA classification. Table 1 shows the physical and chemical properties of the soil used in this study. The soil samples were tested and analyzed according to ASTM standards. Soil analysis was carried out in the Sanitary laboratory of the Environmental Engineering Department, Al-Mustansiriyah University. Other chemical tests were carried out by the State Company of Geological Survey and Mining, Ministry of Industry and Minerals. Other properties of soil used in this study are shown in Tables 3 and 4.

Two types of soil stabilizers were bought from the local market and used in this study; cement and lime which are commonly used in Iraq as building materials. The type of cement and lime used in this study were the ordinary Portland cement and Hydrated lime $Ca(OH)_2$, respectively. The chemical analysis of cement and hydrated lime in this study are shown in Table 2.

TABLE 1

PHYSICAL AND CHEMICAL PROPERTIES OF SOIL USED IN THIS STUDY

							Chemical properties: soil suspension (1:2 soil:water)				
Soil properties	Silt (%)	Clay (%)	Specific gravity	Organic Matter (%)	$CaCO_3$ (%)	$CaSO_4$ (%)	pH	EC, (mS/cm)	SAR	Pb, (ppm)	DR, (%)
value	57	30	2.48	1.09	0.3	0.6	7.4	1.03	7.11	19.5	7.03

TABLE 2

CHEMICAL ANALYSIS OF CEMENT AND LIME USED IN THIS STUDY

Chemical Analysis (%)	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	20.8	3.57	4.62	1.2	0.64	0.29	2.36	3.64	99.5
Lime	72.03	-	0.98	0.21	0.17	1.28	-	-	0.13	25.73	100

V. EXPERIMENTAL PROCEDURE

The soil used in this study was air-dried, broken into small sizes, and sieved through a 4.75 mm sieve according to ASTM standard [30] to ensure that the soil is of uniform grade. The artificial Pb-contaminated soil samples were prepared by mixing lead nitrate, as a source of lead (Pb), to produce a soil sample with 4000 mg/kg lead concentration the soil samples were contaminated with lead (Pb). As a reminder, 300ppm in soil is the maximum acceptable Pb concentration in the EU countries [31].

Different percentages of stabilizers (0%, 3%, 6%, and 9%) by soil weight were added directly to a 2 kg of the lead contaminated soil and mixed by hand until the mixture seems to be homogeneous. The samples were then packed in special plastic (P.V.C) and compacted using Proctor test (ASTM, D698) to be ready for the "Mini" JET tests, as described by Al-Madhhachi *et al.* (2013) [32] and Mutter *et al.* (2017) [33].

It should be noted that all the Jet erodibility tests and were conducted after 7 days of curing time. Most physical and engineering properties were determined at the Hydraulic laboratory of the Environmental Department, Engineering College, Al-Mustansiriyah University according to the ASTM standards. However, scouring depth (SD), erodibility coefficient (k_d) and critical shear stress (τ_c, Pa) of soils were determined by a "mini" JET device developed by Al-Madhhachi *et al.*,

(2013) [32]. The data obtained by the "mini" JET were analyzed with a linear model using Blaisdell solution technique to derive τ_c and k_d. Digital Shore-D durometer (0.0 to 100 scale) to measure the degree of hardness was also used at the Materials Department laboratory, Engineering College, Al-Mustansiriyah University. For chemical tests, 25 g of soil for each stabilizer percentage was placed in a graduated cylinder and 50 ml of distilled water was added (1:2 soil: water ratio) to the soil sample. The mixture was shaking by hand for 1 minute and then left for 2 hours for sand and silt to settle down [34]. The soil solution remaining after 2 hours of sedimentation was subjected to many tests, including pH, EC, SAR, Pb and the dispersion ratio (DR) as a soil aggregate stability index. The dispersion ratio (DR) method, modified from Middleton (1930) [5], represents the ratio of clay particles dispersed in soil solution (< 2μ) to the total percentage of clay found in the original soil sample. All tests on soil sample solutions were carried out at the Sanitary laboratory of the Environment Department, Engineering College, Al-Mustansiriyah University. The soil solution chemical properties, namely pH, EC, soluble Pb, and SAR, were measured in the filtered 1:2 soil solution prepared for this purpose. The pH was measured by a pH-meter, EC by an Electrical Bridge, soluble Pb (ppm), Na, Ca and Mg in (meq/l) by the atomic absorption spectrophotometry.

