*International Journal of Earth Sciences Knowledge and Applications (2023) 5 (2) 293-302*

International Journal of Earth Sciences Knowledge and Applications
journal homepage: http://www.ijeska.com/index.php/ijeska

Review Article
e-ISSN: 2687-5993

# Effect of Soil Salinization on the Liquid Limits of Soils: A Review

**Uddav Ghimire**[1]*

[1]*Department of Civil Engineering &Engineering Mechanics, University of Arizona, Tucson, Arizona, USA*

INFORMATION

**Article history**
Received 28 July 2023
Revised 07 August 2023
Accepted 09 August 2023

**Keywords**
Pore fluid salinity
Soil salinization
Atterberg limits
Expansive soils
Non-expansive soils

**Contact**
*Uddav Ghimire
uddav@arizona.edu

ABSTRACT

Soil salinization is one of the major effects of ongoing climate change, which has both direct and indirect effects in Civil Engineering. Salt deposition is a major problem that has been observed for last the few decades. The presence of salt alters the mechanical, chemical, and hydraulic properties of soil materials. Several attempts have been made by researchers to understand the effect of salt concentration on soil properties and its consequences. A good understanding of this is mostly for sustainable development and analysis of different failures. This paper presents a state-of-the-art review of research on the effect of pore water salinity on the Atterberg properties of soils. The soils having different mineralogical compositions over the different parts of world have been studied, which includes the study of expansive soils and non-expansive soils. The two possible mechanisms that control Atterberg values under the presence of pore water salinity are diffuse double layer theory and soil fabric. Although much research has been conducted, the explanation of the mechanism controlling the liquid limit values of mixed clay minerals in the presence of salinity is still very limited. A possible reason is the lack of study on these types of soils.

## 1. Introduction

The effects of climate change are already being observed in many parts of the world, with impacts on human health, food security, water availability, and infrastructure. Soil salinization is one of the serious effects of climate change, particularly in arid and semiarid regions of the world (Tanji, 1990; Suarez, 2001; Pitman and Lauchli, 2002). The effect of soil salinization in the environment will keep on increasing with climate change. So, a major challenge has emerged in civil engineering to understand whether the infrastructure will be affected by soil salinization and how the design practices must be modified for sustainable development. For this, a good understanding of its influence on the fundamental properties of soil is necessary. Recently, there have been studies focused on understanding the behavior of pore water salinity on different geotechnical properties of soils: Atterberg limits, compaction parameters, permeability, strength, etc. (Warkentin and Yong, 1962; Sridharan and Venkatappa Rao, 1975; Pupisky and Shainberg, 1979; Ogata et al., 19832; Mishra et al., 2005; Mishra et al., 2009; Tiwari and Ajmera, 2014; Dutta and Mishra, 2015; Ghimire et al., 2023).

Soil salinity is a measurement of the concentration of all soluble salts in soil water, and it is commonly expressed in terms of the Electrical Conductivity (EC) or Total Dissolved Solids (TDS) of soils. The major soluble salts are cations such as sodium ($Na^+$), calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), potassium ($K^+$), and anions such as chloride ($Cl^-$), sulfate ($SO_4^{2-}$), bicarbonate ($HCO_3^-$), carbonate ($CO_3^{2-}$), and nitrate ($NO_3^-$). The most commonly used parameter is EC, which is measured in milliSiemens/cm (mS/cm, equivalent to mmhos/cm) for lower salinities and deciSiemens/m (dS/m, equivalent to mmhos/cm) for higher salinities. Salt-affected soil can be classified into different groups based on EC and Exchangeable Sodium Percentage (ESP). ESP is the percentage of the overall Cation Exchange Capacity (CEC) that represents the proportional amount of sodium ions that are present on the soil surface.

Table 1 shows a classification of salt-affected soils (US Salinity Laboratory, 1954). Generally, an ESP of 15 is accepted as the threshold below which soils are classified as non-sodic, and above which soils are sodic (dispersive) and experience severe physical problems in the presence of water.

However, studies in the past state different values of EC, ESP, and pH to define sodic soil (Kelley, 1951; Anon, 1965; Northcote and Skene, 1972; Gupta and Abrol, 1990).

Table 1. Classification of salt-affected soils (US Salinity Laboratory, 1954)

| Class | Ece (dS/m) | ESP (%) | pHs |
|---|---|---|---|
| Nonsaline | <4 | <15 | <8.5 |
| Saline | >4 | <15 | <8.5 |
| Sodic | <4 | >15 | >8.5 |
| Saline-sodic | >4 | >15 | <8.5 |

The Atterberg limits are a fundamental measure of the critical water content of fine-grained soil, consisting of three limits: shrinkage, plastic, and liquid limits. The Atterberg limits can be used to distinguish silt from clay, as well as different types of silt and clay. Consistency limits, also known as Atterberg's limit, are the water content at which soils change from one state to another. These tests are mostly used on clayey or silty soils because they expand and contract as the moisture content changes. Clays and silts interact with water, causing them to change their size and shear strength. Thus, these tests are used widely in the preliminary stages of designing any structure to ensure that the soil will have the correct amount of shear strength and not too much change in volume as it expands and shrinks with different moisture contents.

This paper presents a state-of-the-art review of the research on the effect of pore fluid salinity on the liquid limits of soils. The different types of studied soils with their mineralogical compositions are described. The types of salts used in the study and their effect on the liquid limit values are discussed in detail.

## 2. Background

Soil is made up of solid particles, liquid, and gas. The primary factor controlling the size, shape, and properties of soil particles is mineralogy. Particle size ranges in the soil are shown in Fig. 1. The physical properties of cohesionless soils, which include gravel, sand, and nonplastic silts, are primarily determined by particle size, shape, surface texture, and size distribution. In soil, bulky, nonclay particles make up the majority of the silt fraction, the sand, and the gravel.

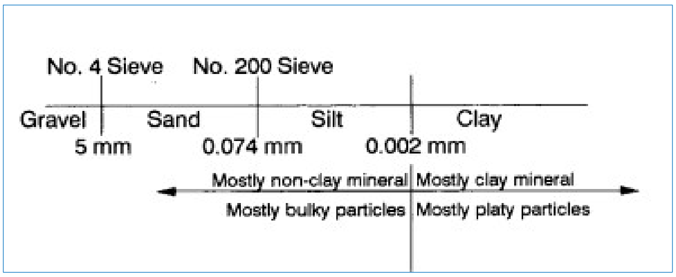

Fig. 1. The particle size of soils

The most common clay minerals found in soils are kaolinite (1:1), smectite (2:1), mica (2:1), and chlorite (2:1:1). Most clay minerals have two basic crystal structures: a tetrahedral silicon-oxygen sheet and an octahedral gibbsite sheet of magnesium or aluminum and hydroxyl. Both attractive and repulsive forces of electrical nature exist between clay particles. Many complex factors exist for the net attractive and repulsive forces between these particles (Lambe, 1953; Rosenqvist, 1955; Mitchell, 1956; Sridharan, 1968). However, most clay minerals develop a net negative charge on the surface which might be the result of isomorphous substitution or broken crystal bonds (Mitchell, 1993).

