Suction- Swell Relationship of Stabilized Expansive Soil

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***Abstract*: Soil that has potential for volume change under changing moisture conditions are generally called as expansive soil. The swelling of soil is due to release of suction in the soil. Hence it is necessary to study the relationship between suction and swell characteristics of expansive soil. The suction-swell relationship of stabilized expansive soil will be different from the natural soil. Locally available soil (natural soil) was collected and it was found that it is CH type soil as per IS classification system. The soil water characteristics curve (SWCC) was measured using pressure plate extractor apparatus and the swell pressure was measured using oedometer by expanding loaded method. The soil was stabilized by using hydrated lime (L), sodium chloride (NaCl), and both at different percentage. The optimum percentage of stabilization agents are 4% lime and 3% of NaCl. The SWCC and swell pressure of both stabilized and natural soil were determined at different initial water content and density. The important observations made from the present study are: i) The influence of the stabilization agent in the consistency limits. ii) The influence of the stabilization agent in the swell pressure. iii) The influence of the stabilization agent in the SWCC. iv) The relationship between suction-swell pressure of stabilized and natural soil.**

Keywords: Stabilization, Suction-Swell, Expansive clay, Soil water characteristics curve.

I. INTRODUCTION

The swelling of soils in India has their origin in subaqueous decomposition of basalt rocks or weathering in-situ. The mineral montmorillonite is formed under alkaline environment. This soil is popularly known as black cotton soil in India. The soil is mostly residual in character and the thickness of deposits is less than 5 m in most cases. However, transported soil deposits of black cotton soils are known to exist and these deposits are much thicker and are around 8.0 m. The marine deposits present in the narrow tidal coastal plains along the east and the west coast India have undergone desiccation over a period and these desiccated clays exhibit characteristics similar to expansive soils. The expansive nature of the soil is most obvious near ground surface where the profile is subject to seasonal, environmental changes. Active clay undergo volume change upon wetting and drying. Expansive soils occur in an active zone which starts at the ground surface down to the saturated part of the zone of capillary rise above the ground water table. Usually lower the shrinkage limit and wider the range of plasticity index, the more likely is the volume change to occur and greater the amount of the suction change .The parent materials that are associated with expansive soils can be placed in two groups .The first group comprises of the basic igneous rocks such as the basalts of the deccan plate in India, the dolerite sills and dykes in the central region of south Africa and the gabbros and norities west of Pretoria North, Transvaal etc. In these soils, the feldspar and pyroxene minerals of the parent rocks decompose to form montmorillonite and other secondary minerals. The second group comprises the secondary rocks that contain montmorillonite as a constituent which breaks down physically to form expansive soils. Examples of these types of rocks are bed rock shale found in north America, marls and stones in Isreal and the shale of South Africa. The swelling of soils in India has their origin in subaqueous decomposition of basalt rocks or weathering in situ. The mineral montmorillonite is formed under alkaline environment. This soil is popularly known as black cotton soil in India. The soil is mostly residual in character and the thickness of deposits is less than 5m in most cases. The expansive nature of the soil is most obvious near ground surface where the profile is subject to seasonal, environmental changes. There are many correlations that are useful in identifying potentially expansive soils. It may also be possible to identify them visually.