VI. RESULTS AND DISCUSSION

Due to the results obtained from this work and the findings of another related detailed study published by the same author (Mutter *et al.*, 2017) [33] both stabilizers used have markedly improved all soil properties related to soil erodibility and stabilization; but cement, with no doubt, was much efficient in stabilizing soils than lime. It should be noted that sometimes the of cement.

This in fact is due the cement higher efficiency than lime even at lower percentages; i.e. there is sharp changes in soil properties at 3% cement sometimes. However, only 6% of both cement and lime were needed for the optimum stabilization.

Table 3 shows the lime impact on the erodibility parameters of lead contaminated soil. In relation to the erodibility coefficient (k_d), only 6% of lime was required to get the optimum soil properties against erosion and lead movement. According to the correlation coefficient (R), lime has a clear impact on shear stress (τ_c, pa) and on the degree of hardness (DH). Hence the scouring depth (SD) was reduced from (24.5 to 1.4 mm) and hence the erodibility coefficient (k_d) from (1090 to 170 cm^3/kN.s). On the chemical properties, lime seems to have a positive impact on soil properties related to soil stability; by increasing divalent cations (Ca and Mg) required for clay flocculation and hence granulation [1]. Emersion (1967) [8] suggests that at least 0.6-2.0 meq/l divalent cation concentration is required in solution to inhibit clay dispersion. Hence, Lime succeeded in reducing suspended solids and dispersion ratio from (7.03 to 1.96%). The decreasing in k_d values with lime was due to the cementing products that strengthen soil layers [27]. Note that the chemical reaction with lime required more time compared with cement [14].

TABLE 3

LIME PERCENTAGES IN RELATION TO ENGINEERING AND CHEMICAL SOIL PROPERTIES

	Lime, %				
Engineering Property	**0**	**3**	**6**	**9**	**Correlation, R***
Liquid Limit (L.L, %)	39	38	37.3	37	-0.94
Plastic Limit (P.L, %)	25	26	26.5	28	0.99
Plasticity Index (P.I, %)	14	12	10.8	9	-0.99
Optimum Moisture Content (O.M.C, %)	18.0	18.2	18.5	19	0.98
Maximum Dry Density (M.D.D, g/cm^3)	1.77	1.62	1.597	1.56	-0.91
Degree of Hardness (DH)	76.5	89.1	93.5	94	0.90
Scour Depth (SD, mm)	24.5	2.925	1.45	1.4	-0.80
Erodibility Coefficient (k_d, cm^3/kN.s)	1090	180	150	170	-0.78
Critical Shear Stress (τ_c, pa)	0.05	4.6	6.2	5.9	0.89
Chemical property					
Electrical Conductivity (EC, mS/cm)	3.50	1.60	1.50	1.40	-0.82
Power of Hydrogen (pH)	7.18	7.85	8.90	9.20	0.98

Sodium Adsorption Ratio (SAR)	6.30	3.70	2.90	1.98	-0.96
Suspended Solids (mg/l)	10550	3895	3135	2995	-0.83
Dispersion ratio (DR-Gravimetric, %)	7.03	2.95	2.09	1.96	-0.83
Lead Ion (Pb, ppm)	48.8	43.9	24.2	19.5	-0.96

*R must equal 0.95 or 0.99 to be significant at 0.05 or 0.01level, respectively.

