

**A STUDY ON THE EFFECT OF SALTS ON THE SWELLING,
HYDRAULIC AND CONSOLIDATION BEHAVIOUR OF
BENTONITES**

Thesis

submitted in partial fulfillment of the requirements

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DOCTOR OF PHILOSOPHY

by

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CERTIFICATE

This is to certify that the thesis entitled “**A Study On The Effect of Salts On The Swelling, Hydraulic And Consolidation Behaviour of Bentonites**” submitted by **Jagori Dutta**, Roll No. 11610406, to the Indian Institute of Technology, Guwahati, for the award of the degree of Doctor of Philosophy in Civil Engineering is a record of bonafide research work carried out by her under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard fulfilling the requirement for the degree of Doctor of Philosophy.

The results contained in this thesis have not been submitted in part or full to any other University or Institute for award of any degree or diploma.

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STATEMENT

I do hereby declare that the matter embodied in this thesis is the result of investigations carried out by me in the Department of Civil Engineering, Indian Institute of Technology Guwahati, Assam, India.

In keeping with the general practice of reporting scientific observations, due acknowledgements have been made wherever the work described is based on the findings of other investigators.

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ABSTRACT

Due to rapid urbanization and industrialization, the geoenvironment and groundwater reserves in most parts of the world are getting damaged due to the harmful effect of pollutants disposed off into the geoenvironment. An effective waste containment system is a very essential aspect of geoenvironmental engineering which contains the leachate generated from waste and prevents the ground water from being contaminated. Due to its high swelling capacity, contaminant adsorption capacity and low hydraulic conductivity, bentonite is primarily used as a liner material in waste containment. However, when bentonite comes in contact with leachate, its swelling property and consequently its hydraulic conductivity gets affected. The extent of the effect of leachate on behaviour of bentonite also varies from bentonite to bentonite depending upon its mineralogical composition.

This work was carried out to study the effect of inorganic salts and heavy metals present in leachates on the behaviour of bentonites. Two bentonites of different mineralogical composition were studied for their change in the index properties, free swelling, swelling potential, swelling pressure, hydraulic conductivity and consolidation parameters due to the presence of various inorganic salts and heavy metals of various concentrations, individually as well as combination of each other. In addition to this, this work has also studied the effect of initial compaction condition on the behavior of bentonite. The results showed that salt has a definite effect on the free swelling, swelling potential, swelling pressure, hydraulic conductivity of the compacted bentonite. The liquid limit, free swelling, swelling potential and swelling pressure of the bentonites decreased with an increase in the salt or heavy metal ion concentration. The reduction in these parameters with increase in the salt concentration is attributed to the decrease in the diffuse double layer thickness. Irrespective

of the initial compaction condition, the hydraulic conductivity of the bentonite increased with an increase in the salt concentrations. The compression index (C_c), coefficient of volume change (m_v), and time required for the 90% of consolidation (t_{90}) of the bentonites decreased; whereas, coefficient of consolidation (c_v) increased with the increase in salt concentration indicating specimens consolidated faster in salt solution in comparison to water. Irrespective of the salt solution present in pore water, c_v was found to be decreased whereas t_{90} increased with increase in the consolidation pressure.

A comparison between the two bentonites showed that salt has a significant effect on Bentonite-B. Bentonite-B, which has a high liquid limit, swelling capacity, SSA, CEC and ESP and termed as high quality bentonite, undergoes a large change in liquid limit, free swelling, swelling pressure and hydraulic conductivity due to increase in the salt concentration. This study concludes that the effect of the salt on the properties of the bentonites depends on the salt type, salt concentration and initial compaction condition of the bentonite. Similarly, mineralogical composition of bentonite also plays an important role in defining the behaviour of bentonite in the presence of salt solution.

Keywords: *Bentonite; salt solutions; heavy metals; consolidation; diffuse double layer; swelling potential; swelling pressure; hydraulic conductivity; compressibility.*

