EFFECTS OF SOME FACTORS ON ELECTRO-OSMOTIC DEWATERING OF LATERITE

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ABSTRACT

Preliminary analyses to determine some geotechnical properties of two soil samples A and B collected from Osun State, Nigeria were carried out. Soil samples passing through sieve with 0.425 mm opening were prepared to different moisture contents (60 or 80%) and poured inside a rectangular electrochemical cell. Direct Current voltage (20 or 40 V) was applied across the moist soil using steel plate electrodes inserted at the end of the soil. The spacing of the electrodes was varied (10 or 20 cm). The electrochemical treatment time was 360 min. The Electro-osmotic (EO) flow was recorded at every 30 min during the experiment. A factorial experiment was performed to determine the factor that had most significant effect on the EO flow. The factors varied were electrode spacing (S), applied voltage (V) and initial moisture content (M). The results showed that S was inversely proportional to the EO flow, while V and M were directly proportional to the EO flow. The initial moisture content (M) has the highest estimated effect (91.825 and 243.35 for samples A and B, respectively) and thus the most significant effect on the EO process. The general effects were same for the two soil samples, but the rate of the effect varied, which implied that EO dewatering was site dependent. It was concluded that EO dewatering was a viable option for dewatering of tropical laterite.

Keywords: Electro-osmosis, Soil Dewatering, Tropical Laterite,

INTRODUCTION

Construction of buildings, power houses, dams, locks and many other structures requires excavation below the water table into water-bearing soils. Such excavations require lowering the water table below the slopes and bottom of the excavation to ensure dry, firm working conditions for construction operations. According to Somerville (1986), construction sites are dewatered to provide suitable working surface of the bottom of the excavation, to stabilise the banks of the excavation thus avoiding the hazards of slides and sloughing and to prevent disturbance of the soil at the bottom of excavation caused by boils or piping. Such disturbances may reduce the bearing power of the soil. Lowering the water table can also be utilized to increase the effective weight of the soil and consolidate the soil layers.

Groundwater can be controlled by means of one or more types of dewatering systems appropriate to the size and depth of the excavation, geological conditions, and characteristics of the soil. The available methods of groundwater control include; gravity drainage in relatively permeable soils using simple pumping equipment, ditches to divert surface water, drainage galleries for removal of large quantities of water and electro-osmosis used in low permeable soils such as silts, clays and peats (Casagrande, 1999).

For low permeable soils such as clays, the normal pumping methods of dewatering may not be adequate. In such cases, the electro-osmosis procedure may be helpful.

Electro-osmotic (EO) dewatering is a technique that removes water from soils under the application of direct current (DC) electric field across the soil to be dewatered. Electro-osmotic flow is defined as the bulk liquid motion that results when an externally applied electric field interacts with the net surplus of charged ions in the diffuse part of an electrical double layer (Doe *et al.*, 2013).

Electro-osmosis is one of the electrokinetic phenomena in soil under the application of DC electric field. In electro-osmosis, when a DC electric field is applied across a wet porous medium (wet soil), water is moved from the positive electrode (anode) to the negative electrode (cathode) as illustrated in Figure 1.