Table 4 shows the cement impact on the erodibility parameters of lead contaminated soil. Only 6% of cement was required to get the best soil properties against erosion and lead movement. According to the correlation coefficient (R), cement has a big impact on shear stress (τ_c, pa) and on the degree of hardness (DH). Hence the scouring depth (SD) was reduced from (24.5 to 0.375) mm and the erodibility coefficient (k_d) from (1090 to 0.0 cm^3/kN.s). On the chemical properties, cement seems to have a significant role on soil properties related to soil stability; by reducing the suspended solids and hence the dispersion ratio (from 7.03 to 1.33%). According to the k_d and DR values, cement was better than lime as a soil stabilizer. The greater decreasing in k_d with cement was due to the cement chemical composition, especially in the existence of divalent and trivalent oxides, and the adhesive and cohesive property that make it capable of flocculating clay and binding fragments of mineral [35]. When Portland cement is mixed with water, it will hydrated forming strong cementing compounds of calcium-silicate-hydrate, calcium-aluminium-hydrate as well as calcium hydroxide [36].

TABLE 4

LIME PERCENTAGES IN RELATION TO ENGINEERING AND CHEMICAL SOIL PROPERTIES

	Cement, %				
Engineering Property	**0**	**3**	**6**	**9**	**Correlation, R***
Liquid Limit (L.L, %)	39	38.5	37	37	-0.99
Plastic Limit (P.L, %)	25	27	28	29	0.98
Plasticity Index (P.I, %)	14	11.5	9	8	-0.99
Optimum Moisture Content (O.M.C, %)	18.0	18.5	19	19.8	0.99
Maximum Dry Density (M.D.D, g/cm^3)	1.77	1.636	1.619	1.609	-0.86
Degree of Hardness (DH)	76.5	92.5	96	98.2	0.90
Scour Depth (SD, mm)	24.5	3.35	2.25	0.375	-0.84
Erodibility Coefficient (k_d, cm^3/kN.s)	1090	170	0.1	0.0	-0.85
Critical Shear Stress (τ_c, pa)	0.05	4.49	7.37	7.74	0.94
Chemical property					
Electrical Conductivity (EC, mS/cm)	3.50	1.61	1.41	1.30	-0.85
Power of Hydrogen (pH)	7.18	7.96	8.46	8.65	0.97
Sodium Adsorption Ratio (SAR)	6.3	3.3	3.02	2.8	-0.85
Suspended Solids (mg/l)	10550	6275	2740	1995	-0.96
Dispersion ratio (DR-Gravimetric, %)	7.03	4.18	1.83	1.33	-0.96
Lead Ion (Pb, ppm)	48.8	17.1	17.1	12.2	-0.84

*R must equal 0.95 or 0.99 to be significant at 0.05 or 0.01level, respectively.

Fig. 1 shows the relation between the dispersion ratio (DR, %) and the erodibility coefficient (k_d). No doubt, the relation is proportional and they are highly correlated, but cement is more efficient than lime in reducing both parameters. Lime can improve soil stability by increasing only divalent cations (Ca and Mg) required for the clay flocculation and hence granulation [1], but Cement can do the lime job and also can provide soil with divalent and trivalent oxides that flocculate clay and bind fragments of mineral [35]. The figure also confirmed that the dispersion ratio test, which is the micro-aggregation or dispersion technique developed by Middleton (1930) [5] and has since been used as a reliable index of aggregate stability, can give a reasonable estimation for soil erodibility and hence the stability of soil aggregates [37-38]. Hence, only DR will be related to the chemistry of treated soil solution.

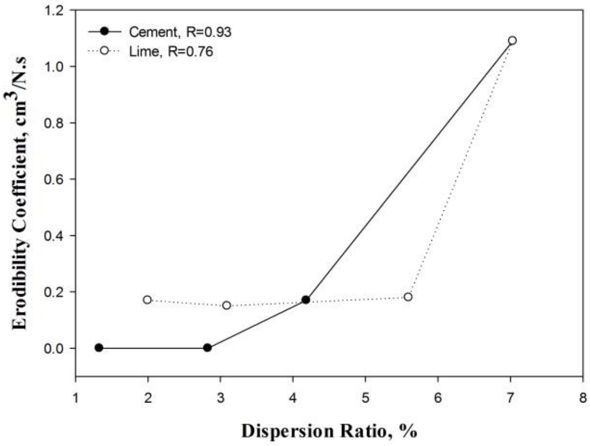

Figure 1: The relation between the erodibility coefficient (k_d) and the dispersion ratio (DR, %) of the stabilized soils