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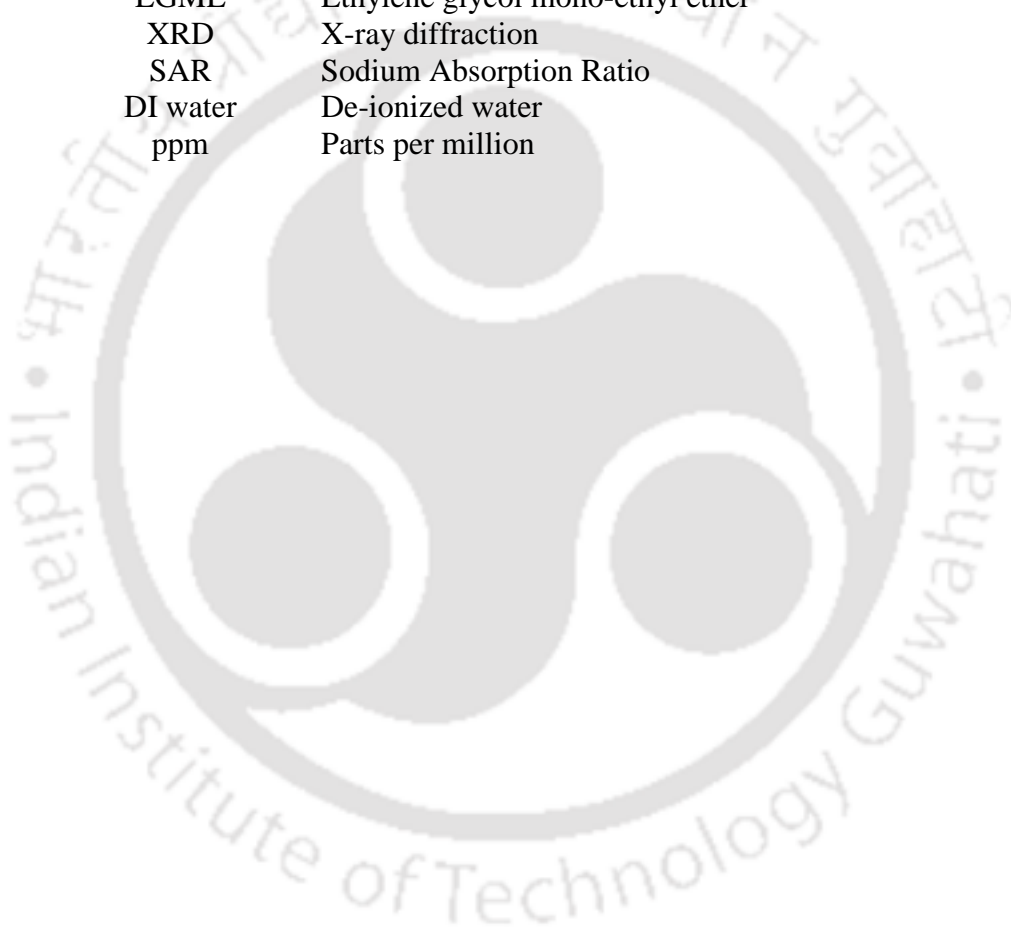
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ABBREVIATIONS

MSW	Municipal Solid Waste
DDL	Diffuse Double Layer
SSA	Specific Surface Area
CEC	Cation Exchange Capacity
ESP	Exchangeable Sodium Percentage
GCL	Geosynthetic Clay Liner
OMC	Optimum Moisture Content
MDD	Maximum Dry Density
ASTM	American Society for Testing and Materials
EGME	Ethylene glycol mono-ethyl ether
XRD	X-ray diffraction
SAR	Sodium Absorption Ratio
DI water	De-ionized water
ppm	Parts per million



Symbols Used

k	Hydraulic conductivity
γ_d	Dry density
m_v	Coefficient of volume change
c_v	Coefficient of consolidation
t_{90}	Time for 90% of consolidation
C_c	Compression index
ΔP	Change in pressure
Δe	Change in void ratio
T_v	Time factor
γ_w	Unit weight of the pore fluid
k_{salt}	Hydraulic conductivity in presence of salt solution
k_{water}	Hydraulic conductivity in presence of DI water
G	Specific gravity of soil solid particles
S	Specific surface area of soil
d	Half distance between the parallel clay plates
n	Molar concentration of ions in pore fluid
k	Boltzmann's constant ($=1.38 \times 10^{-23}$ J/K)
T	Temperature in Kelvin
u	Non-dimensional mid-plane potential function
z	Non-dimensional plane potential at clay surface
B	Base exchange capacity of the clay
v	Valency of exchangeable cation
ξ	Distance function
ϵ	Dielectric constant of the pore fluid
e'	Elementary electric charge ($= 4.8 \times 10^{-10}$ esu)
N	Normality

CHAPTER 1

INTRODUCTION

1.1. GENERAL

With rapid increase in the population and standard of living the total amount of municipal solid waste (MSW) that has been generated has increased by many folds and become one of the serious environmental issue in both developed and developing countries (Beede and Bloom, 1995; Suocheng et al., 2001). Landfill is one of the most widely employed methods for the disposal of these MSW (Rowe et al., 1995; Qian et al., 2002). However, these wastes undergo physico-chemical and biological changes with time and produce leachates which are toxic in nature (Kjeldsen et al., 2002). When these leachates mix with the percolating rain water, it moves towards the groundwater and contaminates it. In order to prevent the groundwater from being contaminated from these leachates, a very low permeable clay liner is provided at the bottom of the landfill which acts as a barrier between leachate and ground water (Daniel, 1984).