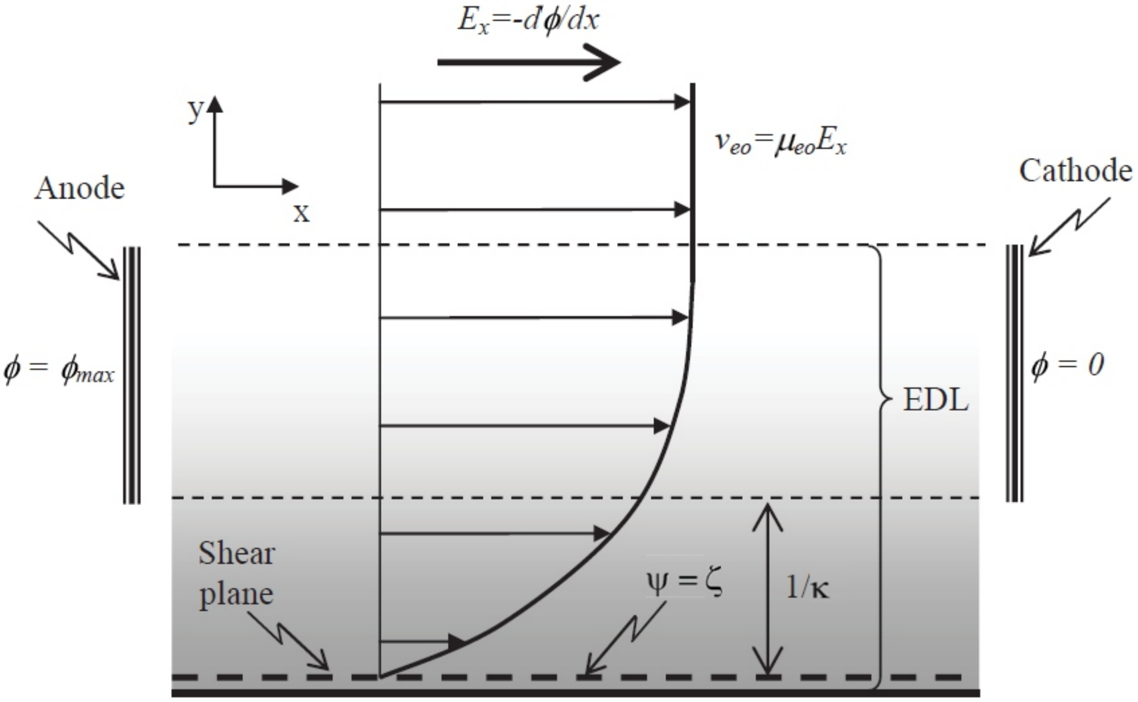

Figure1: Electro-osmotic Flow Illustration (Doe *et al.*, 2013)

According to Casagrande (1999), the treatment of soil by electro-osmosis improves its engineering properties. Such improvements include: increase in the strength of sensitive deposit (Bjerrum *et al.*, 2001), control of the seepage forces in weak deposit (Casagrande, 1993), increase in the load capacity of friction piles (Soderman and Milligan, 1961), and stabilisation of excessive foundation deformations (Casagrande, 1993). According to Buckland and Shang (2000), electro-osmosis processes are characterized by their low cost, non-intrusive character, applicability to a wide range of contaminants and insensitivity to pore size and soil grain size that makes it suitable for fine grained soils.

The Helmholtz-Smoluchowski theory (H-S theory) is the most widely used and accepted description of EO flow as it applies to systems with pores that are large relative to the size of the electric double layer and gives reasonable predictions for EO flow in most soils (Page and Page, 2002). The EO flow rate (q_{eo}) through soil can be determined (equation 1) using the analogy of Darcy's law (equation 2) for hydraulic flow in soil.

$$q_{eo} = -k_{eo}E_zA \qquad (1)$$

where: q_{eo} is EO flow rate (m^3/V-s); k_{eo} is the EO permeability; E_z is applied voltage gradient (V); A is cross-sectional area of the soil (m^2).

$$q_h = k_h i_h \qquad (2)$$

where: q_h is the hydraulic flow rate per unit area (m^3/sm^2); k_h is the hydraulic permeability (m/s) and i_h is the hydraulic gradient.

The EO flow rate can also be expressed according to H-S theory as:

$$q_{eo} = -nA\frac{D\zeta}{\eta}E_z \qquad (3)$$

where: n is the porosity; ζ is the zeta potential (V); D is the Dielectric constant and η is the viscosity of pore fluid

The combination of Equations 1 and 3 gives:

$$k_{eo} = n\frac{D\zeta}{\eta} \qquad (4)$$

Equations 1, 3 and 4 show that the rate of EO flow depends on some factors such as the applied voltage and the zeta potential of the soil. Reddy and Cameselle (2009) pointed out that ζ is a function of clay mineral, ionic species that are present, pH, ionic strength and temperature. This informed this research work on tropical laterite which are rich in iron oxide and possess low contents of alkaline and alkaline earth metals unlike temperate soils. This unique properties of laterite is due to excessive leaching of alkaline and alkaline earth metals due to high temperature and intense rainfall associated with the tropics (Eisazadeh *et al.*, 2012).