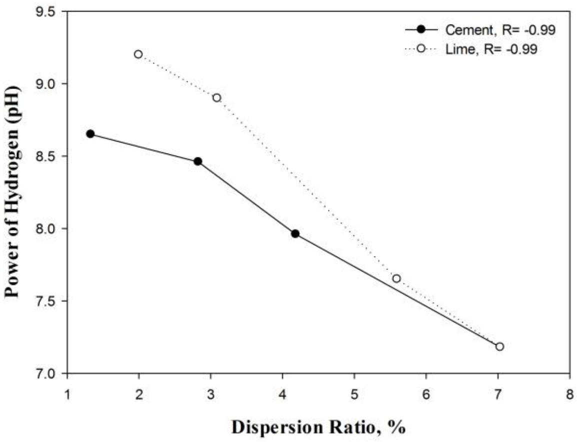

Figure 2 : The relationship between pH and dispersion ratio (DR, %) of the stabilized soils

Fig. 2 shows the relation between pH and the Dispersion ratio (DR, %) of the stabilized soils. It is clear that pH has a major role in the dispersion or flocculation of soil colloids. Both stabilizers have markedly increased pH, but lime seems to have a greater impact in higher percentages. The addition of lime to the soil water system produces (Ca^{+2}) and (OH$^-$). In the cation exchange process, divalent calcium ions (Ca^{+2}) may replace the monovalent cations on clay surfaces and the remaining (OH$^-$) anions in the solution are responsible for the increased pH and [22-23-24]. In soils of high lime contents, i.e. calcareous soils, pH usually increases and disperses soil colloids [6-7]. Cao et al. (2008) [39] noted that the increase in lime addition from 7.5% to 10%, pH increased to more than 9. Chemical stabilizers, (e.g. lime, cement, gypsum and fly ash used to control erosion) increase the pH of soil and pores water to over 9 [40]. Saeed *et al*. (2014) [41] reported that pH values for the 5 % cement-treated kaolin clay samples increase with time and the rise in pH values may be related to the dissociation of OH$^-$ ions, exists in Ca(OH)^2, produced the during the cement hydration.

Fig. 3 shows the relation between the electrical conductivity (EC) and the dispersion ratio (DR, %) of the stabilized soils. In both stabilizers, a clear proportional relationship between the two parameters can be noted. Both stabilizers have markedly reduced the EC in soil solution. This in fact may be connected with their role in increasing pH. Soil pH may probably affect the solubility of salts. More alkaline soils have less amount of soluble salt [42]. This means that low soil pH value may have high soluble salt content; especially sodium salts which may increase SAR and enhance clay dispersion [6-43-44], and therefore high electrical conductivity. According to Bruckner (2012) [45], Soil pH is negatively related with soil electrical conductivity. This negative relation with soil electrical conductivity is in the form of power function and not in linear relationship, because there are several other factors; such as soil mineral, porosity, soil texture, soil moisture and soil temperature, which also affect soil electrical conductivity in the soil [46]. In high PH values, the cation exchange capacity of soil increased and hence more cations are adsorbed on soil particles and this may reduce the soluble cations in soil solution and hence EC [47]. Boardman et al. (2001) [48] suggested that the electrical conductivity of lime treated soil decreases with time and the measurement of electrical conductivity can be used as an effective quality control of lime stabilized subgrades. Changes in the electrical conductivity with time for cement treated soil are also noted by Chen *et al*. (2006) [49]. They found that the pore fluid conductivity decreases because of a decrease in ionic strength of the pore water due to complexes forming from free ions. Reduction in surface conductivity may also be occurring as cement films cover the mineral surfaces for cement treated soils.