Due to its high swelling capacity and low hydraulic conductivity, bentonite is widely used as a liner material (Daniel, 1984). Bentonite is a naturally available very highly plastic swelling clay material produced by deposition and alteration of volcanic ash (Mitchell and Soga, 2005). The swelling capacity of bentonite, which in turn controls its hydraulic conductivity, depends upon the various physico-chemical and mineralogical factors. Bentonite primarily consists of a mineral called montmorillonite (Mitchell and Soga, 2005) and when it interacts with water, it forms diffuse double layer resulting in the swelling of bentonite (Norrish, 1954; Norrish and Quirk 1954; Madsen and Vonmoos, 1989). As the bentonite swells it fills the pore spaces present between the solid particles in a soil matrix and provide a lower value of hydraulic conductivity (Howell and Shackelford, 1997;

Komine, 2008). However, chemicals present in the leachate suppress the thickness of diffuse double layer which in turn shrinks the swollen bentonite (Norrish and Quirk, 1954). As the bentonite shrink, the flow path becomes open and the hydraulic conductivity increases (Quirk and Schofield, 1955; Madsen and Mitchell, 1989). Hence, in order to design a clay liner it is quite essential to study the behaviour of bentonite in the presence of various chemicals present in the leachate.

Many studies have been carried out in the past to investigate the effect of chemicals on the different behaviour of bentonite (Mesri and Olson, 1971; Shackelford et al., 2000; Li and Li, 2001; Li, 2003; Ouhadi et al., 2006; Nakano et al., 2008; Thammathiwat and Chimoye, 2010; Shirazi et al., 2011). In addition to the salt solution, a change in the mineralogical composition such as montmorillonite content, cation exchange capacity, specific surface area, exchangeable sodium percentage of the bentonite also significantly influences its swelling and consequently the hydraulic conductivity (Lee and Shackelford, 2005; Mishra et al., 2009). Since bentonite is a naturally occurring material, these mineralogical properties may vary to a great extent depending upon the source of its origin.

Similar to the hydraulic conductivity, compressibility is one of the most important properties which help in evaluating the settlement of the liner material due to the overburden weight of waste at the waste disposal site (Mishra et al., 2010). Due to their importance on the compressibility behaviour, various consolidation parameters such as compression index (C_c), coefficient of volume change (m_v), coefficient of consolidation (c_v) and time to complete 90% of the consolidation (t_{90}) has attracted much attention among the researchers. Since the factors such as clay mineralogy, type of the exchangeable cations and pore water chemistry influences the thickness of the diffuse double layer (Bolt 1956; Olson and Mesri, 1970; Sridharan and Rao, 1973; Sridharan and Jayadeva, 1982;

Mitchell and Soga, 2005), these same factors may also produce a significance influence on C_c , m_v , c_v , and t_{90} of bentonite (Robinson and Allam, 1998).

Very few of the past studies have focused on the effect of the salt solution and mineralogical parameters on the swelling and consequently on the hydraulic conductivity and compressibility behaviour of bentonite together; where, most of the previous studies mostly focused only on the study of the hydraulic conductivity of bentonite (Quirk and Schofield, 1955; Lee and Shackelford, 2005) or soil-bentonite mixtures (Mishra et al., 2009).

Hence, the main purpose of this study was to investigate the effect of mineralogical and salt solutions of various concentrations on the swelling, hydraulic conductivity and consolidation behaviour of bentonite. Bentonites were studied for their change in the index properties, swelling, swelling potential, swelling pressure, hydraulic conductivity and consolidation parameters due to the presence of different inorganic salts and heavy metals of various concentrations, individually as well as combination of each other.

1.2. ORGANIZATION OF THE THESIS

Chapter 1 presents the introduction to the problem and the importance of its outcome.

Chapter 2 deals with the background study and comprehensive literature review on bentonite used in liners and their interaction with various chemicals present in leachates.

Objectives of the study and its significance are also presented in this chapter.

Chapter 3 provides the materials and experimental procedures used in performing the study.