### 2.1. Soil Fabric

The geometrical arrangement of individual particles in the soil, as well as the geometrical distribution of pore spaces, is referred to as soil fabric. The term "soil fabric" refers to the particle arrangement in both cohesive soils like clays and granular soils like silts, sands, and gravel. Clay particles, in general, occur in multiple groups called fabric units rather than as individual discrete units. A complete description of soil fabric includes the arrangement of individual particles in each fabric unit, as well as the arrangement of various fabric units and pore spaces or voids.

The arrangement of soil particles (soil fabric) as well as the strength of electrical forces acting on the individual particles and between the fabric units make up soil structure. The magnitude of clay's qualities, including shrinkage, swelling, shear strength, compressibility, and permeability, is determined by the soil structure. The particle association in clay can be described as follows (Van Olphen, 1963; Mitchell, 1976).

#### *2.1.1. Flocculated*

A flocculated structure in clays consists of clay particles with the edge-to-face association. In this arrangement, the edge of one particle is in contact with the face of the other particle. As the edge of a clay particle has a small positive charge and the surface of the particle has a negative charge, there is a strong attractive force between the particles giving a stable structure. When attractive forces predominate, flocculated structure develops. In kaolinite and illite, the flocculent structure is, therefore, more common. This type of particle arrangement is found in an acidic environment.

#### *2.1.2. Dispersed*

Face-to-face connection of clay particles or fabric units constitutes a dispersed structure in clays. The repulsive interactions between the particles or between the fabric units are more pronounced in a dispersed structure because of the face-to-face association. Additionally, montmorillonite has a higher proportion of dispersed structure because of the thick double layers and predominance of repulsive forces. Such a particle arrangement is obtained in a low-salt environment.

### 2.2. Diffuse Double Layer

Clay particles are negatively charged because of isomorphous substitution, occupying metal ion positions, and the release of protons from hydroxides. Electrostatic forces exist between the negative surface and exchangeable cations because of the negative charge at the surface of clay particles. The strength of these forces varies with charge, charge position, and valence of the exchangeable cations. A clay particle's negatively charged surface attracts positive ions. The 'diffuse double layer' refers to this region of attracted positive ions in solution and the negatively charged surface of the clay (Fig. 2).

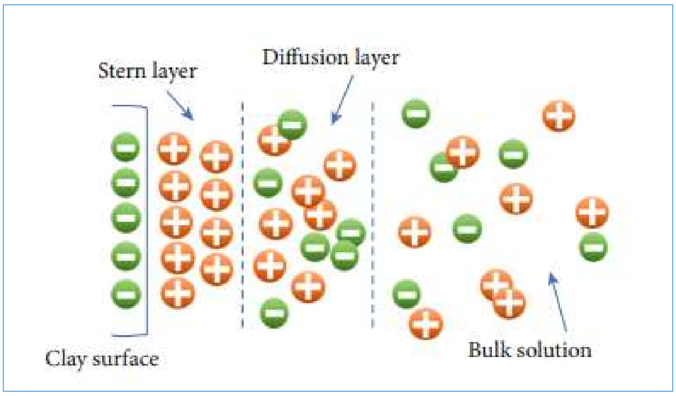

Fig. 2. Schematic representation of ion and possible distribution in a diffuse double layer

Ions are not bound in a single layer around the clay, but rather in two layers. Ions closest to the colloid are most attracted and form the innermost Stern layer. The remaining ions are weaker bound and form the outer or diffuse layer, also known as the Gouy layer. Cation concentration is thus highest against the colloid and decreases as one moves away from the colloid. In contrast, the anion concentration is lowest near the colloid and increases with distance. The boundary of the diffuse double layer is where the cation and anion concentrations are equal (Fig. 3).

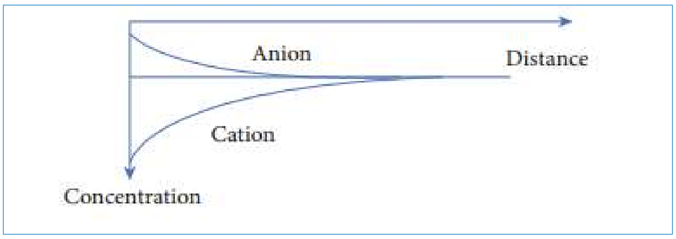

Fig. 3. Ion distribution curve for anions and cations in a diffuse double layer

## 3. Influence of Pore Fluid Salinity on the Liquid Limits

Extensive research has been performed in the past to understand the effect of pore water salinity on the Atterberg limits of soils as explained below (Fig. 3-6 and Table 2).

Rosenqvist (1953) investigated the marine origin illite rich Norwegian quick-clay, Aserumvannet. After adding 3% NaCl to the pore water, the liquid limit increased than treated with distilled water. However, after the addition of NaCl, the plastic limit remained nearly unchanged. This resulted in the conclusion that the plastic properties of clay are highly dependent not only on the content and nature of fine minerals but also on the concentration of electrolytes in the water. An experiment by Bjerrum and Rosenqvist (1956) on illite-rich asrum clay used KCl as pore fluid to study the effect of pore fluid salinity on the liquid limit. The result showed that adding salt enhanced the asrum clay's liquid and plastic limits.

In 1962, Olson and Mitronovas (1962) used standard engineering methods (ASTM,1958) to conduct a study on the effects of changes in the pore water concentration on the liquid limit and plastic limit of Ca- and Mg-Illite. Changes in the pore water-electrolyte concentration had a minimal impact on the limits; the concentration was maximum between 0.01 and 0.1 N. In comparison to Mg-clay, the Ca-clay's limits were marginally higher.

Ohtsubo et al. (1982) investigated the effect of salt addition on the liquid limit of remolded samples of Yamaashi soil (smectite rich). The reduction of salt concentration in pore water decreased the liquid limit. This observation was discovered to be unusual and against the diffuse double layer theory. This decrease in the liquid limit of Yamaashi samples with decreasing salt contents can be attributed to the low-swelling characteristic of the smectite (Egashira and Ohtsubo, 1981; Egashira and Ohtsubo, 1982).