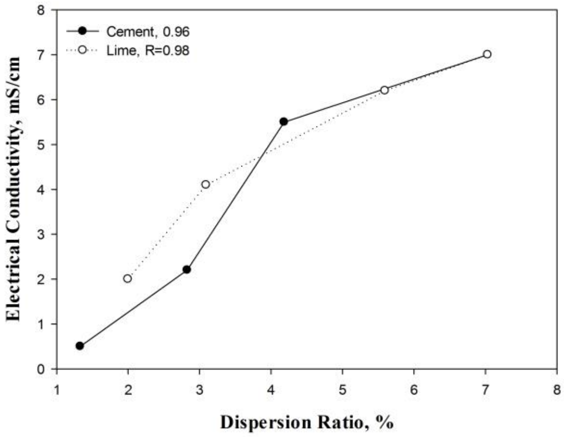

Figure 3: The relationship between the electrical conductivity (EC) and dispersion ratio (DR, %) of the stabilized soils

Fig. 4 shows the relation between the Sodium Adsorption Ratio (SAR) and Dispersion Ratio (DR, %) of the stabilized soils. Both stabilizers have sharply reduced the dispersion ratio, but cement was more efficient in reducing the DR of treated soils. The reductions in SAR and hence in DR are basically related to the increase of divalent and trivalent cations necessary in clay flocculation on the account of sodium [6]. The primary physical processes associated with high sodium concentrations and hence SAR is soil dispersion and also the swelling of clay platelet and aggregate. Calcium and magnesium, supplied by lime and cement, may generally keep soil flocculated by binding clay particles. Increased amounts of calcium and magnesium can reduce the amounts of sodium-induced dispersion [43]. Dispersive clays usually have high percentages of exchangeable sodium ion which is susceptible to replacement by calcium and aluminum ions [44]. Changes in soil characteristics during chemical treatment are likely due to the cation exchange of Na^{+} with Ca^{+2} and Al^{+3}, reduction in the thickness of diffused double layer, and the subsequent reduction in the repulsive forces of the clay particles. Vakili (2013) [50] found variations in electrical conductivity (EC) and percent sodium (PS) of samples treated by pozzolan and cement. The ion exchange reaction may apparently reduce the double layer thickness within the clay structure. In an ion exchange reaction, cations such as Ca^{+2} and Al^{+3} replace sodium cation, Na^{+}, which is the specific feature of dispersive soils. Due to this replacement, the dispersive soil fabric changes to flocculated fabric, with decreased inter-particle repulsion and thus decreased dispersion potential and DR as a result.

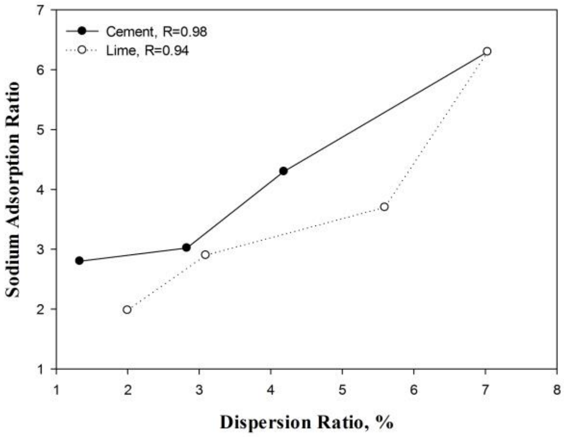

Figure 4: The relationship between the sodium adsorption ratio (SAR) and dispersion ratio (DR, %) of the stabilized soils

Fig. 5 shows the relation between the DR and soluble lead concentration (Pb, ppm) of the stabilized soils. In both stabilizers and whenever soil erodibility and DR values are low, lead soluble concentration in soil solution decreased. This means that both stabilizers have succeeded in reducing both the lead solubility and presumably its mobility and leachability. Depending on the lead cationic strength and soil type, lead may be strongly adsorbed on the soil colloidal surfaces leading to the reduction of lead concentration in soil solution. Lead precipitation may also occur in the soil and water systems as Pb carbonates [51]. In alkaline conditions and in the presence of carbonate, sulphides and silicates; as in the case of the current studied soil (Table 1), many metals including lead may precipitate and be less in soil solution [47]. It should be noted however that some stabilizers, like lime stones or fillers like lime or cement, may actually neutralize the acid causing the pH to rise and the soil aggregates to be destabilized [52]. They also reported that at highly alkaline condition (pH>9), Pb leachability may be enhanced due to a dissolution of Pb ions.