The main aim of this research was to study the effect of applied DC voltage, electrode spacing and soil initial moisture content on the EO dewatering of selected soil samples.

MATERIALS AND METHODS

Soil samples (A and B) were collected from two locations within Ile-Ife, Osun State, in Southwestern, Nigeria. The soil samples were collected at a depth of about 1 m after the topsoil has been removed. The collected soil samples were air dried in the laboratory for two weeks after which some tests were carried out using America Society of Testing and Materials (ASTM, 2003) standard methods. The tests carried out were the index properties such as pH, specific gravity, G (ASTM D 854), particle size distribution (ASTM D 422), Liquid Limit, LL and Plastic Limit, PL (ASTM D 4318). The moisture density relations (Optimum Moisture Content, OMC and Maximum Dry Density, MDD) were also determined using standard method (ASTM D 698).

The soil samples used for the EO experiment were sieved through sieve No. 40 (with sieve opening 0.425 mm) to represent a soft fine grained soil. The EO dewatering set up (Figure 2) consisted of transparent Perspex rectangular cell with soil compartment dimension 10 x 20 x 10 cm^3 and with additional compartment (as flow compartment) of dimension10 x 5 x 10 cm^3 (where water flow from the soil can be collected). The soil compartment internal wall was perforated to allow the flow of water from the soil sample. Steel plate electrodes were placed at the end of the soil samples (Figure 2). Filter cloth was placed behind each of the electrodes to prevent soil samples from flowing into the flow compartment. The cathode was perforated to allow the flow of water into the flow compartment (water flow is expected to be from the anode to the cathode).

Factors such as the soil initial moisture content (M), applied voltage (V) and electrode spacing (S) were varied during the EO dewatering process using 2^3 factorial experiment (Table 1). The volume of water at the flow compartment was recorded at regular time intervals. The factorial experiment was analysed using Yates algorithm to determine the factor with significant effect on the EO dewatering system.

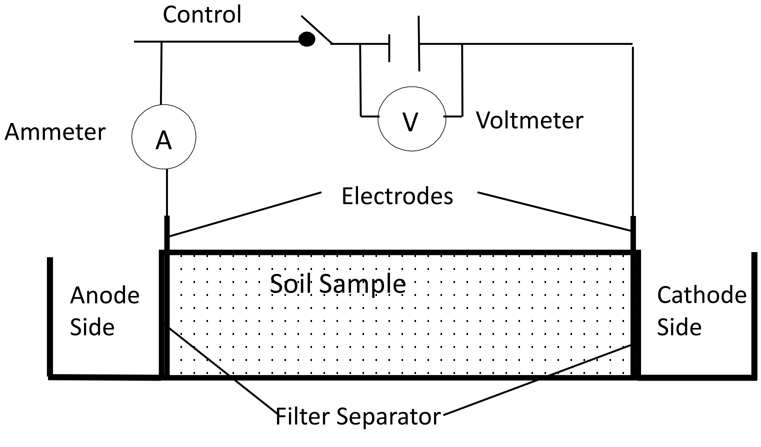

Figure 2: EO Dewatering Set Up

Table 1: 2^3 Factorial Experiment Arrangement

Test program	Initial soil moisture content, M (%)	Code	Applied Voltage, V (V)	Code	Electrode Spacing, S (cm)	Code
T1	60	-	20	-	10	-
T2	80	+	20	-	10	-
T3	60	-	40	+	10	-
T4	80	+	40	+	10	-
T5	60	-	20	-	20	+
T6	80	+	20	-	20	+
T7	60	-	40	+	20	+
T8	80	+	40	+	20	+

RESULTS AND DISCUSSION

Results of Preliminary Analysis of Soil Samples

Some properties of the soil samples are presented in Table 2. The results show that the soil samples are both low plasticity silt (fine grained soils). The pHs of the soil samples are acidic which is typical of tropical laterite (Gidigasu, 1976; Eisazadeh *et al.*, 2011).