Sridharan et al. (1988) investigated ten different soils from different parts of India. They all were kaolinite high clays with other minerals on them. The liquid limits were plotted against the sodium exchangeable content. The lack of a relationship between liquid limit and exchangeable sodium content in kKaolinitic soils led to the conclusion that liquid limit is not a function of diffuse double layer thickness.

Moore (1991) conducted an experiment on montmorillonite and kaolinite clays. The liquid limit of both Na-kaolinite and Ca-kaolinite increased with increasing molar solution concentrations. Similarly, the liquid of Na-montmorillonite and Ca-montmorillonite increased with increasing molar solution concentrations. This observation on montmorillonite contradicted the diffuse double layer theory (Fig. 6).

Rao et al. (1993) investigated the liquid limit of artificial seawater equilibrated bentonite using Casagrande's method. The impact of pore salt leaching on the liquid limit was investigated. The pore salt leached from 40 $gL^{-1}$ to 0.32 $gL^{-1}$ and the liquid limit values were noted. The liquid limit values decreased with a decrease in salt concentration on leaching below 1.1 $gL^{-1}$. This observation contradicted the diffuse double layer theory because the clay was montmorillonite rich. Below pore fluid salinity of 1.1 $gL^{-1}$, liquid limit values were governed by the clay fabric rather than the diffuse double layer.

Di Maio (1996) carried experimental research on Ponza Bentonite to investigate the impact of three salt solutions—KCl, $CaCl_2$, and NaCl—on the liquid limit. As salt content increased, the liquid limit values dropped significantly. It was discovered that a 1 M solution was enough to bring the limit down to minimum values. This was explained in terms of diffuse double layer theory.

Gleason et al. (1997) investigated the effect of calcium chloride ($CaCl_2$) added pore fluid on group A bentonite's liquid limit. The liquid limit of both Na-bentonite and calcium bentonite decreased as the molarity of calcium chloride increased. This observed result agreed with the diffuse double layer theory. The sodium bentonite was observed to go a larger reduction in liquid limit than the calcium bentonite.

Anson and Hawkins (1998) investigated the effect of calcium solutions on the liquid limit and plastic limit of kaolinite and Na-montmorillonite. With the addition of 80 mg/l Ca+2, the initial liquid limit of the kaolinite clays (57%) increased by around 8%, but it reduced somewhat for the sample treated with 160 mg/l $Ca^{++}$. It remained constant with further rising $Ca^{++}$ concentrations anywhere between 58 and 61 percent on average. This could be attributed to the flocculation of kaolinite particles due to a decrease in the dielectric constant.

Contrarily, when 80 mg/l $Ca^{++}$ was added, the liquid limit of the sodium montmorillonite material dropped sharply to less than half its initial value of 740 percent and continued to drop from 330 percent (80 mg/l $Ca^{++}$) to 225 percent (320 mg/l $Ca^{++}$). This gradual decrease can be explained due to the development of a strong bond between the particles of montmorillonite with an increase in $Ca^{++}$ concentrations in the pore fluid.

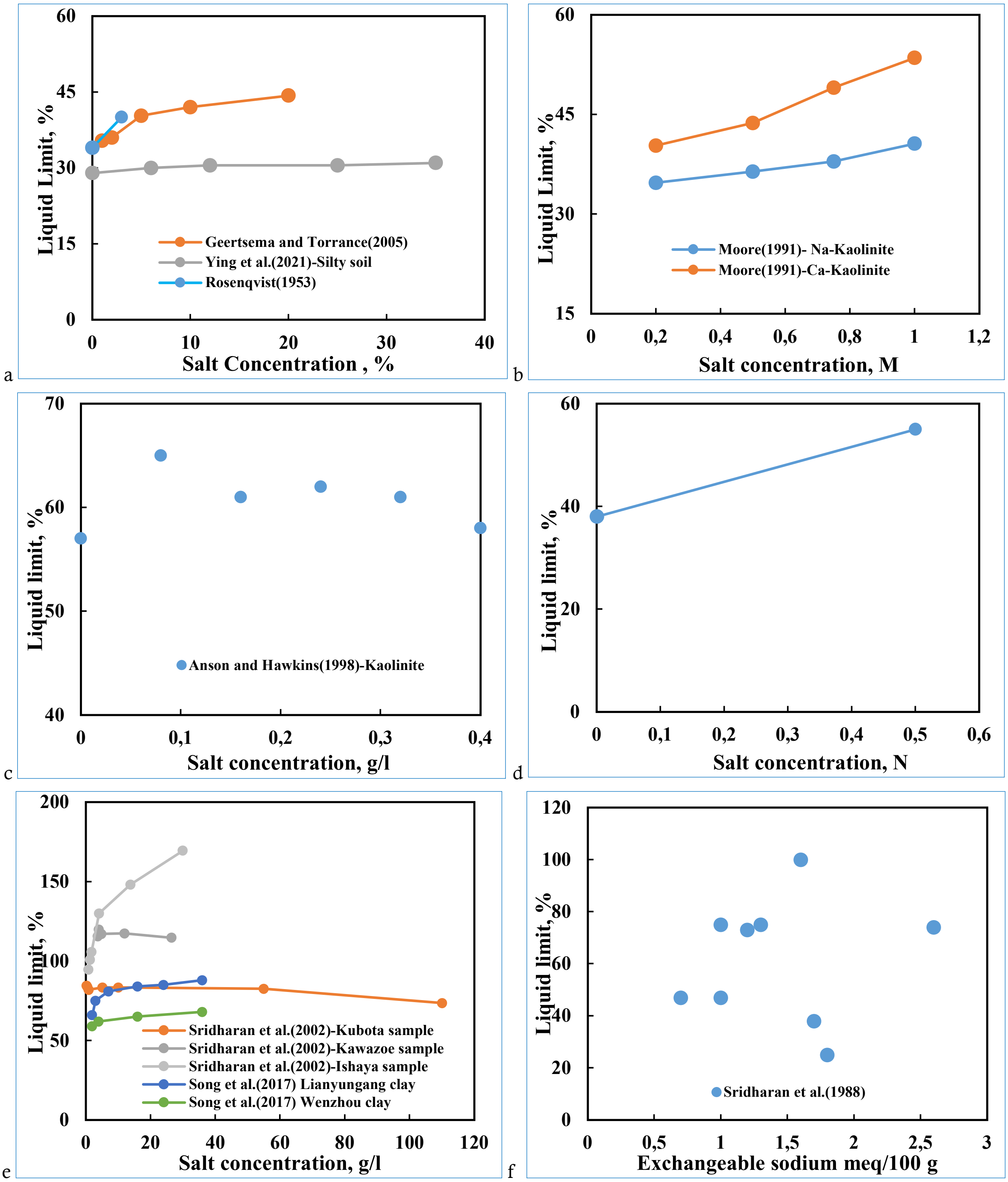

Fig. 4. Liquid limit variation of various non-expansive soils with pore fluid salinity