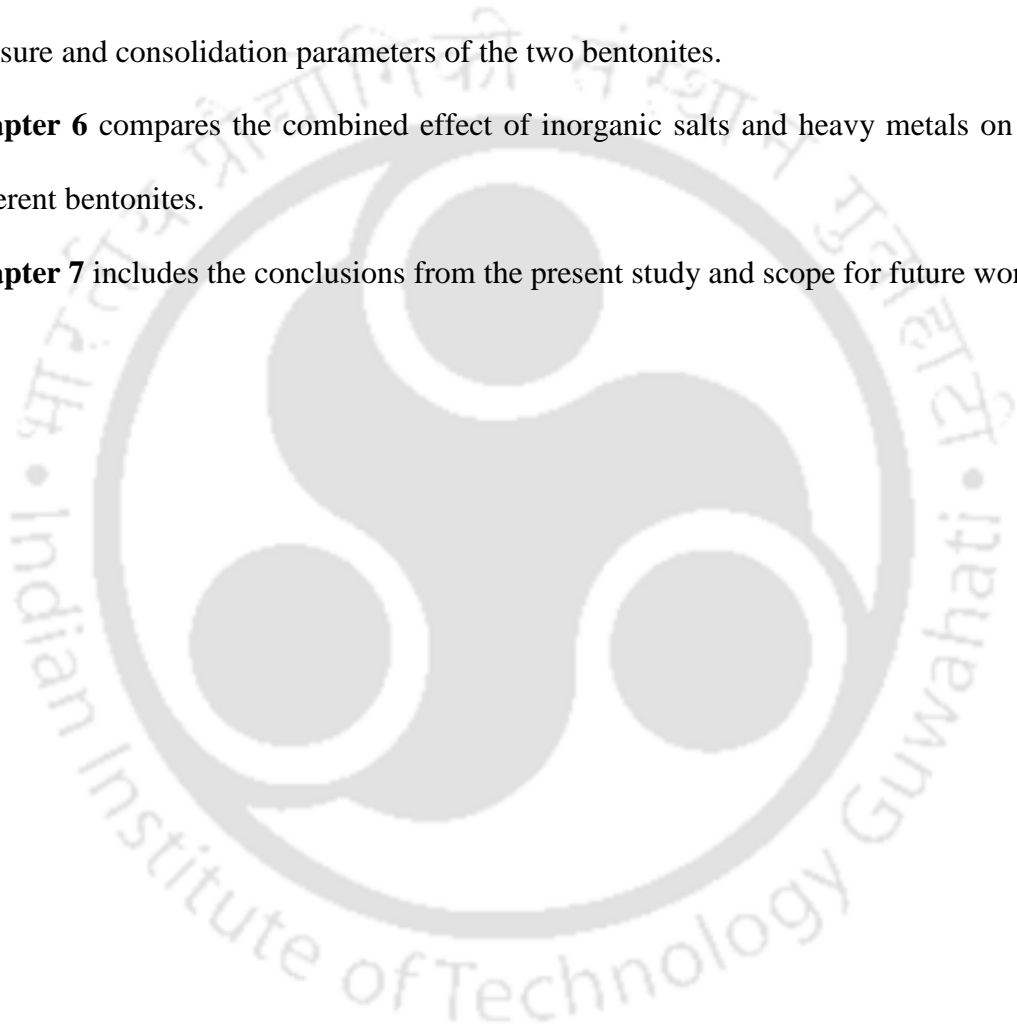
Chapter 4 deals with the study to investigate the effect of inorganic salts of NaCl and CaCl₂ of varying concentrations on the free swelling, Atterberg limits, hydraulic conductivity, swelling potential, swelling pressure and various consolidation parameters

such as compression index (C_c), coefficient of volume change (m_v), coefficient of consolidation (c_v) and time to complete 90% of the consolidation (t_{90}) of two bentonites of different mineralogical composition and swelling capacity and compacted at two different initial compaction conditions.

Chapter 5 investigates the effect of heavy metals (Zn^{2+} , Pb^{2+} and Cu^{2+}) present in leachate on the free swelling, Atterberg limits, hydraulic conductivity, swelling potential, swelling pressure and consolidation parameters of the two bentonites.

Chapter 6 compares the combined effect of inorganic salts and heavy metals on the two different bentonites.

Chapter 7 includes the conclusions from the present study and scope for future work.



BACKGROUND AND LITERATURE REVIEW

2.1. GENERAL

Compacted clay liners are generally provided as a barrier between the leachates generated from the waste and the groundwater. Due to its higher swelling capacity, low hydraulic conductivity and contaminant adsorption ability, bentonite is used as a barrier material at the waste disposal site as a means of controlling migration of contaminated leachate into the surrounding environment (Daniel, 1984). The higher swelling capacity and consequently the lower hydraulic conductivity of bentonite have been attributed to its ability to form the diffuse double layer with water (Norrish and Quirk, 1954; Olson and Mesri, 1970). However, the contaminants present in the leachate suppress the thickness of the diffuse double layer; which in turn, shrinks the bentonite resulting in a reduction in the swelling capacity (Norrish and Quirk, 1954) and an increase in the hydraulic conductivity (Olson and Mesri, 1970).

Hence, in order to design a clay liner it is quite essential to study the behaviour of bentonite in the presence of various chemicals present in the leachate. This chapter deals with a background study and comprehensive literature review on bentonite and their interaction with the chemicals present in leachates.

2.2. PRESENT SITUATION OF WASTE MANAGEMENT AND DISPOSAL

Due to increase in the urbanization and industrialization, huge amount of wastes are being generated which is polluting the geo-environment and ground water. The quantities of wastes produced by the developed and developing countries of the world are increasing due to an increase in the affluence and improved standard of living. The rise in the quantum of waste

generated in the cities has emerged as a major concern over the past years. Landfilling has been the most widely accepted method of solid waste disposal in the various countries around the world. Implementation of waste reduction, recycling, and transformation technologies has decreased landfill burdens, but landfills remain an important component of an integrated solid waste management strategy. Landfill liners protect the surrounding environment including soil, surface water and ground water against contamination.

The waste can be broadly classified into two types as the municipal solid waste (MSW) and industrial waste. The industrial wastes are, burnt residue, sewage, waste oils, waste acid, waste alkali, waste plastics, waste paper, wood waste, waste textile, animal and plant residues, animal solid deadwood, waste rubber, waste metal, glass waste, concrete waste and pottery waste, slag, debris, animal feces and urine, dead animal, ash dust, and wastes treated to treat above nineteen kinds of industrial waste.