Electro-osmotic Flow and Cumulative Water Removed during Testing

The Helmhotz-Smoluchowski's (H-S) expression in equation 3 implies that the EO flow will be from the anode to the cathode if the soil sample has a negative zeta potential. If the soil sample

Table 2: Geotechnical Properties of Selected Soil Samples

Properties	Sample A	Sample B
Specific Gravity (G)	2.56	2.52
Plastic Limit (%)	40.82	40.00
Liquid Limit (%)	49.30	48.80
Plasticity Index (%)	8.48	8.80
OMC (%)	16.50	27.00
MDD (Mg/m^3)	1.72	1.552
pH	5.09	4.77
USCS Classification	ML	ML
Colour	Light brown	Reddish brown

exhibited charge reversal in response to the pH level of soil pore water, and the zeta potential becomes positive, then the direction of flow will be reversed (i.e. the flow will then be from the cathode to the anode). According to Ayodele (2014), the soil samples did not exhibit charge reversal based on negative zeta potential both in acidic and basic conditions, thus the flow throughout the test was from the anode to the cathode. The cumulative flow in each of the tests with different varied factors is presented in Table 3. The rate of EO flow with time is also presented for samples A and B in Figures 3 and 4, respectively.

The cumulative percent water removed is also presented in Table 3. The highest percent of water removed from the soil samples are 32.75 and 57.21 % for samples A and B, respectively. The lowest percent of water removed are 5.75 and 4.69 % for samples A and B, respectively. The highest values were recorded in test T4 while the lowest values were recorded in test T5 for both soil samples.

Table 3: Cumulative Flow of Water Obtained for the Factors Varied for the Soil Samples

Electrode Spacing (cm)	Voltage	Initial moisture content	Cumulative flow (ml) For Sample A	Cumulative water removed (%)	Cumulative flow (ml) For Sample B	Cumulative water removed (%)
10	20	60	94.30	15.42	129.90	21.25
		80	152.00	18.65	358.40	43.96
	40	60	139.00	22.73	192.30	31.45
		80	267.00	32.75	466.40	57.21
20	20	60	70.30	5.75	57.30	4.69
		80	127.00	7.79	237.30	14.55
	40	60	87.10	7.12	118.70	9.71
		80	212.00	13.00	409.50	25.12