Table 2. Studies on the effect of pore water salinity on liquid limits

| No. | References | Soil | Minerals | Salt type | Remark |
|---|---|---|---|---|---|
| 1 | Rosenqvist (1953) | Aserumvannet | Illite rich | NaCl | Fig 4(a) |
| 2 | Bjerrum & Rosenqvist (1956) | Asrum clay | Illite-60%, others-quartz and feldspar | KCl | |
| 3 | Olson & Mitronovas(1962) | Illite | mixed-layer material | MgCl2&CaCl2 | |
| 4 | Ohtsubo et al. (1982) | Yamaashi soil | Smectite rich | _ | Fig 6(a) |
| 5 | Sridharan et al. (1988) | Ten different clays | Kaolinite rich | _ | Fig 4(f) |
| 6 | Moore (1991) | Kaolinite | Kaolinite rich | NaCl&CaCl2 | Fig 4(b) |
| | | Montmorillonite | Montomorillonite rich | | Fig 4(b) |
| 7 | Rao et al.(1993) | Bentonite | Montomorillonite rich | CaCl2,MgCl2,NaCl &KCl | Fig 6(a) |
| 8 | Di Maio (1996) | Ponza Bentonite | Na-Montmorillonite rich | CaCl2,NaCl&KCl | Fig 5(e) |
| 9 | Gleason et al. (1997) | Group A bentonite | Smectite rich | CaCl2 | Fig 5(e) |
| 10 | Anson & Hawkins (1998) | Kaolinite | Kaolinite rich | CaCl2 | Fig 4(c) |
| | | Sodium Montmorillonite | Montomorillonite rich | | |
| 11 | Sridharan & Prakash (1999) | Bentonite | Montomorillonite rich | NaCl | Fig 5(d) |
| | | Black Cotton Soil | Montomorillonite rich | | Fig 5(d) |
| | | Kundara Clay | Kaolinite rich | | Fig 4(d) |
| 12 | Sridharan et al. (2002) | Kubota clay | Smectite-11.5%,Kaolinite-9.9%,Vermiculite-10.7%, Illite-18.9% | NaCl | Fig 4(e) |
| | | Kawazoe clay | Smectite-15.1%,Kaolinite-9.2%,Vermiculite-11.5%, Illite-22.3% | | Fig 4(e) |
| | | Isahaya clay | Smectite-12.8%,Kaolinite-12.8%,Vermiculite-14.7%, Illite-25.6% | | Fig 4(e) |
| 13 | Oren & Kaya(2003) | Canakkale clay | Montomorillonite-40-55%,illite-20-30%,kaolin-10-15%,quartz-2-3% | NaCl,CaCl2&AlCl3 | |
| 14 | Di Maio et al. (2004) | Ponza Bentonite | Na-smectite-70-80%, Kaolinite-20% | NaCl | Fig 5(e) |
| | | Commercial Kaolin | Kaolinite-75-80%,Illite-8-10%,Smectite<5% | | |
| | | Bisaccia clay | Kaolinite-10%, Illite-20%, Ca-smectite-30% | | Fig 5(e) |
| | | Marino clay | Kaolinite-30%,Illite-10%, Illite-smectite-10% | | |
| 15 | Tiwari et al. (2005) | Bentonite clay | Smectite- 94% | NaCl | Fig 5(a) |
| 16 | Geertsema & Torrance (2005) | Mink Creek | Chlorite-41%,Illite-37%,Kaolinite-22% | NaCl | Fig 4(a) |
| 17 | Mansour et al.(2008) | Lisan Marl | Kaolinite rich | Dead sea brine-CaCl2,MgCl2,NaCl &KCl | |
| 18 | Yukselen-Aksoy et al. (2008) | Ten different clays | Illite rich, Montmorillonite rich, Mixed minerals | Aegean seawater | |
| 19 | Horpibulsuk et al. (2011) | Kaolinite | Kaolinite rich | Nacl & $CaCl_2$ | |
| | | Bentonite | Montomorillonite rich | | |
| | | Bangkok clay | _ | | |
| 20 | Dutta & Mishra (2015) | Bentonite-A | Clay - 57% & Silt - 43% | Nacl & CaCl2 | Fig 5(d) |
| | | Bentonite-B | Clay - 68% & Silt - 32% | | Fig 5(d) |
| 21 | Song et al. (2017) | Wenzhou clay | Illite-68%,Chlorite-11%,Kaolinite-8%,Smectite-13% | _ | Fig 4(e) |
| | | Lianyungang clay | Illite-76%,Chlorite-11%,Kaolinite-13%,Smectite-0 | | Fig 4(e) |
| 22 | Ying et al. (2021) | MX80 Na-bentonite | Smectite-92%,Quartz-3% | NaCl | Fig 5(c) |
| | | Silty soil | Illite-10.8%,Chlorite-3.6%,Kaolinite-1.3%,non-clay minerals-84.3% | | Fig 4(a) |

In 1999, Sridharan and Prakash (1999) conducted an experiment in which they observed the liquid limits of bentonite and Black cotton soil (both montmorillonite clays) using the percussion method and Kundara clay (kaolinitic clay) using the cone penetration method. Distilled water and 0.5N NaCl solution were used to treat all three clays. When treated with salt solution, the liquid limit of bentonite and black cotton soil increased, but the liquid limit of kundara clay decreased. The controlling mechanisms were explained in terms of double-layer thickness reduction for both montmorillonite clays and the flocculation of clay particles for kaolinitic clay (Fig. 5).