MSW indicates wastes other than industrial waste, are generated mainly from a home besides human waste and also includes the wastes from business activities generated from the offices and restaurants. The waste having possibility of inflicting damage on human health or life environment such as being explosive, toxic and infectious among these wastes are classified with “specially controlled MSW” or “specially controlled industrial wastes” and they are strictly controlled in all processes from collection to disposal.

The total amount of waste generated annually worldwide is more than 4 billion tons. Global urban MSW production, which has nearly doubled in the last 10 years, is projected to double again in the next 15 years, increasing from 1.3 billion tons a year in 2010 to 2.2 billion tons a year in 2025 (Hoorweg and Bhada, 2012). The increase is mostly attributed to developing countries, where it is driven by the combination of high urbanisation rates and economic

development. In developing countries, the per capita waste generation rate ranges from 0.4 to 1.1 kg per day, reaching in some urban areas 2.4 kg per day and more in tourist areas.

The estimated quantity of MSW generated worldwide is 1.7 – 1.9 billion metric tons (UNEP, 2010). In many cases, MSW are not well managed in developing countries, as cities and municipalities cannot cope with the accelerated pace of waste production. More than 50 % of the collected waste is often disposed of through uncontrolled landfilling and about 15 per cent is processed through unsafe and informal recycling (Chalmin and Gaillochet, 2009). The United States is the country that generates the biggest amount of MSW in the world as it accumulates on a yearly basis of around 387 million tonnes of MSW (2010).

2.3. LANDFILL LINERS

The design of waste disposal facilities typically involves some form of barrier which separates the waste from the ground water. This barrier is intended to minimize the migration of contaminants from the facility, thus the environmental impact of the facility is intimately related to its design and long term performance. Natural clayey deposits or compacted clayey liners frequently represent a key component of these barriers.

These days, barriers are usually includes one or more of the following types:

- (i) Natural clayey soils such as lacustrine clay or clayey till;
- (ii) Compacted clayey liners;
- (iii) Cut-off walls;
- (iv) Natural bedrock;
- (v) Composite liner system consisting of geomembranes

Out of the above mentioned types generally compacted clayey liners and composite liner system with geomembranes are used at the waste disposal site. Landfilling employs an

engineered method of disposing MSW on land in a manner that minimizes any environmental hazards. A landfill liner is relatively a thick structure of compacted natural clayey soil or manufactured material (i.e. geomembrane or geosynthetic clay liners) which serves as a barrier between leachate and ground water to control the movement of leachate that reaches or mixes with the groundwater.



Figure 2.1 Cross section of a typical waste disposal site

Figure 2.1 shows the cross section of a typical waste disposal site. Clay liners are frequently installed at waste disposal sites to prevent pollutant migration and to minimize or eliminate the risk for ground water contamination due to low hydraulic conductivity and adsorption capability of the liner material. The liner may be required for one or two reasons; firstly, if the natural soil is fractured clayey soil then the liner may be required to retard movements of contaminant along the fractures, secondly, if the surroundings natural soil does not have a low

enough hydraulic conductivity to provide an adequate barrier, a liner is provided. There are some situations where the conceptual designs may not provide sufficient confidence that there will be negligible effect on ground water quality. Under these circumstances, an additional level of engineering in the form of a secondary leachate collection system or hydraulic control layer may be provided.

2.4. LANDFILL DESIGN METHOD ADOPTED IN DIFFERENT COUNTRIES

In the late 1980's the European Commission began to draft the Council Directive on the Landfill of Waste. The Directive went through much iteration until it was finally agreed in 1999 and proposed that landfill liners should satisfy at least one of the hydraulic conductivity and thickness requirements for protection of soil, groundwater and surface water:

Landfill for hazardous waste:

Hydraulic conductivity (k) $< 1 \times 10^{-9}$ m/sec; thickness > 5 m

Landfill for non-hazardous waste:

Hydraulic conductivity (k) $< 1 \times 10^{-9}$ m/sec; thickness > 1 m

Landfill for inert waste:

Hydraulic conductivity (k) $< 1 \times 10^{-7}$ m/sec; thickness > 1 m

The thickness and hydraulic conductivity criteria of the mineral barrier used in liners varies from country to country and are shown in Figs. 2.2 and 2.3. The thickness of the barrier to be used should be less than 0.6 m and 1 m for USA and UK respectively and the hydraulic conductivity (k) should be less than 10^{-9} m/sec. For Japan, the thickness of the barrier should be less than 5 m and k should be less than 10^{-9} m/sec.