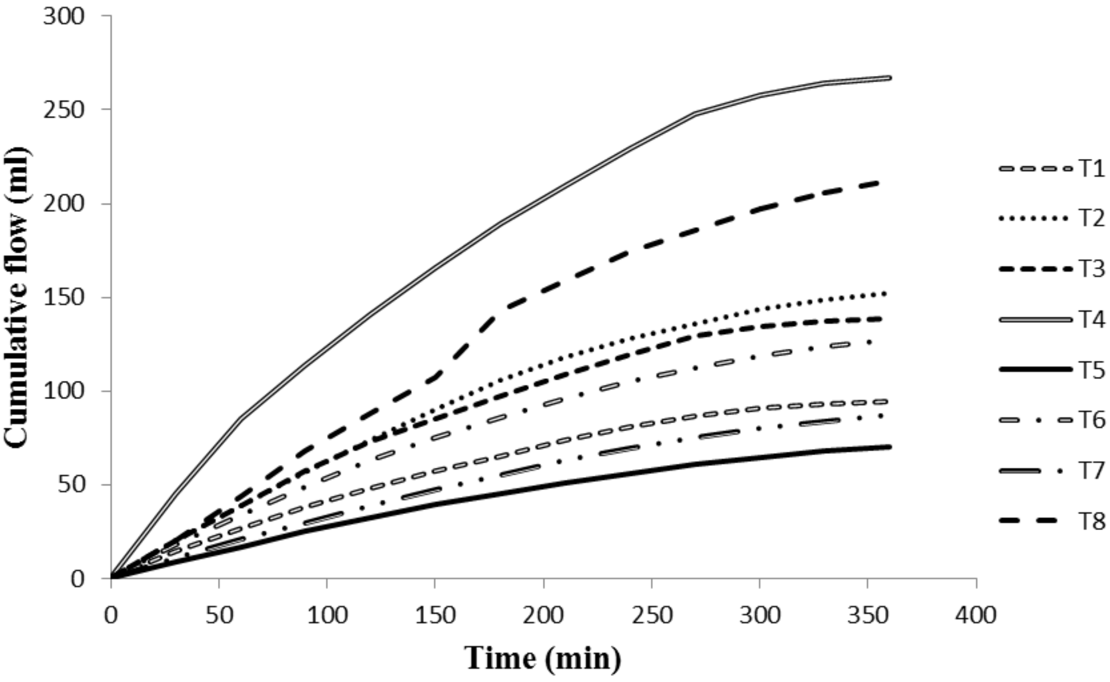

Figure 3: Variation of Cumulative Flow with Time for Soil A

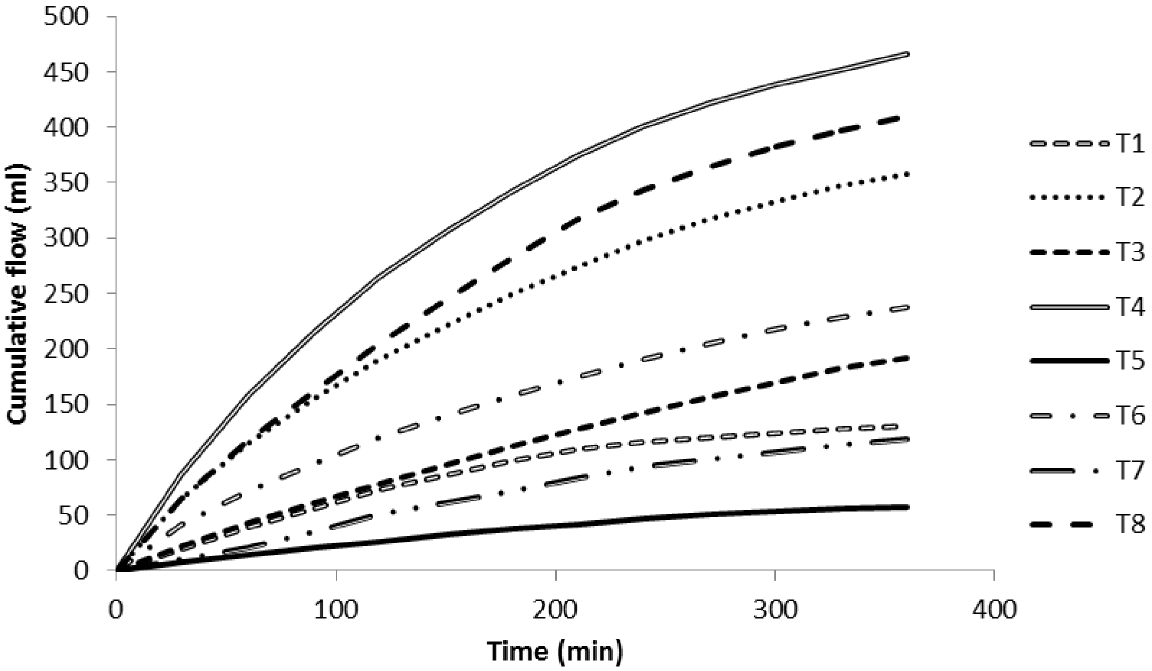

Figure 4: Variation of Cumulative Flow with Time for Soil B

Effect of Electrode Spacing on EO Flow

Electrode spacing is one of the vital parameters that control the effectiveness of EO dewatering irrespective of the moisture content of the soil used and the voltage applied. The effect of electrode spacing is clearly seen in test T5 for the two soil samples as presented in Figures 3 and 4. Increase in the electrode spacing reduced the rate of flow with time and hence, the cumulative flow. The effect is more pronounced in sample B.

The effect of electrode spacing is also seen in test T4 where the highest rate and cumulative flow was recorded for both the tested soil samples. This result shows that reducing the electrode spacing increases the EO flow considerably. The electrode spacing in test T5 is double that in test T1. The cumulative flow is 94.30 and 70.30 ml in T1 and T5, respectively for sample A. Doubling the electrode spacing however does not result in doubling the cumulative flow for sample A. The cumulative flow was however more than doubled for sample B with values 57.3 and 129.9 ml in tests T1 and T5, respectively. These results show that the dewatering process is also a function of the soil tested but for both soil samples, the electrode spacing is inversely proportional to the rate of EO flow.