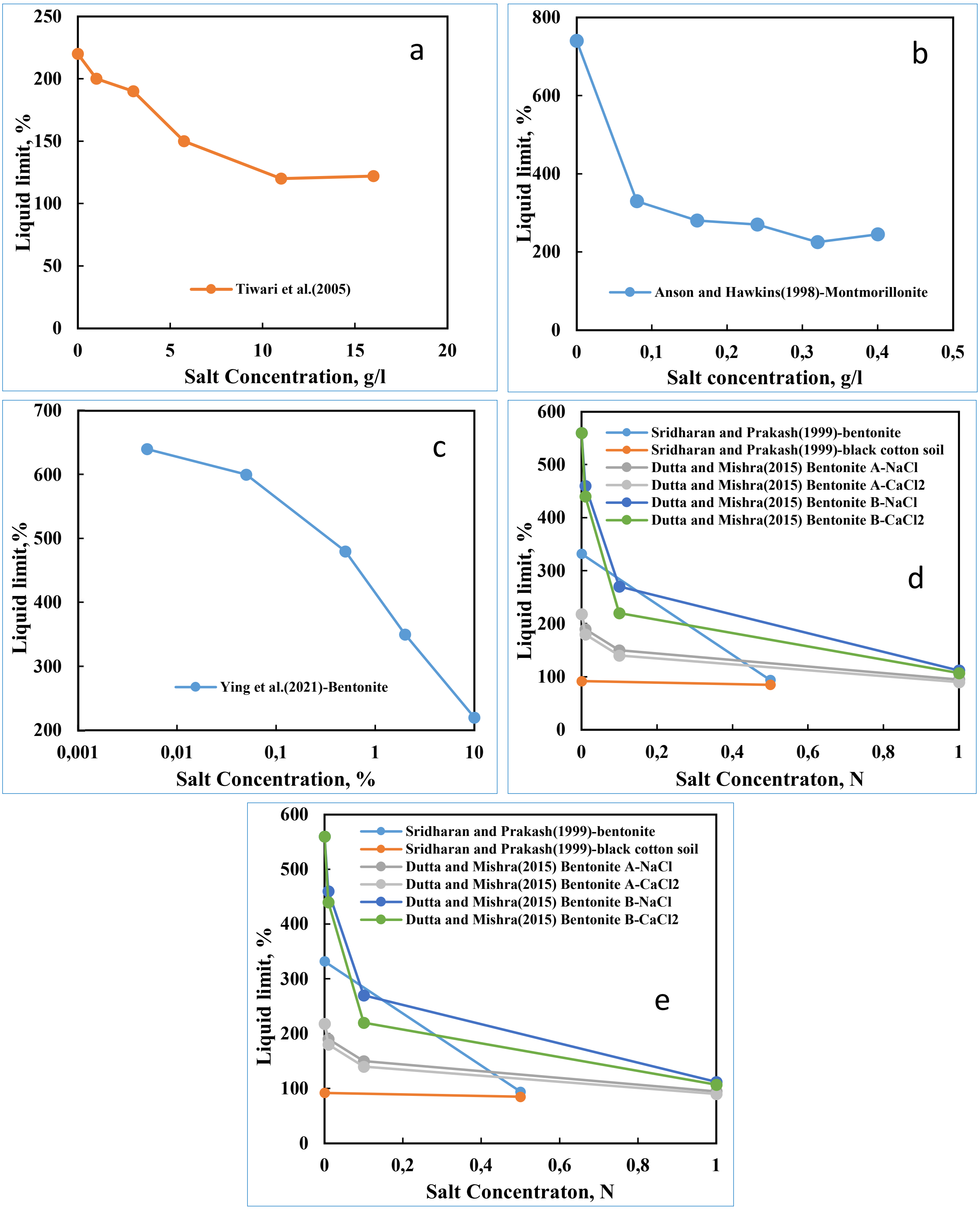

Fig. 5. Liquid limit variation of various expansive soils with pore fluid salinity

Sridharan et al. (2002) used both the percussion cup method and fall cone penetration method to investigate the effect of pore fluid salinity on the liquid and plastic limits of three clays: Kubota, Kawazoe, and Isahaya with initial salt concentrations of 0.45, 2.39, and 30.0 (g/L). The liquid limit of Kubota and Kawazoe Clays increased with increasing amounts of NaCl. Because the salinity of Isahaya clay was higher, leaching was done, and liquid limit values were determined after each leaching. The liquid limit of Isahaya clay decreased as salt concentration decreased due to leaching. This was due to particle flocculation or open fabric leading to an increase in the water holding capacity/liquid limit.

In 2003, Oren and Kaya (2003) used a clay sample from Turkey as the subject of an experimental investigation to investigate the liquid limit with a fall cone test apparatus. Deionized water was used for the tests after the sample had been homoionized by being treated with Na+, Ca++, and Al+++ ions. With an increase in cation valence, the homoionized soil's liquid limit increased. Despite having a large amount of montmorillonite, the sample's reported liquid limit behavior was against the diffuse double layer theory. This may be caused by the kaolin materials' propensity to control the behavior of the mixed mineral soil's liquid limit.

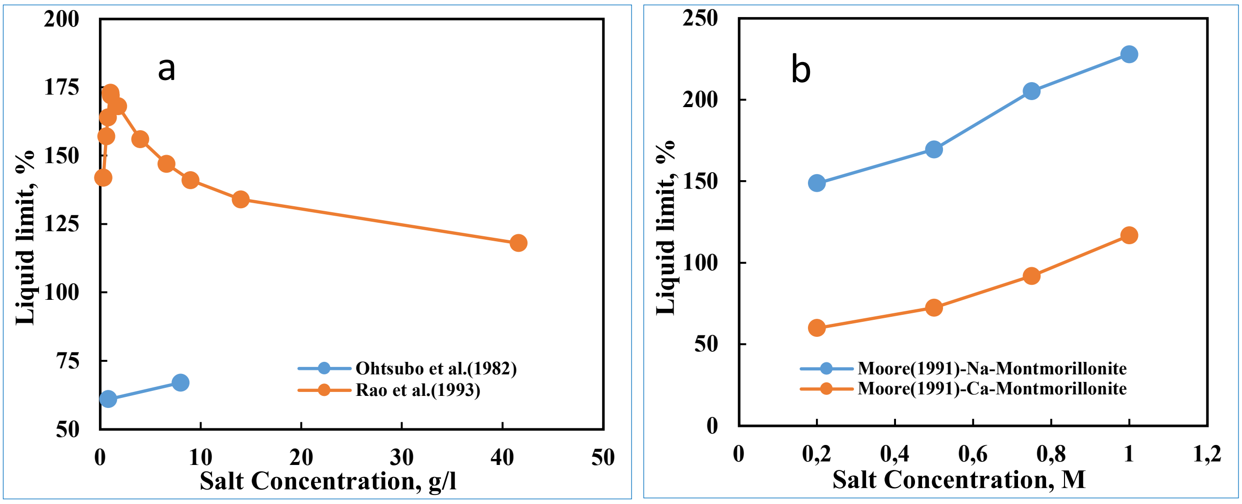

Fig. 6. Liquid limit variation of various expansive soils that contradict the diffuse double layer theory

Using the fall cone test, Di Maio et al. (2004) determined the liquid limit of various soils using NaCl solutions of varying concentrations. The liquid limit of Ponza bentonite decreased as the molarity of the NaCl solution increased and this observation agreed with diffuse double layer theory. Commercial kaolin, on the other hand, showed nearly constant values. The results of the other two clays, Bisaccia clay, and Marino clay, were also mentioned, where liquid limit values decreased with increasing molarity for both.

