A comparative study on strengthening of peat and expansive soils using electro-osmosis consolidation – A case study from Tamil Nadu, India

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Abstract
Construction activities on peat and expansive soils have proven to be a challenging task to engineers as these soil types are highly compressible. Such soils have low shear strength, high swelling and high shrinkage potential. Electrokinetic treatment is a relatively new method that is being adopted in many parts of the world to increase the shear strength of such soils. This paper provides a comparison between the electro-osmotic consolidation of peat and expansive soils for improving their shear strength. The consolidation behavior of these soils is studied by odeometer consolidation and electro osmosis consolidation.

The results suggest that the electro-osmotic consolidation accelerates the consolidation process and the primary consolidation is completed in 15 days duration. The increase in shear strength of peat soil by electro-osmotic consolidation is significant when compared to expansive soil. The settlement and degree of consolidation is higher in electro-osmosis consolidation compared to odeometer consolidation for peat soils.

Keywords: Electro-osmosis consolidation, Odeometer consolidation, Peat soil, Expansive soil, Shear strength.

Introduction

Settlement of buildings and bridges, road embankments, dams, etc. has been reported and many have attempted to mitigate these damages. Soil improvement techniques are being adopted to improve the strength of the soft problematic soils prior to the beginning of such construction activities. The purpose of such improvement techniques include increasing the strength, controlling shrinkage and swelling, controlling permeability and reduction of water pressure, prevention of physical and chemical changes due to environmental conditions etc.[1]

Conventional methods such as vacuum loading or pre-loading for soil improvement are time consuming and have less favourable effect[2]. Electrokinetic treatment is comparatively new methodology that is being used in many parts of the world. Electro-osmosis was first introduced by Reuss[3] in 1809[4]. This technique has been used in the past by researchers for various applications like contaminant removal[5,6], foundation reinforcement[7,8], embankment stabilization[9,10], pile capacity improvement[11,12], dewatering of sludge and mine tailings[13,14], strengthening of marine sediments[15]. Electro-osmosis is especially remarkable in strengthening fine-grained soils such as silts, soft clays, organic soils, etc. This is because the reinforced effect of electro-osmosis is independent of the size of the particle[2].

Although field studies are quite expensive and time consuming, many field studies have also been conducted in the past using electro-osmosis[16]. Similarly, many laboratory studies have also being conducted with the help of electro-osmosis. Electrochemical effects of electro-osmosis were studied by various researchers in the past[17-23]. The effect of electro-osmosis on consolidation properties was studied by Bergado[24], Bo et al[25], Lim[26] and Shang et al.[27]

Various researchers have studied the effect of electro-osmosis on different types of soils. The electro-osmosis technique was used for improvement of the shear strength on clayey soils[28,29]. The study of the same for kaolinite was carried out by Liaki et al[30], Chien et al[31], Hamir et al[32], Liu et al[33] and for silts sand by Mohamedelhassan and Shang[34], Shang et al.[35] Although numerous studies have been conducted for clay, kaolinite and sandy soils, very few studies have been conducted for expansive and peat soils.

Adamson et al[36] collected fourteen soil samples from Menlo Park, California and Conejo valley, near California for the electrochemical treatment. They concluded that that shrinkage in soils rich in clay could be considerably reduced using the treatment but the improvement was insignificant for the rock flour (quartz, feldspar, etc. of clay size).

Abdullah and Al-Abadi[37] performed cationic-electrokinetic soil stabilization for expansive soils using K^+ and Ca^+ ions as stabilizing agents. Yee and Kaniraj[38] presented the results of electro-osmotic consolidation (EOC) experiments conducted on peat soil with two different types of drainage conditions, namely, at the bottom and through the drainage well. They concluded that the drainage well scheme has good potential for implementation of the electro-osmotic conditions.

Kaniraj et al[39] used electrokinetic geosynthetics (EKG) such as pre-fabricated electric vertical drains (EVD or ePVD) for strengthening of peat soil and organic clayey silt soils of Malaysia. EVD is known to have the potential for electro kinetic strengthening of soft soils and increasing solids content in mine tailings and sludges. They found EVD to be effective in improvement of peat, over a large range of initial water contents.

While it is evident from the above review of literature that electro-osmosis has been used for strengthening of expansive and peat soils, a study on the comparison of these soils has not been reported till now. The aim of this paper is to conduct a comparative study on the performance of EOC on expansive and peat soils collected in the state of Tamil Nadu, India. Various parameters like degree of consolidation, shear strength, void ratio, settlement after consolidation have been compared for both the soils consolidated using odeo meter and electro-osmosis consolidation.