The percent decrease in EO flow for test pairs T1-T5, T2-T6, T3-T7 and T4-T8 are 25.45, 16.45, 37.34 and 20.60 %, respectively, for sample A and 55.89, 33.79, 38.27 and 12.20 %, respectively, for sample B.

Effect of Applied Voltage on EO Flow

Voltage is one of the important parameters to be considered during Electro-osmotic treatment of soil (Shang *et al.*, 2004). It is shown in the H-S expression of Equation 3 that higher voltage (electric field) leads to higher dewatering rate, but according to Reddy and Cameselle (2009) higher voltage on the other hand leads to higher energy expenditure. In the present study, increase in voltage led to increase in EO flow as presented in Figures 3 and 4. This increase is also indicated when tests T1, T2, T5 and T6 are compared with tests T3, T4, T7 and T8, respectively. In each comparison, the other two factors were held constant, while only the applied voltage was increased. Subsequently, more EO flow rates were recorded in tests T3, T4, T7 and T8 than in tests T1, T2, T5 and T6. In the pair of tests T1-T3, T2-T4, T5-T7 and T6-T8, the percent increase in the EO flow are 32.16, 43.07, 19.29 and 40.09 %, respectively for sample A, while for sample B the percent increase in the flow rate are 32.45, 23.16, 51.73 and 42.05 % for test pairs T1-T3, T2-T4, T5-T7 and T6-T8, respectively. There is no definite but varying arithmetic pattern between the percent increases in the EO flow i.e. it cannot be said that doubling the electric voltage will double the EO flow rate. These varying percent increase in EO flow rate, suggests that, complex physicochemical reactions take place within the wet soil sample on the application of electric field according to Yeung *et al.* (1997).

Effect of Soil Initial Moisture Content on EO Flow

Increase in the initial soil water content improves considerably the cumulative EO flow and the rate of dewatering as shown in Figures 3 and 4. Increasing the moisture content of the soil, will lead to increase in void volume and thus increase porosity (which is ratio of the volume of void to the total volume). The H-S expression of equation 3 shows that porosity affects EO flow, thus, increasing the initial soil moisture content will lead to increase in EO flow.

In comparing the test pairs T1-T2, T3-T4, T5-T6 and T7-T8 when only M was increased while the other two factors were kept constant, there were appreciable increase in EO cumulative flow. Percent increase in each of the test pairs T1-T2, T3-T4, T5-T6 and T7-T8 were 37.96, 47.94, 44.65 and 58.92 %, respectively for sample A and 63.76, 58.77, 75.85 and 71.01 %, respectively for sample B. These results show that percent increase in EO flow was more when M was increased and also notably in sample B.

Coupled Effect of Selected Factors on EO Flow

The analysis of factorial experiment was carried out in order to determine the factor that has the highest effect on the EO flow. The summary of the factorial experiment analysis is presented in Tables 4 and 5 for samples A and B, respectively. The factorial experiment shows that some factors and interactions effects have positive effects while some others have negative effects. The factors and interactions with positive effects have positive influence on the EO flow (they are directly proportional to the EO flow). This indicates that higher values of these factors and interactions increase the EO flow. The factors and interactions with negative effects decrease the EO flow i.e. they are inversely proportional to the EO flow. This indicates that the higher the value of these factors the lower the EO flow.

Under the negative effects, the electrodes spacing factor is present in all the factors and interactions. This indicates that any increment in the electrode spacing will reduce the EO flow even when the applied voltage and initial moisture content is increased.

Tables 4 and 5 show that for both soil samples, increasing M and V increases cumulative flow whereas increasing S reduces cumulative flow as also pointed in earlier sections. The interaction of M and V is relatively smaller than the individual effects. The interaction of M and S is very small when compared to the interaction of V and S, this is because M has more positive effect on the EO flow than V.

Considering individual effects, the initial moisture content has the most considerable effect on the EO dewatering rate as indicated by highest estimate effect for both soil samples.

The model equations that relate the factors together are presented in equations 5 and 6 for samples A and B, respectively.

$$Y = 143.59 + 45.915M + 32.69V - 19.49S \tag{5}$$

$$Y = 246.22 + 121.675M + 50.5V - 40.525S \tag{6}$$

The Analysis of Variance (ANOVA) of the Yate's algorithm are presented in Tables 6 and 7 for samples A and B, respectively.