II. LITERATURE REVIEW

Gueddouda et al. [7] evaluated the effect of salt, lime, cement, combinations of lime and cement, and combination of lime and salt on the swelling potential of expansive soil. Stabilization of combined lime + cement has given satisfying results. Stabilization using lime + salt, has given better effect than the combined lime and cement stabilization. For a combination of 6% lime +1.5 M NaCl, stabilization 80% reduction in free well and more than 95% reduction in swelling pressure were observed. **Thyagaraj et al. [9]** examined a lime precipitation technique in stabilizing an expansive soil through laboratory investigation. Precipitation of lime was achieved by sequential mixing of expansive soil with calcium chloride and sodium hydroxide solutions. The swell potential of soil specimen was reduced to 0% of the untreated value of 4.95%.The reason for the reduction of swell potential was the strong lime modification reactions and poorly developed cementation products formed during the early stages of curing in the treated soil. **khemissa et al. [8]** studied about the stabilization of expansive clay using cement and lime. It has been concluded that the mechanical properties of expansive clay treated with mixture of various cement and lime content is improved. The best performance was obtained for the combination of 8%cement and 4% lime. Potential is gradual up to swell percent of 8% and is rapid beyond this value. **Puppala et al. [2]** studied about the swell prediction model. The swell prediction models were generated based on a limited number of expansive clays and pertain to a specific suction and void ratio. The new parameter, mechanical hydro chemical parameter is used for both matric suction and clay mineralogy information. **Yaqoub et al. [11]** investigated the volume change behavior of swelling soil. In this paper the author concluded that swelling occur for degree of saturation higher than 80%. If hydraulic diffusivity decreases the equilibrium swelling pressure will increase. It is observed that the coefficient of permeability of expansive soil depends on degree of saturation and void ratio. The swelling rate of expansive soil decreases as the surcharge pressure increases. **Christopher et al. [5]** studied about the emerging trends in expansive soil stabilization. Properties of expansive clay can be improved by changing soil micro fabric, pore sizes and constituents. Chemical stabilization can be accelerated by injection techniques and deep soil mixing technique. Instead of using one additive as stabilizing agent, it is advisible to use of number of additives to achieve economy. In addition nanotechnology also has been proven to be a suitable method for stabilization of expansive soils.

The project aim is to study the effects of stabilization in the soil water characteristic curve and study the effect of stabilization in the swell pressure, and also obtain the relationship between soil suction and swell pressure based on drying soil water characteristic curve. The present study are carried out to understand the influence of addition of both Hydrated Lime and Sodium chloride (NaCl) in the soil water characteristic curve (SWCC), and swell characteristics of expansive soil. The lime and NaCl were added to the soil individually and in combinations. Stabilized soil changes the internal force system, which in turn may alter the suction-swell relationship. Hence it is decided to establish the suction-swell relationship for stabilized expansive clays of selected area

III. METHODS AND MATERIALS

The expansive soil was collected from Shanthi colony, Anna Nagar, Chennai. The soil was air-dried, and the soil classification tests were carried out. The index and compaction characteristics of the soil are presented in Table I. To establish the suction-swell relationship, the expansive soil is considered as different initial state. To determine the lime fixation point the pH test was carried out. For that 1% to 8% of lime is mixed with soil to obtain a pH of 12.40 or equivalent to pH of lime. From the observation, for lime content beyond 4%, the pH remained constant as 12, so optimum lime content is fixed as 4%.

Table- I: Index Properties and Compaction Characteristics of Natural Soil

S.No.	Soil description	Value
1	Specific gravity, Gs	2.70
2	Gravel (%)	0
	Sand (%)	0
	Silt (%)	36
	Clay (%)	64
3	Liquid Limit (%)	74
4	Plastic Limt (%)	32
5	Shrinkage Limit (%)	13
6	Plasticity Index (%)	42
7	Free swell index (%)	70
8	Maximum Dry Density (g/cc)	1.38
9	Optimum Moisture Content (%)	31
10	IS Classification of soil	CH

A. Preparation of Soil Mix

The known weight of pulverized dry soil was taken. The dry weight of lime was calculated for different percentage and added to the dry soil. Similarly, the dry weight of NaCl also calculated. As per different combinations, the dry soil mix was prepared and the tests were carried out by adding respective water content.

B. Pressure plate apparatus (Axis translation technique)

To determine the suction pressure to the soil, the pressure plate apparatus was used. The apparatus consists of totally six specimen rings of dimension 60 mm internal diameter and 10 mm height, which is made of Poly Vinyl Chloride (PVC) material. The sample was packed in a specimen ring of required density and water content. The prepared specimens were subjected to full degree of saturation by submerging in water, such that the sample was allowed for drainage at both top and bottom .After assuring complete saturation of specimens were tested in the pressure plate apparatus .The saturated specimens were placed on the air-entry ceramic disk with maximum capacity of 15 bar in air pressure chamber. Initially, air pressure of 2 bar was applied for 24 hours on the saturated specimens.

After application of this air pressure, the weight of the specimen was noted. Then, the air pressure was increased to 4 bar and the same procedure was repeated up to the air pressure of 14 bar. After completion of 14 bar the specimens were taken and kept for oven drying for 24 hours and it were weighed for moisture content determination. Finally, the soil-characteristics curve was obtained from the graph drawn for suction pressure and gravimetric water content. The soil water characteristics curve determined for different initial conditions as listed in Table II.

Table-II: Soil with different initial condition for suction test.