Material and Methods

The sample of peat soil for this study was collected at a latitude of 11°23’16. 44’’ N and longitude of 76°33’52.14’’ E (Ooty, Kothagiri road, Madhuvana). The sample of expansive soil was collected at a latitude of 11°00’16.85’’Nand longitude of 76°9’55.83’E (Coimbatore, Government college of Technology Alumni block). Laboratory tests were conducted to determine the physical properties of both peat and expansive soils. The results of the same have been provided in Table 1 and 2.

Physical properties: Laboratory tests were conducted to determine the index and engineering properties of peat and expansive soils. The various physical properties, namely natural moisture content, specific gravity, plasticity characteristics, swell-shrink characteristics, grain size distribution, organic content, optimum moisture content and unconfined compressive strength of peat soil samples were determined and the results are shown in table 1.

Table 1
Physical properties of peat soil

S.N.	Properties	Values
1	Natural Moisture Content	91.67%
2	Specific Gravity (G)	1.67
3	Organic Content	52.59
4	Free Swell Index	21.67 %
5	Gravel	0%
	Sand	16%
	Organic silt	42.17%
	Inorganic silt	37.63%
	Clay	4.20%
6	Soil classification	Pt
7	Liquid Limit	52.50%
	Shrinkage Limit	35.45
	Plastic Limit	Non Plastic
8	Optimum Moisture Content (OMC)	33.89%
	Maximum Dry density	1.21 g/cc
9	Unconfined Compressive Strength (q_u)	26 kN/m^2
	Cohesion (cu)	13 kN/m^2

From table 1, it is observed that peat soil has very high moisture content (91.67%). The specific gravity of this soil is below 2. The organic content in the soil is more than 50% indicating the peat soil is rich in organic matter. The free swell index is 21.67%, which is quite low. Silt content, both organic and inorganic, form the major composition of the peat soil. The soil was observed to be non-plastic. The OMC for this soil is 33.89%. The unconfined compressive strength of 26 kN/m^2 indicates that the peat soil can included in the category of soft soils.

The various physical and engineering properties of namely natural moisture content, specific gravity, plasticity characteristics, swell-shrink characteristics, grain size distribution, optimum moisture content and unconfined compressive strength of expansive soil samples were determined and the obtained results are shown in table 2.

Table 2
Physical properties of expansive soil

S.N.	Properties	Values
1	Natural Moisture Content	16.42
2	Specific Gravity	2.71
3	Free Swell Index	60%
4	Gravel	0%
	Sand	28.1%
	Silt	24.45%
	Clay	47.45%
5	Liquid Limit	59%
6	Plastic Limit	25%
	Shrinkage Limit	14.4%
	Flow Index (I_f)	13.5
	Plasticity Index (I_p)	26
	Liquidity Index (I_L)	-0.65
	Toughness Index (I_T)	1.9
	Consistency Index (I_c)	1.65
7	Soil classification	CH
8	Optimum Moisture Content	23.56%
9	Maximum Dry density	1.64g/cc
10	Unconfined Compressive Strength	61.3 kN/m^2
11	Cohesion	30.65 kN/m^2

From table 2, it is observed that the soil has a very high swelling index (60%). Liquid limit of 59% indicates that the soil is highly compressible. Plasticity index of 26 reflects the highly plastic nature of this soil. The liquidity and consistency index values indicate that the soil is very stiff. Toughness index of 1.9 indicates that the soil is not friable. An unconfined compressive strength of 61.3 kN/m^2 shows that the soil has medium consistency.

Permeability characteristics: Permeability characteristics of peat and expansive soils were determined by falling head permeameter test and the results of the coefficient of permeability (k_h) is shown in table 3.

Table 3
Coefficient of permeability of peat and expansive soil

S.N.	Type of soil	Coefficient of permeability (k_h)
1	Peat Soil	5.80x10^{-7} m/sec
2	Expansive soil	4.52x10^{-7}m/sec

From table 3, it is observed that the peat soil has higher coefficient of permeability compared to the expansive soil. Peat soil is known for its high moisture content and this characteristic of the peat soil enhances the movement of water through the pores resulting in high permeability. Since peat has a higher permeability compared to expansive soils, the degree of consolidation will be higher in peat soils compared to expansive soils.