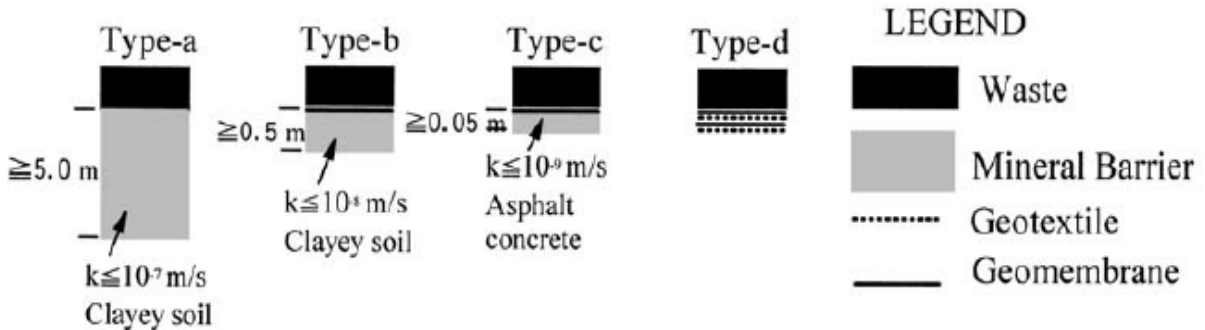
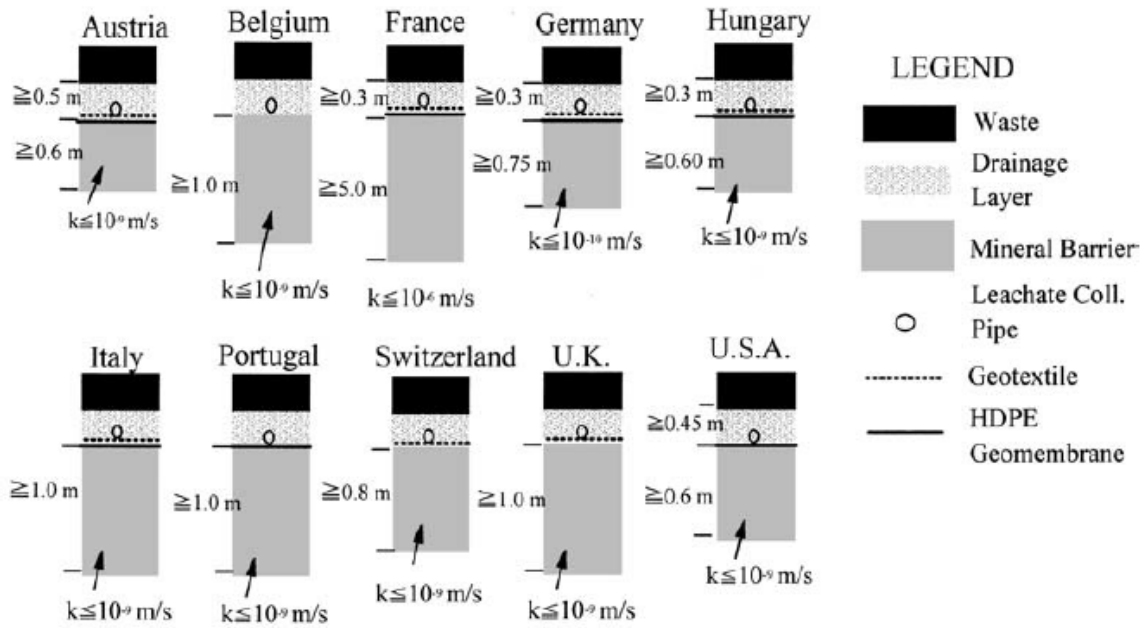


Figure 2.3 Japanese liner systems (Chai and Miura, 2002)

2.5. GENERATION OF LEACHATE FROM MSW

Leachate is generated as a result of multiple chemical and biological reactions of solid waste within the landfill and has harmful impacts on the surrounding soil and groundwater if not controlled properly. Leachates are generally classified as aqueous liquids or solutions containing contaminants which are miscible in water; non-aqueous liquids composed of

organic compounds which are immiscible in water; or mixtures of both aqueous and non-aqueous liquids which results in the formation of two separate liquid phases. An efficient and well managed modern landfill prevents releases of leachate into the environment. The liner serves as a barrier and prevents the potentially pollutant leachate from contaminating the underlying ground water resources.

2.5.1. Composition of leachate

Pollutants in MSW and industrial landfill leachate can be divided into four groups:

- a) Dissolved organic matter, quantified as Chemical Oxygen Demand (COD) or Total Organic Carbon (TOC), volatile fatty acids (which accumulate during the acid phase of the waste stabilization) (Christensen and Kjeldsen, 1989) and more refractory compounds such as fulvic-like and humic-like compounds.
- b) Inorganic macro-components, which include calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), ammonium (NH_4^+), iron (Fe^{2+}), manganese (Mn^{2+}), chloride (Cl^-), sulfate (SO_4^{2-}) and hydrogen carbonate (HCO_3^-).
- c) Heavy metals, such as cadmium (Cd^{2+}), chromium (Cr^{3+}), copper (Cu^{2+}), lead (Pb^{2+}), nickel (Ni^{2+}) and zinc (Zn^{2+}).
- d) Xenobiotic organic compounds (XOCs) originating from household or industrial chemicals and present in relatively low concentrations (generally less than 1.0 mg/l of individual compounds). These compounds include among others a variety of aromatic hydrocarbons, phenols, chlorinated aliphatics and pesticides.