Soil with different Stabilizers	**Water content (%)**	**State of soil**	**Bulk Density (g/cc)**
Natural soil	74	Liquid State	1.103
	32	Plastic State	1.728
	13	Solid State	1.728
Natural Soil +2%lime	67	Liquid State	1.103
	45	Plastic State	1.728
	15	Solid State	1.728
Natural Soil +4%lime	55	Liquid State	1.106
	43	Plastic State	1.728
	28	Solid State	1.728
Natural Soil +2%lime+ 2% NaCl	66	Liquid State	1.056
	37	Plastic State	1.728
	13	Solid State	1.728
Natural Soil +4%lime+ 3% NaCl	57	Liquid State	1.116
	37	Plastic State	1.728
	23	Solid State	1.728

IV RESULTS AND DISCUSSION

A. Effect on Atterberg Limits

The liquid limit, plastic limit, and shrinkage limit tests are determined in the laboratory. The above values of soil mix with lime and NaCl are presented in the Table III and Table IV.

Table-III: Atterberg Limits Test Results for the Addition of Lime and NaCl Mix with Soil in individual

Natural Soil With Stabilizers Combination	**Atterberg Limits**			
	Liquid limit	**Plastic limit**	**Plasticity index**	**Shrinkage limit**
Natural Soil	74	32	42	13
Natural Soil+2%L	67	45	22	15
Natural Soil+4%L	55	43	12	28
Natural Soil+6%L	56	42	14	16
Natural Soil+2%NaCl	62	36	26	11

L = Lime, NaCl = Sodium Chloride

Table-IV: Atterberg Limits Test Results for the Soil Stabilized with Different combinations of Lime and NaCl

Natural Soil With Stabilizers Combination	**Atterberg Limits**			
	Liquid limit	**Plastic limit**	**Plasticity index**	**Shrinkage limit**
Soil+2%L + 2%NaCl	66	37	29	14
Soil+2%L + 3%NaCl	64	35	29	12
Soil+4%L + 2%NaCl	58	40	18	23
Soil+4%L + 3%NaCl	57	37	20	23
Soil+6%L + 2%NaCl	58	45	13	17
Soil+6%L + 3%NaCl	58	40	18	26

L = Lime, NaCl = Sodium Chloride

The natural soil has the liquid limit value of 74%. When the soil mixed with 2%, 4% and 6% of lime, the liquid limit decreased to 67%, 55% and 56% respectively. When 2% of NaCl is added to the natural soil the liquid limit decreased to 62%. The liquid limit of the soil specimen decreased up to 7% on addition lime. This is because the electrolyte concentration on addition of ca^{2+} ions reduces the double layer thickness leading to reduction in liquid limit. But beyond 4% lime content the liquid limit remained constant because the influence of stabilization on double layer reduction is insignificant. The variation of liquid limit with lime content is shown in Fig 1.

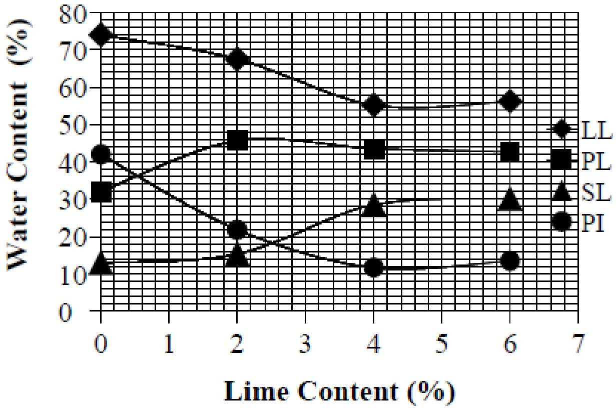

Fig. 1. Soil with different Lime content

The plastic limit of the natural soil is 32%. When soil is mixed with 2%, 4% and 6% of the lime, the plastic limit increased to 45%, 43% and 42% respectively. For 2%NaCl the plastic limit increased to 36%. Beyond 4% lime very slight decrease in the plastic limit is noticed. The lime induced flocculation enhanced the inter particle resistance against movement, thus the plastic limit decreased. A decrease in the plasticity index was observed with the addition of lime and NaCl with soil. It is to be noted that with the above treatment, the plasticity index of the expansive soil decreased from 42% to 26%.