Odeometer consolidation: The one-dimensional consolidation testing procedure was first suggested by Terzaghi (1925). This test is performed in aodeometer. The schematic diagram of aodeometer is shown in Figure 1. The soil specimen was placed inside a metal ring with two porous stones, one at the top of the specimen and another at the bottom. The specimens are 60 mm in diameter and 20 mm thick. The load on the specimen was applied through a lever arm and compression is measured by a micrometer dial gauge. The specimen was kept under water during the test. Each load was kept for 24 hours. Thereafter, the load is doubled, thus doubling the pressure on the specimen and the compression measurement was continued. At the end of the test, the dry weight of the test specimen was determined. Figure 2 shows the Odeometer test under operation.

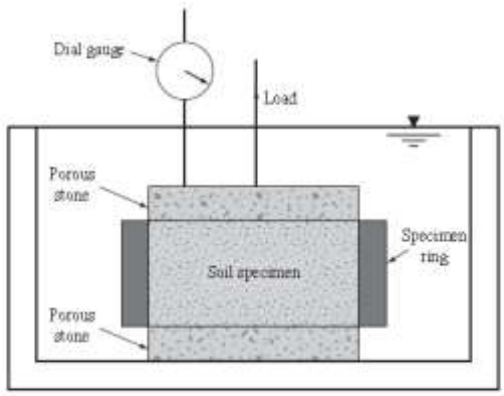

Fig. 1: Schematic Diagram of an Odeometer

The odeometer consoildation was carried out for both peat and expansive soils in the laboratory.The testing conditions which were varied include the overbuden pressure of the soil and the duration of the odeometer consolidation. Peat and expansive soils were consolidated to diferent overburden pressures like 5kPa,10kPa and 15kPa in the odeometer consolidation process.The odeometer consolidation was then extended to 3 days and 7 days.The purpose was to extract the potential benefits of extented treatment,namely,the strength and consolidation behaviour of peat and expansive soils.The sample in the test cell was having a density 1.18 g/cc for peat soil and 1.30 g/cc for expansive soil.

Fig. 2: Odeometer test in progress

Electro-osmosis Consolidation (EOC): A transparent plexi glass cylinder with 100 mm inner diameter and 300 mm height was fabricated as a component of the electro-osmosis. Electro osmosis cell can accommodate a soil specimen of 100mm in diameter and about 250mm high confined between the electrodes. A filter paper was used for drainage purpose at both electrodes and prevented clogging of soil particles at the porous stone.

Ferum was used as electrode material for this study. Copper wire was soldered onto the electrodes and grease was applied to the inner circumference of the cell to reduce side friction between the soil sample and the cell during sample set up and consolidation. Load was applied by means of a piston which was fixed above the electro osmosis cell. Direct current (D.C) power was used as the power supply. Cathode was applied at the bottom. The water movement generally takes place from anode to cathode. Voltmeter was used to monitor the voltage and an ammeter was used to monitor the charge. In the bottom of the electro osmosis cell the drainage valve is attached to collect the water. The various components adopted in the electro osmosis test is shown in figure 3 and figure 4 shows the electro-osmosis test under operation.

EOC was carried for both peat and expansive soils. Peat and expansive soils were consolidated to diferent overburden pressures like 5kPa,10kPa and 15kPa in electro osmosis consolidation process.The voltage gradient of 4V was chosen so that the electro osmosis consolidation treatment could be initiated and the results could be visible within a short duration for each test. Furthermore, a very high voltage gradient was not chosen considering safety and power economy.

The current produced in the soil sample during electro osmosis is based on the electrical conductivity of soil samples. The electrical conductivity was determined by using conductivity meter in the laboratory. The electrical conductivity of expansive soil (0.6dS/m) was higher than that of peat soil (0.4dS/m). The sample in the test cell having density 1.18 g/cc for peat soil and 1.30 g/cc for expansive soil. The current produced in peat soil is about 6mA for expansive soil it is about 21mA. After electro osmotic testing the samples were removed from the test cell and conducting the shear strength test by using vane shear apparatus.

Fig. 3: Various components of EOC test

Fig. 4: EOC Test in Progress

Results and Discussion

A comparative study of odeometer and electro-osmosis consolidation on peat and expansive soils has been performed. The physical properties, permeability characteristics, consolidation characteristics of both soils have been compared. In addition, water content, void ratios, shear strength, degree of consolidation results were also compared.

Consolidation characteristics: Consolidation characteristics of peat and expansive soils were determined by odeometer consolidation test. The consolidation characteristics like compression Index (c_c), coefficient of compressibility (a_v), coefficient of consolidation (c_v), degree of consolidation, pre-consolidation pressure of peat soil is shown in table 4.