To explore the effect of NaCl concentration on the liquid limit of smectite-containing clays, bentonite was treated with pore fluid of various NaCl concentrations, and the consistency limits were measured (Tiwari et al.,2005). The liquid limit decreased exponentially as the NaCl concentration increased. This decrease in liquid limit with increasing pore fluid concentration could be attributed to the diffuse double layer theory.

Geertsema and Torrance (2005) studied the influence of various concentrations of sodium chloride (NaCl) on the liquid limit of Mink creek clay. On increasing the salinity percentage of NaCl, the liquid limit increased. This could be attributed to the particle flocculation leading to an increase in liquid limit with the increase in salt content.

Mansour et al. (2008) studied the consistency limits of kaolinite-rich soils from Lisan Marl cliff, Dead Sea, Jordan by BS standard. Tests were done using both distilled water and dead sea brine. A decrease in liquid limit was observed when treated with brine than distilled water. This was the result of salts replacing the water in the double layer, which reduced its thickness and water content.

Yukselen-Aksoy et al. (2008) compared the liquid limit and plastic limit values of ten different clays from different parts of Turkey when treated with distilled water and seawater. The study's findings revealed that the seawater effect becomes significant when the liquid limit with distilled water exceeds 110 percent.

Horpibulsuk et al. (2011) conducted an experimental study on the liquid limit of three soils: kaolin, bentonite, and Bangkok clay. The liquid limit of Na-kaolin and Ca-kaolin increased as the molarity of NaCl and $CaCl_2$ increased respectively. The increase in ion concentration coagulated kaolinite particles, increasing shear resistance and liquid limit. Bentonite's liquid limit, on the other hand, decreased as the salt concentration increased. This decrease is caused by the diffuse double layer shrinking. The liquid limit of Na-Bangkok clay and Ca-Bangkok clay increased with increasing molar concentrations of NaCl and $CaCl_2$, respectively.

Dutta and Mishra (2015) investigated the impact of sodium chloride (NaCl) and calcium chloride ($CaCl_2$) solutions on the Atterberg limits of Bentonite-A and Bentonite-B. According to the data, the liquid limits of both bentonites decreased as the salt content increased. The liquid limit of Bentonite-A, which had a lower CEC, fell from 218.0 percent with DI water to 94.9 percent and 90.0 percent, respectively, with solutions containing solutions of 1 N concentrations of

NaCl and $CaCl_2$. Comparatively, the liquid limit of Bentonite-B, which had a greater CEC, dropped from 560.0 percent with DI water to 112 percent and 107.0 percent, respectively, with 1 N concentrations of sodium chloride and calcium chloride solution. The liquid limit is reduced because the inter-particle repulsion is reduced with an increase in salt concentration, allowing particles to move freely at lower water contents or closer spacing.

Song et al. (2017) investigated Wenzhou clay and Lianyungang clay, two illite-rich coastal clays. For both clays, the liquid limit was reduced as the salinity of the pore fluid increased. This decrease from salt leaching was brought on by the illite-rich clays' increased interparticle repulsive interactions.

Ying et al. (2021) examined the influence of sodium chloride solution of various concentrations on commercial MX80 Na-bentonite and silty soil by using the cone penetration method. Compared to the result obtained with deionized water, the liquid limit for the sample prepared with 0.005 percent NaCl solution increased slightly, from 630 to 652%. The liquid limit was then reduced as the water's salinity increased further, from 0.005 to 10%. This phenomenon was found in other expansive soils as well, and it was explained by a decrease in diffuse double layer brought on by an increase in salt concentration.

## Discussion

This section includes the discussion on the mechanism controlling the liquid limits of soils under the effect of pore water salinity.

Other factors remaining constant, the electrical attractive forces vary inversely with the dielectric constant of the pore fluid medium, and the repulsive forces vary directly with the dielectric constant (Sridharan, 1968; Sridharan and Rao, 1973). The shearing resistance of particles increases as the attractive force increases, and vice versa. As a result, as the dielectric constant decreases, the attractive force increases and the repulsive force decreases, increasing shearing resistance (Sridharan and Rao, 1973).

In the case of non-expansive clays such as Koilinite or Illite, the increase in pore fluid salinity or decrease in dielectric constant resulted in a reduction in repulsive force and an increase in attractive force among the clay particles, increasing not only shearing resistance but also the extent of particle flocculation (Warkentin and Yong, 1962; Sridharan and Rao, 1975; Yong and Warkentin, 1966, 1975; Anson and Hawkins, 1998; Sridharan and Prakash, 1999; Sridharan et al., 1986; Sridharan et al., 1988; Sridharan et al., 2002; Horpibulsuk et al., 2011). This will increase the water holding capacity in a more flocculated structure. As a result, the liquid limit will eventually be increased. In determining the liquid limit of kaolinitic soils, interparticle interactions play a significant effect. The particle arrangement is controlled by the forces of attraction and repulsion between the particles, which in turn controls the liquid limit values. The diffuse double layer cannot be used to examine the behavior of non-swelling clays and can only be used to study the behavior of expansive montmorillonites (Sridharan, 1991).

Sridharan et al. (1988) explained the influence of different cations and pH values on the flocculation behavior of Kaolinite clay where, positive edge-negative face flocculation was encouraged by the presence of divalent and trivalent cations and a low soil pH, whereas monovalent sodium ions and a high soil pH prevented particle flocculation. The dispersion of clay particles in the salt solution also accounted for the rise in the liquid limit of non-swelling clays with pore fluid salinity (Arasan and Yetimoglu, 2008). The emergence of new expanding compounds was another explanation for this increase (Sivapullaiah and Manju, 2005). However, this increase in the liquid limit of non-expansive clays with pore fluid salinity was explained by the occurrence of nano-fissures brought on by minor shrinking of diffuse double layer, which required the use of more water to fill them (Ying et al., 2021).