Fig.2. and Fig.3. shows the variation of the liquid limit, plastic limit, shrinkage limit and plasticity index for different percentages of lime with 2% NaCl. When 2%, 4% and 6% of lime added along with 2% NaCl, the liquid limit decreased from 74% to 66%, 58% and 58% respectively. For the same combinations, when NaCl is increased to 3%, the liquid limit decreased to 64%, 57%, and 58% respectively. The plastic limit increased from 32% to 37%, 40% and 45% respectively for lime and 2% NaCl. For lime and 3% NaCl, the plastic limit increased to 35%, 37% and 40%. The test result values are tabulated in Table IV.

The plasticity index decreased with increase in lime content. For the combination of soil with 6% lime and 2% NaCl, the plasticity index decreased by 69%, and for the combination of soil with 6% lime and 3% NaCl plasticity index decreased by 57%. The significant improvement in the consistency of the soil is contributed by an appreciable decrease in liquid limit and plasticity index.

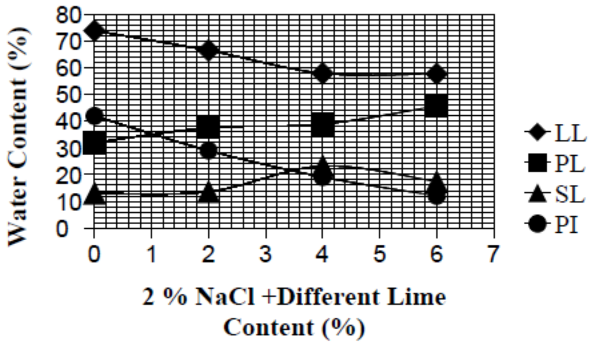

Fig.2. Soil with 2%NaCl with different Lime content

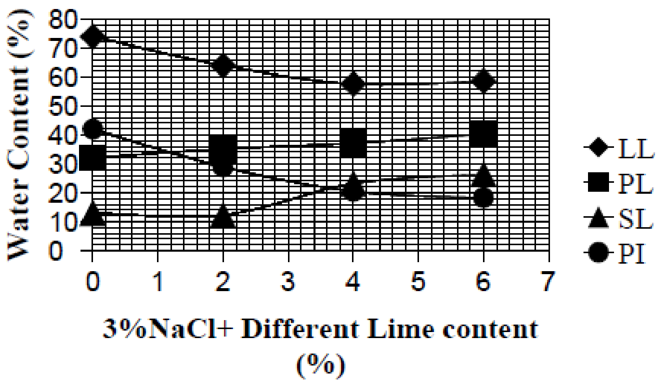

Fig.3. Soil with 3%NaCl with different Lime content

B. Influence of Stabilization on Soil Water Charateristics Curve (SWCC)

The suction tests were carried out by adding lime and NaCl for various proportions. From the soil water characteristic curve (SWCC) the following data were calculated for the interpretation of the suction - swell relation. For the suction test the samples were prepared at different initial water content corresponding to the mix proportion. From the SWCC air entry value (ψ_i), residual water content (w_r), residual suction (ψ_r), and slope of the curve ($c_{w\psi}$) for natural soil were obtained. The above mentioned parameters are obtained from the graph, and they are shown in Fig.4. Similarly the SWCC for the mix proportions 2%Lime+natural soil, 4%Lime+ natural soil, 2%Lime+2%NaCl+ natural soil, 4%Lime+3%NaCl+ natural soil are obtained.

The SWCC parameters determined made from the graph are presented below in the form of tables. The SWCC parameters for stabilized soils are determined and it shown in Table-V to Table-IX.

From the Table 4.3 it is found that the air entry value and the slope of SWCC of natural soil decreased with decrease in initial water content. Since the residual suction of the natural soils at different initial conditions is greater than 1400 kN/m^2, it is not possible to report the residual suction value.