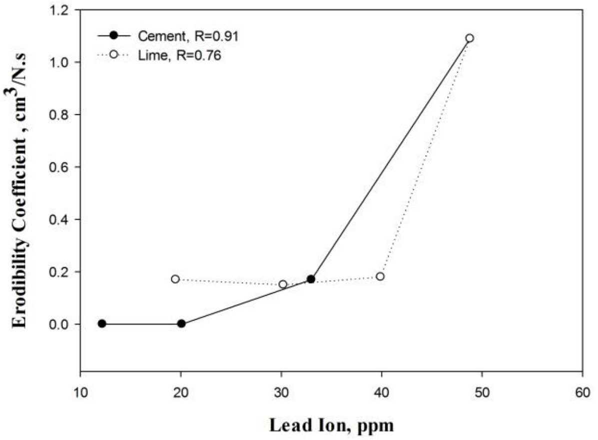

Figure 5: The relationship between the soluble lead (Pb, ppm) and dispersion ratio (DR, %) of the stabilized soils

VII. CONCLUSION

From the results, it could be concluded that both lime and cement stabilizers can markedly improve the stability of the lead contaminated soil; as measured by the “Mini” JET device (as SD, k_d and τ_c) or by the gravimetric dispersion ratio methods (as DR, %), and cement was better stabilizer than lime. Both stabilizers have improved soil engineering properties related to soil stabilization. It should be noted, however, that lower correlation between properties of cement treated soils, here and there, is in fact not because cement is not a good stabilizer, but because a smaller amount (only 3%) of cement has sharply affected the properties of all treated soils. Thus, lime has reduced both the scouring depth (SD, from 24.5 to 1.4 mm; R= -0.80) and the erodibility coefficient (k_d, from 1090 to 0.17 cm^3/kN.s, R= -0.78). Cement has also reduced both the scouring depth (SD, from 24.5 to 0.375 mm, R= -0.84) and the erodibility coefficient (k_d, from 1090 to 0.0 cm^3/kN.s, R= -0.85). Moreover, the DR (%) seems to be highly correlated with the k_d of all stabilized soils (R= 0.76 and 0.93 for lime and cement, respectively). Lime and cement have also improved the soil chemical properties that have an important role in soil clay dispersion and lead mobility; such as pH, EC and SAR and the solution chemistry of treated soils was of prime important in this respect. Noticeably, both stabilizers have reduced both the DR values (from 7.03 to 1.33%, R= -0.96 in cement; from 7.03 to 1.96%, R= -0.83 in lime) and lead solubility and mobility; by rising pH (from 7.18 to 9.20, R= 0.98 for lime and from 7.18 to 8.65, R= 0.97 for cement) and decreasing both EC (from 3.50 to 1.40 mS/cm, R= -0.82 for lime; from 3.50 to 1.30 mS/cm, R= -0.85 for cement) and SAR (from 6.30 to 1.98, R= -0.96 for lime; from 6.3 to 2.8, R= -0.85 for cement) in treated soil solutions. Concerning the pH changes, lime has more effect than cement in increasing pH, especially in higher additions (i.e. 9%, pH in lime is 9.20 and in cement is 8.65), and this may be the reason behind the failure of lime and to be less efficient than cement as a stabilizer. However, cement was much efficient than lime as a stabilizer by reducing both the DR and the lead solubility (from 48.8 to 12.2 ppm; R= -0.84 in cement; from 48.8 to 19.5ppm, R= -0.96 in lime) in the solutions of lead contaminated soil.

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