In case of expansive clays, such as smectite/montmorillonite, the diffuse double layer water plays a significant role in controlling the liquid limit of soils (Yong and Warkentin, 1975; Sridharan et al., 1986; Sridharan et al., 2002). An increase in salt concentration reduces the surface potential, which leads to a decrease in the diffuse double layer thickness (Mitchell and Soga, 2005). So, the inter-particle repulsive forces decrease, which makes the particles stay with each other at a low inter-particle distance, and the liquid limit decrease (Warkentin, 1961; Sridharan and Rao, 1975). With any increase in salt concentrations or decrease in dielectric constant in the pore fluid, the thickness of the diffuse double layer decreases which leads to a decrease in the liquid limit of expansive clays (Sridharan and Jayadeva, 1982; Yong et al., 1992; Mitchell, 1993; Rao et al., 1993; Di Maio, 1996; Sridharan et al., 2002; Yukselen-Aksoy et al., 2008; Ying et al., 2021). The decrease in liquid limit values of bentonite on decreasing pore fluid salinity was attributed to the function of particle arrangement of bentonite which was governed by the role of cations (Rao et al., 1993). A similar decreasing observation in liquid limit with a decrease in salt concentration on smectite-rich soil was explained due to the low-swelling characteristics of the smectite (Egashira and Ohtsubo, 1982; Ohtsubo et al., 1982).

## Conclusions

Based on the extensive review of the various studies regarding the effect of pore water salinity on the Atterberg limits of soils, the following conclusions can be stated:

The potential effect of climate change (soil salinization) on the liquid limits of soil has been identified.

The major factors that alter the liquid limits of soil under the influence of salt concentration are identified to be the mineralogical composition, inter-particle force, and clay content.

For the non-expansive soils, the change in liquid limit values with pore water salinity can be better explained in terms of particle flocculation or clay fabrics.

For expansive soils, the change in liquid limit values with pore water salinity can be better explained in terms of diffuse double layer theory.

Although much research has been conducted, the explanation of the mechanism controlling the Liquid limit values of mixed clay minerals in the presence of salinity is still very limited. A possible reason is the lack of study on these types of soils.

## Conflict of Interest

The author has no conflict of interest to declare.

## References

American Society for Testing Materials, 1958. Procedures for Testing Soils, April, 544 pp.

Anon, 1965. Glossary of soil science terms. Soil Science Society of America: Madison, WIS.

Anson, R.W.W., Hawkins, A.B., 1998. The effect of calcium ions in pore water on the residual shear strength of kaolinite and sodium montmorillonite. Geotechnique 48(6): 787-800.

Arasan, S., and Yetimoglu, T., 2008. Effect of inorganic salt solutions on the consistency limits of two clays. Turkish Journal of Engineering and Environmental Sciences 32 (2), 107-115.

Bjerrum, L., Rosenqvist, I.T., 1956. Some experiments with artificially sedimented clays. Geotechnique 6 (3), 124-136.

COMISSION, O.C., 2021. Title 165: Corporation Commission Chapter 10: Oil and Gas Conservation.

Di Maio, C., 1996. Exposure of bentonite to salt solution: osmotic and mechanical effects. Geotechnique 46 (4), 695-707.

Di Maio, C., Santoli, L., Schiavone, P., 2004. Volume change behaviour of clays: the influence of mineral composition, pore fluid composition and stress state. Mechanics of Materials 36 (5-6), 435-451.

Dutta, J., Mishra, A.K., 2015. A study on the influence of inorganic salts on the behaviour of compacted bentonites. Applied Clay Science 116, 85-92. https://doi.org/10.1016/j.clay.2015.08.018.

Egashira, K., Ohtsubo, M., 1981. Low-swelling smectite in a recent marine mud of Ariake Bay. Soil Science and Plant Nutrition 27 (2), 205-211. https://doi.org/10.1080/00380768.1981.10431272.

Egashira, K., Ohtsubo, M., 1982. Smectitw in marine quick-clays of Japan. Clays and Clay Minerals 30, 275-280.

Franklin W.T. Schmehl. W.R. 1973. Physical, Salinity and Fertility Analysis of Selected Soils. Water Management Technical Report No. 28, Colorado State University, Fort Collins, CO.

Geertsema, M., Torrance, J.K., 2005. Quick clay from the Mink Creek landslide near Terrace, British Columbia: geotechnical properties, mineralogy, and geochemistry. Canadian Geotechnical Journal 42 (3), 907-918.

Ghafoor, A., Muhammed, S., Ahmad, N., Mian, M.A., 1988. Indices for the estimation of ESP from SAR of soil solution. Pakistan Journal of Sciences 39-40 89-98.

Ghimire, U., Bheemasetti, T. V., Kozak, P., Kunza, L., 2023. Geochemical Properties and Atterberg Limits of Low Saline Sand-Clay Mixtures. In Geo-Congress 2023, pp. 405-414.

Gleason, M.H., Daniel, D.E., Eykholt, G.R., 1997. Calcium and sodium bentonite for hydraulic containment applications. Journal of Geotechnical and Geoenvironmental Engineering 123 (5), 438-445.

Gupta, R.K., Abrol I.P., 1990. Salt affected soils: their reclamation and management for crop production. Advances in Soil Science 11, 224-882.

Horpibulsuk, S., Yangsukkaseam, N., Chinkulkijniwat, A., Du Y.J., 2011. Compressibility and permeability of Bangkok clay compared with kaolinite and bentonite. Applied Clay Sciences 52 (1-2), 150-159.

Kelley, W.P., 1951. Alkali Soils: Their Formation, Properties, and Reclamation (Reinhold Publishing Corporation: New York, N.Y.)

Kim, Y.T., Do, T.H., 2011. Experimental evaluation of leaching effects on the compressibility of marine clay and its strain rate dependency. Marine Georesources and Geotechnology 29 (1), 16-29.

Lambe, T.W., 1953. The structure o f inorganic soil. Proceedings of the American Society of Civil Engineers 79, 1-49.

Locat, J., Lefebvre, G., 1985. The compressibility and sensitivity of an artificially sedimented clay soil. The Grande-Baleine Marine Clay, Québec, Canada. Marine Georesources & Geotechnology 6, 1-28.

Mansour, Z.M., Taha, M.R., Chik, Z., 2008. Fresh-brine water effect on the basic engineering properties of Lisan Marl-Dead Sea-Jordan. Journal of Applied Sciences 8 (20), 3603-3611. https://doi.org/10.3923/jas.2008.3603.3611.

Mishra, A.K., Ohtsubo, M., Li, L., Higashi, T., 2005. Effect of salt concentrations on the permeability and compressibility of soil-bentonite mixtures. Journal of the Faculty of Agriculture Kyushu University 50 (2), 837-849. https://doi.org/10.5109/4692.

Mishra, A.K., Ohtsubo, M., Li., L.Y., Higashi, T., Park, J., 2009. Effect of salt of various concentrations on liquid limit, and hydraulic conductivity of different soil-bentonite mixtures. Environmental Geology 57, 1145-1153 (2009). https://doi.org/10.1007/s00254-008-1411-0.