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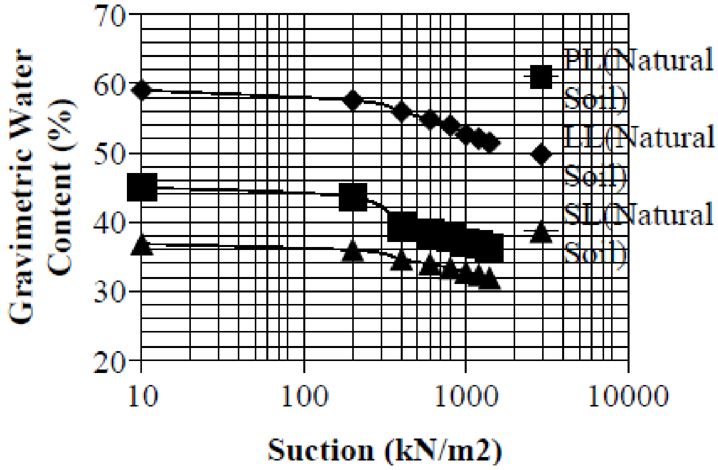

Fig.4. Suction versus Gravimetric Water Content for Natural soil

Table-V: Natural Soil with Different Initial Condition

Sl.No.	State of Soil	Bulk Density(g/cc)	Initial water Content W_i(%)	Residual Water Content W_r (%)	Air Entry Value ψ_i (kN/m^2)	Residual suction ψ_r (kN/m2)	Slope of SWCC
1	Liquid State	1.103	60	-	150	>1400	0.08
2	Plastic State	1.728	45	-	130	>1400	0.06
3	Solid State	1.728	37	-	90	>1400	0.04

Table-VI: Soil and 2% of Lime with Different Initial Condition

S.No.	State of Soil	Bulk Density(g/cc)	Initial water Content W_i(%)	Residual Water Content W_r (%)	Air Entry Value ψ_i (kN/m^2)	Residual suction ψ_r (kN/m2)	Slope of SWCC
1	Liquid State	1.103	74	47	120	800	0.33
2	Plastic State	1.728	67	43	80	700	0.26
3	Solid State	1.728	55	34	35	450	0.19

From the above Table-VI, it is found that 2% addition of lime, the air entry value and slope of SWCC decreased with decrease in initial water content. But the air entry value was lesser than that of the natural soil and the slope of SWCC was greater than that of natural soil. Since the slope of SWCC was greater than natural soil, the soil+ 2% lime reached the residual state and the residual suctions were lesser than 1400 kN/m^2. In addition, increase in the initial water content increased the residual suction.

From the below Table VII, it is found that on 4% addition of lime, the air entry value and slope of SWCC decreased with decrease in initial water content. Since the residual suction of the soil at different initial conditions is greater than 1400 kN/m2, it is not possible to report the residual suction value. The air entry value was greater than that of the natural soil and the slope of SWCC was greater than that of natural soil. In addition, the air entry value was greater than that of the natural soil+ 2% lime and the slope of SWCC was lesser than that of natural soil+ 2% lime.

From the Table VIII, it is found that addition of 2% Lime+ 2%NaCl, the air entry value and slope of SWCC decreased and then increased with decrease in initial water content. The residual suction of soil + 2% Lime+ 2%NaCl at different initial conditions are lesser than 1400, and the residual suction value increased with decrease in initial water content. The air entry value was greater than that of the natural soil and the slope of SWCC was greater than that of natural soil. The air entry value and residual water content were greater than that of the natural soil+ 2% lime. The air entry value was greater than that of the natural soil+ 4% lime and residual suction was lesser than natural soil+ 4% lime.

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Table-VII: Natural Soil and 4%Lime with Different Initial Condition

SL.NO.	State of Soil	Bulk Density(g/cc)	Initial water Content W_i(%)	Residual Water Content W_r (%)	Air Entry Value ψ_i (kN/m^2)	Residual suction ψ_r (kN/m2)	Slope of SWCC
1	Liquid State	1.106	57	-	400	>1400	0.1
2	Plastic State	1.728	49	-	170	>1400	0.08
3	Solid State	1.728	34	-	120	>1400	0.05

Table-VIII: Natural Soil + 2% Lime+ 2%NaCl with different initial condition

S.No.	State of Soil	Bulk Density(g/cc)	Initial water Content W_i(%)	Residual Water Content W_r (%)	Air Entry Value ψ_i (kN/m^2)	Residual suction ψ_r (kN/m2)	Slope of SWCC
1	Liquid State	1.056	80	65	210	600	0.34
2	Plastic State	1.728	60	54	170	600	0.11
3	Solid State	1.728	50	50	250	800	0.15