Table 4
Consolidation Properties

S.N.	Properties	Peat soil	Expansive soil
1	Compression Index (c_c)	0.17	0.11
2	Coefficient of compressibility (a_v)	0.125	0.17
3	Coefficient of consolidation (c_v)	5.47×10^{-4} cm^2/min	4.82×10^{-4} cm^2/min
4	Degree of consolidation	22.22%	12.77%
5	Pre consolidation pressure	0.53kg/cm^2	0.35kg/cm^2
6	Coefficient of permeability	8.98×10^{-7} m/sec	1.068×10^{-8} m/sec

From table 4, it is observed that the compression index, coefficient of compressibility, coefficient of consolidation, the degree of consolidation, the pre-consolidation pressure and coefficient of permeability are higher in the peat soil compared to the expansive soil.

Water content: The quantity of water that was collected during the electro-osmosis process in both the soils has been provided in table 5.

Table 5
Quantity of Water Collected

Load Applied	Time Duration	Quantity of Water Collected (ml) during EOC	
		Peat Soil	Expansive Soil
5 kPa	1 Day	8	1
	3 Days	10	3
	7 Days	11	5
10 kPa	1 Day	10	2
	3 Days	14	4
	7 Days	16	6
15 kPa	1 Day	17	4
	3 Days	22	6
	7 Days	26	8

It can be observed from the above table that the amount of water collected increased with time duration in both peat and expansive soils. The quantity of water collected in the first day for peat soil is significant irrespective of the load applied. Furthermore, the quantity of water collected on the first day increases with increase in load application. The amount of water collected (17 ml) for peat soil is substantial on the first day when a maximum load of 15 kPa was applied, while only 8ml was collected for expansive soils. When compared to expansive soil, the amount of water collected is more in peat soil because peat soil is more compressible.

Void Ratio: Void ratio of soils was 0.4269 for peat soil and 0.342 for expansive soil initially. The reduced void ratio was determined using the quantity of water collected after electro osmosis consolidation. The void ratio after electro osmosis consolidation for various load conditions and time durations for peat and expansive soils is shown in table 6.

From the table 6, it is observed that the void ratio reduction is marginally higher in peat soil compared to expansive soils after EOC at different time duration for different load application. Peat soil has more void spaces compared to expansive soil, which was already evident from its high permeability and degree of consolidation.

Shear Strength: The shear strength of the peat and expansive soil was determined using vane shear test after EOC. The shear strength of peat and expansive soils for various load conditions with respect to time duration is shown in table 7. The percentage of shear strength improvement in peat soil and expansive soils is shown in figs. 6 and 7.

Table 6
Void ratio Reduction

Load Applied	Time Duration	Void Ratio after EOC	
		Peat Soil	Expansive Soil
5 kPa	1 Day	0.422807	0.34149
	3 Days	0.417685	0.340469
	7 Days	0.412048	0.339446
10 kPa	1 Day	0.406926	0.34098
	3 Days	0.399741	0.339958
	7 Days	0.391521	0.338934
15 kPa	1 Day	0.382783	0.339958
	3 Days	0.371446	0.338934
	7 Days	0.35802	0.333739

Table 7
Shear Strength after EOC

Load Applied	Time Duration	Shear Strength after EOC (kg/cm^2)	
		Peat Soil	Expansive Soil
5 kPa	1 Day	0.462	0.656
	3 Days	0.566	0.691
	7 Days	0.611	0.722
10 kPa	1 Day	0.536	0.689
	3 Days	0.611	0.709
	7 Days	0.655	0.745
15 kPa	1 Day	0.566	0.712
	3 Days	0.640	0.745
	7 Days	0.685	0.801

The shear strength of expansive soil is higher than that of peat soil at different time duration for different load conditions. As time increases, there is a gradual increment in the shear strength irrespective of the load applied. Thus, expansive soils can be opted when higher shear strength is required.

Degree of Consolidation: The ultimate degree of consolidation was observed for the time period of 15 days for the 15kPa load applied. The settlement was noted for the primary consolidation. The degree of consolidation was determined by the ratio of the settlement of the consolidation of different load with respect to time of the ultimate settlement. The settlement recorded for various load conditions with respect to time duration after electro osmosis consolidation process is shown in Table 8 for peat and expansive soils. The settlement recorded for various load conditions with respect to time duration after odeometer consolidation process is shown in Table9 for peat and expansive soils.