Mitchell, J.K., 1956. On the Fabric of Natural Clays. Proceedings of H.R.B. 35.

Mitchell ,J.K., 1993. Fundamentals of soil behavior. 2nd ed. John Wiley & Sons, Inc. New York.

Mitchell, J.K., Soga, K., 2005. Fundamentals of soil behaviour. 3rd edn. John Wiley Hoboken

Moore, R., 1991. The chemical and mineralogical controls upon the residual strength of pure and natural clays. Geotechnique 41 (1), 35-47. https://doi.org/10.1680/geot.1991.41.1.35.

Northcote, K.H., Sltene, J.K.M., 1972. Australian soils with saline and sodic properties. CSIRO Aust. Soil Publication 27.

Ogata, N., Yasuda, M., Kataoka, T., 1983. Effects of salt concentration on strength and creep behavior of artificially frozen soils. Cold Regions Science and Technology 8 (2), 13,9-53. https://doi.org/10.1016/0165-232X(83)90005-8.

Ohtsubo, M., Takayama, M., Egashira, K., 1982. Marine quick clays from Ariake Bay area, Japan. Soils and Foundations 22 (4), 71-80. https://doi.org/10.3208/sandf1972.22.4_7.

Olson, R.E., Mitronovas, F., 1962. Shear strength and consolidation characteristics of calcium and magnesium illite. Clays and Clay Minerals 9, 185-209. https://doi.org/10.1346/CCMN.1960.0090110.

Ören, A.H., Kaya, A., 2003. Some engineering aspects of homoionized mixed clay minerals. Environmental Monitoring and Assessment 84 (1-2), 85-98. https://doi.org/10.1023/a:1022839215231.

Pitman, M.G., Lauchli, A., 2002. Global impact of salinity and agricultural ecosystems. Salinity: Environment - Plants - Molecules pp. 3-20. https://doi.org/10.1007/0-306-48155-3_1.

Pupisky, H., Shainberg, I., 1979. Salt effects on the hydraulic conductivity of a sandy soil. Soil Science Society of America Journal 43 (3), 429-433.

Rao, S.M., Sridharan, A., Chandrakaran, S., 1993. Consistency limits behavior of bentonites exposed to sea water. Marine Georesources & Geotechnology 11 (3), 213-227.

Rosenqvist, I.T., 1953. Considerations on the sensitivity of Norwegian quick-clays. Geotechnique 3 (5), 195-200.

Rosenqvist, I.T., 1955. Investigations in the clay-electrolyte-water system. Norwegian Geotechnical Institute.

Song, M.M., Zeng, L.L., Hong, Z.S., 2017. Pore fluid salinity effects on physicochemical-compressive behaviour of reconstituted marine clays. Applied Clay Science 146, 270-277. https://doi.org/10.1016/j.clay.2017.06.015.

Sridharan, A., 1968. Some Studies on the Strength of Partly Saturated Clays. Ph. D. Thesis, Purdue University, Lafayette, Indiana.

Sridharan, A., Rao, G.V., 1973. Mechamisms Controlling the volume Change Behaviour of Saturated clays and the Role of the Effective Stress Concept. Geotechnique 23, 359-382.

Sridharan, A., Rao, G.V., 1975. Mechanisms controlling the liquid limit of clays. In Proceedings of the Istanbul Conference on Soil Mechanics and Foundation Engineering Vol. 1, 65-74.

Sridharan, A.S., Rao, M., Murthy, N.S., 1986. Liquid limit of montmorillonitic soils. American Society for Testing and Materials, Geotechnical Testing Journal 9, 156-159.

Sridharan, A., Rao, S.M., Murthy, N.S., 1988. Liquid limit of kaolinitic soils. Géotechnique 38 (2), 191-198.

Sridharan, A., Prakash, K., 1999. Mechanisms controlling the undrained shear strength behaviour of clays. Canadian Geotechnical Journal 36 (6), 1030-1038. https://doi.org/10.1139/t99-07.

Sridharan, A., Prakash, K., 2000. Percussion and cone methods of determining the liquid limit of soils: controlling mechanisms. Geotechnical Testing Journal 23 (2), 236-244.

Sridharan, A., El-Shafei, A., Miura, N., 2002. Mechanisms controlling the undrained strength behavior of remolded Ariake marine clays. Marine Georesources and Geotechnology 20 (1), 21-50.

Suarez, D.L., 2001. Sodic soil reclamation: Modelling and field study. Australian Journal of Soil Research 39, 1225-1246.

Sumner, M.E., Rengasamy, P., Naidu, R., 1998. Sodic soils: A reappraisal. In Sodic Soil: Distribution, Management and Environmental Consequences, pp. 3-17.

Tanji, K.K., 1990. Nature and extent of agricultural salinity. In Agricultural Salinity Assessment and Management, Manuals and Reports on Engineering Practices No. 71, pp. 1-17.

Tiwari, B., Tuladhar, G.R, Marui ,H., 2005. Variation in residual shear strength of the so.il with the salinity of pore fluid. Journal of Geotechnical and Geoenvironmental Engineering 131 (12), 1445-1456.

Tiwari, B., Ajmera, B., 2014. Effects of saline fluid on compressibility of clay minerals. Environmental Geotechnics 1(2), 108-120.

Warkentin, B.P., 1961. Interpretation of the upper plastic limit of clays. Nature 190, 287-288.

Warkentin, B.P., Yong, R.N., 1962. Shear strength of montmorillonite and kaolinite related to interparticle forces. Clays and Clay Minerals, Proceedings of the Ninth National Conference on Clays and Clay Minerals 1962, 210-218.

Yong, R.N., Warkentin, B.P., 1966. Introduction to soil behavior. New York: Macmillan.

Yong, R.N., Warkentin, B.P., 1975. Soil Properties and Behavior. New York: Elsevier.

Yong ,R.N., Mohamed, A.M.O., Warkentin, B.P., 1992. Principles of contaminant transport in soils. Elsevier, Amsterdam, pp. 327.

Ying Z., Cui Y.J., Duc M., Benahmed N., Bessaies-Bey H., Chen, B., 2021. Salinity effect on the liquid limit of soils. Acta Geotechnica 16 (4), 1101-1111 (2021). https://doi.org/10.1007/s11440-020-01092-7.

Yukselen-Aksoy, Y., Kaya, A., Ören, A.H., 2008. Seawater effect on consistency limits and compressibility characteristics of clays. Engineering Geology 102 (1-2), 54-61. https://doi.org/10.1016/j.enggeo.2008.07.005.