From the Table IX, it is found that addition of 4% Lime+ 3%NaCl; the air entry value remains the same for all states irrespective of the initial water content. The slope of SWCC decreased and then increased with decrease in initial water content. Similar pattern is observed for 2% Lime+ 2%NaCl. The air entry value and residual water content were greater than that of the natural soil+ 2% lime. But the slope of SWCC is lesser than the natural soil+ 2% lime. The residual suction of the soil at different initial conditions is greater than 1400, for natural soil+ 4% lime+3% NaCl and natural soil+ 4% lime. The residual suction is greater than natural soil + 2% Lime+ 2%NaCl

Table- IX: Natural Soil + 4% Lime+ 3%NaCl with different initial condition

S.No.	State of Soil	Bulk Density(g/cc)	Initial water Content W_i(%)	Residual Water Content W_r (%)	Air Entry Value ψ_i (kN/m^2)	Residual suction ψ_r (kN/m2)	Slope of SWCC
1	Liquid State	1.116	77	-	200	>1400	0.15
2	Plastic State	1.728	56	-	200	>1400	0.05
3	Solid State	1.728	50	-	200	>1400	0.10

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C. The Influence of Stabilization on the Percent

Swell and Swell Pressure

The treated samples immediately showed a reduction in swell pressure and percent swell. However, a significant decrease in the percent of swell and pressure values were obtained for an increase in lime up to 4%. Moreover, with the addition of 4% lime, the percent swell dropped to zero.

This decrease in swelling characteristics is attributed to the reduced amount of water absorption in calcium saturated clay owing to cation exchange reaction, and also due to the development of acementitious bonding produced by the reaction between the lime and the clay minerals. However, increase in pH due to the addition of lime induced an additional negative charge on the edges of the clay particle leads to edge-to-face attraction which result a flocculated structure. The relatively open structure of the flocculants fabric holds more water, and increased the percent swell and swell pressure, for the soil treated with 2% lime and 3% NaCl. The addition of 4% of lime with 3% NaCl almost eliminates both the swell pressure and percent swell of the treated soil.

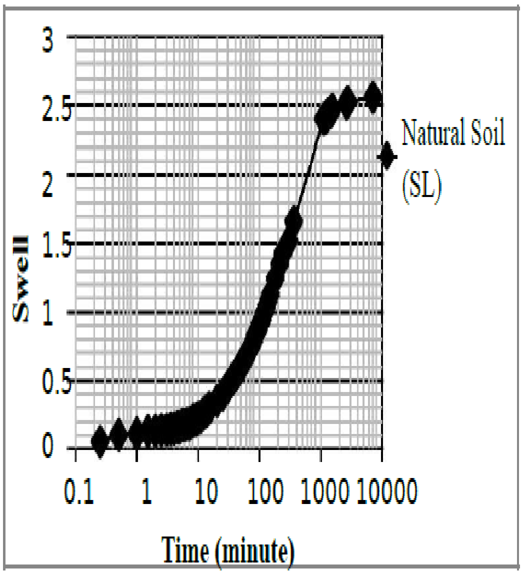

Fig 4.5 Time versus Swell(mm) for Natural Soil at Solid State

D. Suction – Swell Relation

The suction and swell tests were carried out for different proportions of lime and NaCl. The samples were prepared for soil at initially plastic state condition and the suction values are obtained from SWCC and the samples are initially at saturated condition or state. The suction values

Pressure, for the soul treated with 2% lime and 3% NaCl. The addition of lime with 3% NaCl almost eliminate both the swell pressure and percent swell of the treated soil.

are limited up to 1400 kN/m^2, So that in the graph the curve was extended then the values are obtained (suction values plotted in x-axis see Fig.4.).

The suction test were carried out by adding lime and NaCl for various proportions. From the soil water characteristic curve the following data were calculated

Table –X: Percent Swell and Swell Pressure Test Results

Soil Composition	Swell Percent (%)	Swell Pressure (kPa)
Natural Soil	12.8	480
Natural Soil	2.6	82
Natural Soil + 2% L	2.75	252
NaturalSoil+2%L+2%Nacl	2.3	102
NaturalSoil+2% L+3%Nacl	7.00	282
Natural Soil+4%L+2%Nacl	1.38	165
Natural Soil+4%L+3%Nacl	0.30	38

L - Lime , NaCl- Sodium Chloride, SL- Solid State, PL-Plastic State

The decreasing swell characteristics is attributed to the reduced amount of water absorption in calcium saturated clay owing to cation exchange reaction, and also due to the development of a cementitious bonding produced by the reaction between lime and the clay minerals. Samples treated with 4% of lime gives lower selling according to seed et al(1962).However increase in pH due to the addition of lime induced an additional negative charges on the edges of the clay particles leads to edge to face attraction which resulted a flocculated structure. The relatively open structure of the flocculant fabric holds more water, and increase the percent swell and swell, for the soil treated with 2% lime and 3% NaCl. The addition of 4% of lime with 3% NaCl almost eliminates both the swell pressure and percent swell of the treated soil.
Suction swell relationship with different water content is listed from table XI to table XIII.