The composition of these compounds in leachate varies due to a number of different factors such as the age and type of waste and operational practices at the site. Most of landfill leachate has high BOD, COD, ammonia, chloride, sodium, potassium, hardness and boron levels. Raw

leachate contains concentrations of heavy metals in excess of the drinking water standards, which is harmful for the human body. Toxic substances may be present in variable concentrations and their presence is related to the nature of waste deposited.

2.5.2. Effect of leachate on liner material

Chemicals in the landfill leachate with low dielectric constant, high electrolyte concentration, or high cation valence may cause the diffuse double layer of bentonite to shrink which in turn leads to an increase in hydraulic conductivity (Olson and Mesri, 1970; Mishra et al., 2005). Presence of various chemicals in waste could affect the contamination adsorption capacity of bentonite and in turn reduce its usefulness as barrier material. To properly design a clay barrier it is important to understand the composition of contaminants, the extent of the accumulation of contaminants in liner material and influence on the clay structure which in turn affect the swelling and hydraulic conductivity of the clay barrier.

2.6. DESIGN PARAMETERS FOR LANDFILL LINERS

2.6.1. Hydraulic conductivity

The primary concern about liners is their hydraulic conductivity. A well designed clay liner must have a low hydraulic conductivity to minimize leachate leakage. Mitchell and Jaber (1990) stated that moisture content and dry density affect a soil's ability to restrict the transmission of flow. Placement conditions that result in a high dry density and a moisture content wet of optimum leads to the lowest values of hydraulic conductivity (k) because the soil particles are arranged in a dispersed pattern, whereas a dry side of compaction produces a flocculated pattern (as shown in Fig. 2.4), which offers better paths for the flow of water leading to a higher k . Wet of optimum, the clay can be easily remoulded, clods and macropores

are broken up. Since hydraulic conductivity through clay micropores is very low, the overall hydraulic conductivity is also low.

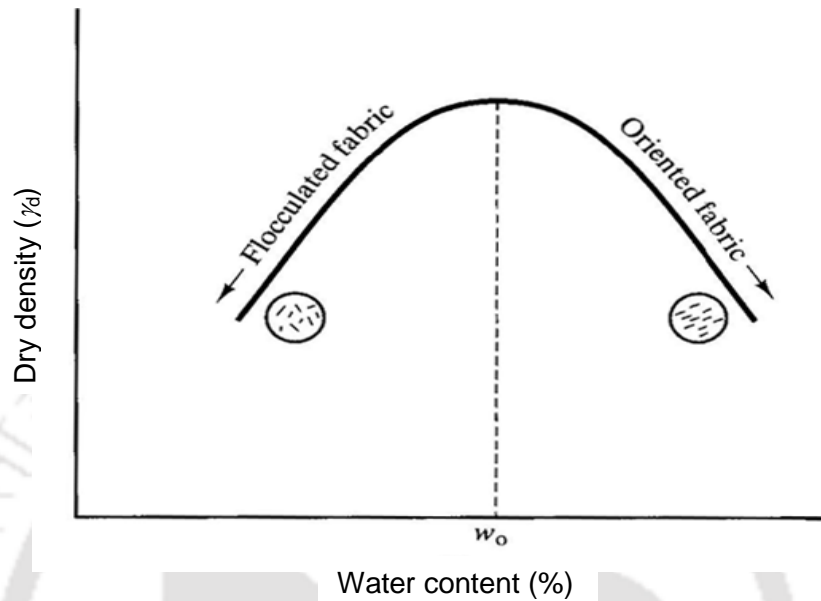


Figure 2.4 The effect of compaction water content (w) and dry density on the orientation of the soil fabric (Lambe, 1958a)

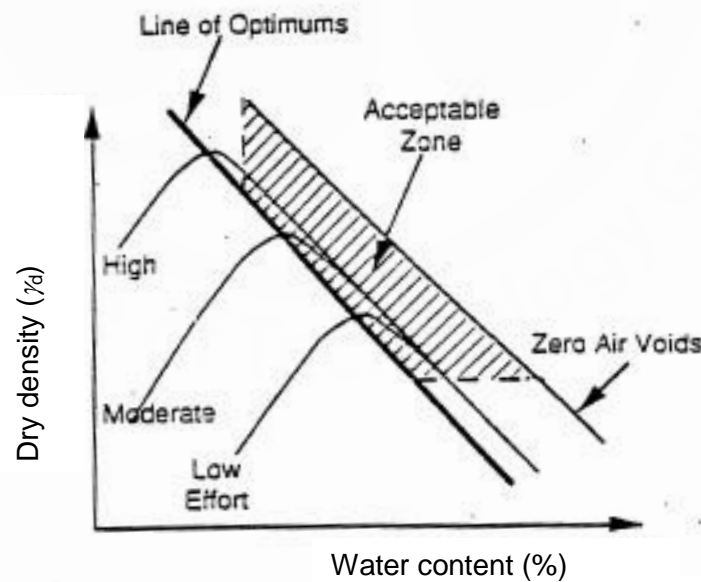


Figure 2.5 Acceptable zone for hydraulic conductivity (Daniel and Benson, 1990)