Table 8
Settlement after EOC

Load Applied	Time Duration	Settlement after EOC (mm)	
		Peat Soil	Expansive Soil
5 kPa	1 Day	5.02	1.83
	3 Days	6.78	2.51
	7 Days	9.77	4.34
10 kPa	1 Day	6.64	2.15
	3 Days	10.12	3.50
	7 Days	13.36	5.67
15 kPa	1 Day	7.44	3.23
	3 Days	12.96	4.88
	7 Days	17.89	6.93

From the table 8, it is observed that the settlement in peat soil is higher than expansive soil for different loads considered. Peat soil contains high amount of organic content and void ratio, resulting in high settlement. The difference in settlement between the two soils is higher as the load is increased from 5 kPa to 15 kPa.

Table 9
Settlement after OC

Load Applied	Time Duration	Settlement after OC (mm)	
		Peat Soil	Expansive Soil
5 kPa	1 Day	0.396	0.248
	3 Days	0.581	0.394
	7 Days	0.994	0.874
10 kPa	1 Day	0.582	0.325
	3 Days	1.051	0.671
	7 Days	1.468	1.245
15 kPa	1 Day	0.642	0.567
	3 Days	1.369	0.962
	7 Days	1.932	1.546

In the case of odeometer consolidation also, the settlement in peat soils is higher than expansive soils but the magnitude of settlement is less when compared to EOC. There is an order of increment in the settlement of the soils when subjected to EOC when compared to OC. Thus, EOC is more efficient compared to OC and due to this reason, EOC is preferred over OC for consolidation of soft soils.

The degree of consolidation of peat soil after OC and EOC is provided in table10 and the same in expansive soils is provided in table 11.

Table 10
Degree of Consolidation of Peat Soil

Load Applied	Time Duration	Degree of Consolidation (%)		% increment
		OC	EOC	
5 kPa	1 Day	11.09	20.81	9.72
	3 Days	16.28	28.11	11.83
	7 Days	27.85	40.51	12.66
10 kPa	1 Day	16.31	27.53	11.22
	3 Days	29.45	41.96	12.41
	7 Days	41.14	55.38	14.24
15 kPa	1 Day	17.99	30.85	12.86
	3 Days	38.36	53.73	15.37
	7 Days	54.14	74.17	20.03

From the table 10, it is observed that the degree of consolidation increased by 9.72%, 11.83% and 12.66% at the end of 1day, 3 days and 7 days when EOC was performed for a load of 5 kPa on the peat soil. Similarly, the degree of consolidation increased by 11.22%, 12.41% and 14.24% for a load of 10 kPa and the same increased by 12.86%, 15.37% and 20.03% for a load of 15 kPa. Thus, the degree of consolidation is more effective during EOC when compared to OC as the water moves from the anode to the cathode due to application of electric potential. As the load is increased, the degree of consolidation also increases.

Table 11
Degree of Consolidation of Expansive Soil

Load Applied	Time Duration	Degree of Consolidation (%)		% increment
		OC	EOC	
5 Kpa	1 Day	8.49	11.29	11.29
	3 Days	13.50	27.13	13.63
	7 Days	29.95	46.91	16.96
10 Kpa	1 Day	11.13	23.24	12.11
	3 Days	22.99	37.83	16.90
	7 Days	42.67	61.30	18.63
15 Kpa	1 Day	19.43	34.91	15.48
	3 Days	32.96	52.75	19.79
	7 Days	52.98	74.92	21.94

From the table 11, it is observed that the degree of consolidation increased by 11.29%, 13.63% and 16.96% at the end of 1day, 3 days and 7 days when EOC was performed for a load of 5 kPa on the expansive soil. Similarly, the degree of consolidation increased by 12.11%, 16.90% and 18.63% for a load of 10 kPa and the same increased by 15.48%, 19.79% and 21.94% for a load of 15 kPa. Thus, the degree of consolidation is more effective during EOC when compared to OC even for expansive soils. The magnitude of increment in the degree of consolidation is higher in expansive soils compared to peat soils.

Conclusion

In this paper, a comparative study on the application of EOC on peat and expansive soils was conducted. EOC is gaining momentum and is being widely applied to increase the shear strength of soft soils. Consolidation was performed using OC as well as EOC for peat and expansive soils. The following results were derived from this study:

1. The permeability of peat soil is higher than the permeability of expansive soils.
2. The quantity of water collected during EOC is higher in peat soil compared to expansive soils.
3. Void ratio reduction is marginally higher in peat soil compared to expansive soils.
4. After EOC, the shear strength of expansive soil is higher than that of peat soil.
5. The degree of consolidation and settlement is higher in peat soils in comparison with expansive soils.
6. Settlement in the soils through EOC is higher than OC by an order of magnitude.
7. The magnitude of increment in the degree of consolidation is higher in expansive soils compared to peat soils.

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