S.NO	Water content (%)	Swell pressure (kN/m^2)	Swell percent (%)	Suction at different initial condition of soil (kN/m^2)		
				Liquid State	Plastic State	Solid State
1	28	0	0	20000	60000	4000
2	43	0	0	3000	1200	0
3	55	0	0	300	0	0

Table- XI**:** Suction –Swell characteristics of natural soil + 4% of Lime with Different Initial Condition.

Table- XII**:** Suction –Swell characteristics of Natural Soil +2% Lime +c2% NaCl with Different Initial Condition**.**

S.NO	Water content (%)	Swell pressure (kN/m^2)	Swell percent (%)	Suction at different initial condition of soil (kN/m^2)		
1	13	102	2.3	10^8	10^7	1200000
2	37	0	0	1000000	10^5	17000
3	66	0	0	600	0	0

Table- XIII**:** Suction - Swell characteristics of Natural soil + 4% Lime + 3% NaCl with Different Initial Condition

SL.NO	Water content (%)	Swell pressure (kN/m^2)	Swell percent (%)	Suction at different initial condition of soil (kN/m^2)		
				Liquid State	Plastic State	Solid State
1	23	38	0.3	400000	10^9	20000
2	37	0	0	12000	400000	2800
3	57	0	0	2200	0	0

1. The relationship between swell and suction are different for soil and soil stabilized with different stabilizing agent.

2. The relationship between swell and suction of both soil and stabilized soil are different for different initial states.
3. The interaction of stabilizing agent with soil is different at different initial water content.
4.

a) Suction – swell relationship based on SWCC, initially at liquid state

The Natural soil exhibits swell properties from low suction values. Addition of 2% lime,4%lime and 2%lime+2%NaCl completely suppressed the swell properties. But addition 3%NaCl with 4% lime stimulated the soil to swell at higher suction value 4000 kN/m^2.

b) Suction – swell relationship based on SWCC, initially at plastic state

For initially plastic state, the natural soil exhibited swell properties from very low suction value. Natural soil +2%lime exhibited swell properties for suction value 13000 kN/m^2. For all the combination of stabilizing agent there is no swell and properties of natural soil were suppressed by the stabilizing agent.

c) Suction – swell relationship based on SWCC, initially at solid state

For SWCC at initially solid state, natural soil exhibited swell properties from lower suction value. The natural soil+2%lime exhibited swell properties at suction value 170 kN/m^2. The natural soil+4% lime +3%NaCl exhibited swell properties at suction value 2000 kN/m^2. The natural soil +2%lime +2%NaCl exhibited the swell properties at higher suction value than 4%lime +3%NaCl.

d) Suction – swell relationship based on SWCC, initially at liquid state

The Natural soil exhibits swell properties from low suction values. Addition of 2% lime, 4%lime and 2%lime+2%NaCl completely suppressed the swell properties. But addition 3%NaCl with 4% lime stimulated the soil to swell at higher suction value 4000 kN/m^2.

e) Suction – swell relationship based on SWCC, initially at plastic state

For initially plastic state, the natural soil exhibited swell properties from very low suction value. Natural soil +2%lime exhibited swell properties for suction value 13000 kN/m^2. For all the combination of stabilizing agent there is no swell and properties of natural soil were suppressed by the stabilizing agent.

f) Suction – swell relationship based on SWCC, initially at solid state

For SWCC at initially solid state, natural soil exhibited swell properties from lower suction value. The natural soil+2%lime exhibited swell properties at suction value 170 kN/m^2. The natural soil+4% lime +3%NaCl exhibited swell properties at suction value 2000 kN/m^2. The natural soil +2%lime +2%NaCl exhibited the swell properties at higher suction value than 4%lime +3%NaCl.