Table 4: Yate's Algorithm Analysis of Factorial Experiment Sample A

Run	M	V	S	Yield	Yate's Algorithm			Divisor	Estimate Effect	Remark
					1	2	3			
1	-	-	-	94.30	246.30	652.30	1148.70	8	143.59	Mean
2	+	-	-	152.00	406.00	496.40	367.30	4	91.83	M
3	-	+	-	139.00	197.30	185.70	261.50	4	65.38	V
4	+	+	-	267.00	299.10	181.60	138.50	4	34.63	M x V
5	-	-	+	70.30	57.70	159.70	-155.90	4	-38.98	S
6	+	-	+	127.00	128.00	101.80	-4.10	4	-1.03	M x S
7	-	+	+	87.10	56.70	70.30	-57.90	4	-14.48	V x S
8	+	+	+	212.00	124.90	68.20	-2.10	4	-0.53	M x V x S

Table 5: Yate's Algorithm Analysis of Factorial Experiment Sample B

Run	M	V	S	Yield	Yate's Algorithm			Divisor	Estimate Effect	Remark
					1	2	3			
1	-	-	-	129.90	488.30	1147	1969.8	8	246.22	Mean
2	+	-	-	358.40	658.7	822.8	973.4	4	243.35	M
3	-	+	-	192.30	294.6	502.6	404	4	101	V
4	+	+	-	466.40	528.2	470.8	156.4	4	39.1	M x V
5	-	-	+	57.30	228.5	170.4	-324.2	4	-81.05	S
6	+	-	+	237.30	274.1	233.6	-31.8	4	-7.95	M x S
7	-	+	+	118.70	180	45.6	63.2	4	15.8	V x S
8	+	+	+	409.50	290.8	110.8	65.2	4	16.3	M x V x S

Table 6: Significant Analysis of results for Sample A

Run	M	V	S	Yield	Estimate Effect	Sum of Squares	Degree of Freedom	MSS	F-values
1	-	-	-	94.30	143.59	41234.74		41234.74	
2	+	-	-	152.00	91.83	16863.66	1	16863.66	5.98
3	-	+	-	139.00	65.38	8547.78	1	8547.78	3.03
4	+	+	-	267.00	34.63	2397.78	1	2397.78	0.85
5	-	-	+	70.30	-38.98	3038.10	1	3038.10	1.08
6	+	-	+	127.00	-1.03	2.10	1	2.10	0.00
7	-	+	+	87.10	-14.48	419.05	1	419.05	0.15
8	+	+	+	212.00	-0.53	0.55	1	0.55	0.00
				Error			4	4214.685	
				Total sum of squares				156193.3	

Table 7: Significant Analysis of results for Sample B

Run	M	V	S	Yield	Estimate Effect	Sum of Squares	Degree of Freedom	MSS	F-values
1	-	-	-	129.90	246.22	121253.50		121253.50	
2	+	-	-	358.40	243.35	118438.45	1	118438.45	28.10
3	-	+	-	192.30	101	20402.00	1	20402.00	4.84
4	+	+	-	466.40	39.1	3057.62	1	3057.62	0.73
5	-	-	+	57.30	-81.05	13138.21	1	13138.21	3.12
6	+	-	+	237.30	-7.95	126.40	1	126.40	0.03
7	-	+	+	118.70	15.8	499.28	1	499.28	0.12
8	+	+	+	409.50	16.3	531.38	1	531.38	0.13
Error							4	4214.685	
Total sum of squares								156193.3	

CONCLUSION

Based on the analysis of the EO dewatering test conducted on the two soil sample for varying applied voltage, electrode spacing and soil initial moisture content, the following conclusions may be drawn.

a. Lower value of electrode spacing, higher value of applied voltage and higher value of moisture content led to higher dewatering rate and vice versa.
b. Among the selected factors, the initial soil moisture content has most significant effect on the dewatering rate.
c. The effects of the selected factors on the two soil samples are same in qualitative terms but different in quantitative terms which imply that the dewatering process is site dependent.

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