V CONCLUSIONS

A. Effect on Consistency Limits

The natural soil was found to be CH type soil. Its liquid limit, plastic limit, plasticity index and shrinkage limit values are 74%, 32%, 42% and 13% respectively.

a) *Reduction in Liquid Limit and Plasticity Index* Upon addition of 2% lime, 4% lime and 2% NaCl, its liquid limit decreased by 10%, 26% and 12% respectively. And its plasticity index decreased by 47%, 71% and 38% respectively.

On addition of the combination of 2% lime+2% NaCl, 2% lime+3% NaCl, 4% lime+2% NaCl and 4% lime+3% NaCl the decrease in the liquid limit and plasticity index were in the range of 10% – 23% and 30% – 69% respectively.
The electrolyte concentration on addition of ca+ ions reduces the double layer thickness reduces the liquid limit.

B. Increase in Plastic Limit and Shrinkage Limit

Upon addition of 2% lime, 4% lime and 2% NaCl, its plastic limit increased by 29%, 26% and 11% respectively. And its shrinkage limit increased by 13%, 54% and 15% respectively.

On addition of the combination of 2% lime+2% NaCl, 2% lime+3% NaCl, 4% lime+2% NaCl and 4% lime+3% NaCl the increase in the plastic limit and shrinkage limit were in the range of 9% – 40% and 8% – 77% respectively.
The lime induced flocculation enhanced the inter particle resistance against movement, thus the plastic limit decreased for beyond soil+4% lime.

The orders of reduction in plasticity index for different combination of lime and NaCl with the selected CH type soil are

Natural soil > Natural soil +2%lime+2%NaCl = Natural soil +4%lime+3%NaCl

> Natural soil +2%NaCl > soil+4%lime+2%NaCl > soil+2%NaCl = soil+6%lime+3%NaCl > soil+4%NaCl > soil+6%lime+2%NaCl > soil + 4%lime.

C. Effect on Swell Properties

A significant decrease in percent swell and swell pressure were obtained for increase of percentage of lime up to 4% the lime fixation percentage. Addition of 2%NaCl enhanced the swell characteristics but addition of 3%NaCl with lime reduced the swell characteristics.

The order of swell characteristics for different combinations of lime and NaCl are

Natural soil > Natural Soil +2%lime +3%NaCl > Natural Soil +2%lime > Natural Soil +2%lime +2%NaCl > Natural Soil +4%lime +2%NaCl > Natural Soil +4%lime +3%NaCl

D. *Effect on SWCC Parameters*

The SWCC parameters of the stabilized soil depend on the interaction between different combinations of lime and NaCl. Generally on addition of the higher percentage of stabilizing agents, the slope of SWCC, residual suction and air entry value increases.

For soil+2% lime the residual suction and air entry value are lesser than the natural soil. The slope of SWCC of soil+2% lime and soil+2% lime +2% NaCl are greater than the other values of slope.

Addition of lesser percent of lime (lesser than lime fixation point) increased the slope desaturation zone, which made the soil to attain residual state at lower suction value. Addition of higher percentage of stabilizing agent reduced the slope of desaturation zone and the residual states are attained at higher suction value. More data are required to propose the order of variation in the SWCC parameters.

E. Relation between Suction and Swell Properties

The relationship between suction and swell are different for soil and soil stabilized with a different stabilizing agent. The relationship between the suction and swell of both soil and stabilized soil are different for different initial states. The interaction of stabilizing agent with soil is different at different initial water content.

The order of suction value at which the natural soil and natural soil with different combinations of stabilizing agent exhibited swell properties are give below

a) SWCC at Initially Liquid State

Natural soil > Natural soil + 4%lime+3%NaCl

> Natural soil + 2%lime > Natural soil + 4%lime, and > Natural soil + 2%lime+2% NaCl

b) SWCC at Initially Plastic State

Natural soil > Natural soil + 2%lime+2% NaCl > Natural soil + 4%lime+3% NaCl > Natural soil + 4%lime > Natural soil + 2%lime.

c) SWCC at Initially Solid State

Natural soil > Natural soil + 2%lime > Natural soil + 2%lime+2% NaCl > Natural soil + 4%lime+3% NaCl > Natural soil + 4%lime.

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From the above statement is concluded that the stabilized soil exhibits different suction- swell relation if its initial water content at liquid state. The suction swell relationship of stabilized soil is same if it is initially in plastic state and solid state.

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