The line of optimums can be plotted on water content vs. dry density graph by performing modified standard and reduced proctor tests. The acceptable zone for hydraulic conductivity may be defined with the line of optimums as the bottom boundary and zero air voids curve as the top limit (Fig. 2.5).

2.6.2. Shear Strength

Clay liners should feature adequate strength to maintain the integrity of the liner against the overburden stress imposed by the material above it and to make the liner stable when employed on slopes, for example, in the side wall of a waste containment facility. The required strength for a clay liner to support the maximum bearing stress in a landfill project was calculated to be 30 psi or 200 kPa (Daniel and Wu, 1993).

2.6.3. Volumetric shrinkage

Clay soils used in liners are typically placed and compacted at the wet of optimum moisture content to minimize the hydraulic conductivity of the compacted soil. As the molding water content of a compacted soil is increased, the shrinkage potential of the soil increases as well. Desiccation or shrinkage cracking can occur if liners are exposed to atmosphere in hot weather and can result in an increase in the hydraulic conductivity by many folds. Daniel and Wu (1993) investigated a clayey soil in West Texas in 1993 and concluded that the volumetric shrinkage upon drying should be less than or equal to 4 %.

2.7. BENTONITE

2.7.1. Introduction

Bentonite is widely used as a backfill material during the construction of slurry trench walls, as a soil admixture for the construction of seepage barriers, as a grout material, as a sealant for piezometer installations and for various other civil engineering construction techniques.

Bentonite is an absorbent aluminium phyllosilicate, essentially impure clay, formed as a deposit of volcanic ashes at shallow wet sites in various location of the world (Grim & Guven, 1978). These deposits are variable, depending on the nature of the volcanic ashes and the salinity of the water into which they were deposited. Since the bentonite is a natural material, its mineral composition, chemical state, and grain size distribution varies considerably from one source to another. Different parameters such as mineralogical composition (i.e. amount and type of montmorillonite), type of exchangeable cations, surface area and the surface charge density affect the behaviour of bentonite considerably.

Bentonite is primarily composed of the smectite group of minerals, most common among which is montmorillonite $(Al_{1.7}Mg_{0.3})[Si_4O_{10}(OH)_2]^{-0.3}(M)^{+0.3}$, where M represents the exchangeable cation (Mitchell and Soga, 2005). The behaviour of bentonite primarily is governed by montmorillonite which has characteristics like a large specific surface area (as high as $800 \text{ m}^2/\text{g}$), high charge deficiency (0.5-1.2 per unit cell), high cation exchange capacity (80-150 cmol_c/kg), and ability for interlayer swelling. These factors contribute to the high swelling, low hydraulic conductivity and contaminants adsorption ability of the bentonite.

2.7.2. Structure of Montmorillonite

Clays are the particles with an effective diameter smaller than $2\mu\text{m}$ and phyllosilicates as its main mineralogical components. These phyllosilicates are made of silica (SiO_2) tetrahedral sheets and Aluminium (Al^{3+}) or magnesium (Mg^{2+}) oxides octahedral sheets. Montmorillonite has a prototype structure similar to that of pyrophyllite consisting of an octahedral sheet sandwiched between two tetrahedral sheets (2:1 mineral) and diagrammatically in three dimensions (Fig. 2.6). The silica and gibbsite sheets are combined in such a way that the tips of the tetrahedron of each silica sheet and one of hydroxyl layers of octahedral sheet form a

common layer and all the tips of the tetrahedral point toward the center of the unit cell. The oxygen forming the tips of the tetrahedral is shared with the octahedral sheet as well. The anions in the octahedral sheet that fall directly above and below the hexagonal holes formed by the bases of the silica tetrahedral are hydroxyls. Bonding between successive layers is by vander Waal's forces and by cations that balance charge deficiencies in the structure. These bonds are weak and water or other polar liquids can easily enter between the layers, causing them to expand significantly. It has a lateral dimension of 1000 to 5000 A^0 and thickness 10 to 50 A^0 .

The layers formed in this way are continuous in 'a' and 'b' directions and stacked one above the other in the 'c' direction. Bonding between successive layers is by van der Waal's forces and by cations that balance the charge deficiencies in the structure. These bonds are weak and easily separated by cleavage or adsorption of water or other polar liquids. The basal spacing in the c direction, $d_{(001)}$, is variable, ranging from about 0.96 nm ($1 \text{ nm} = 10^{-6} \text{ mm}$) to complete separation.

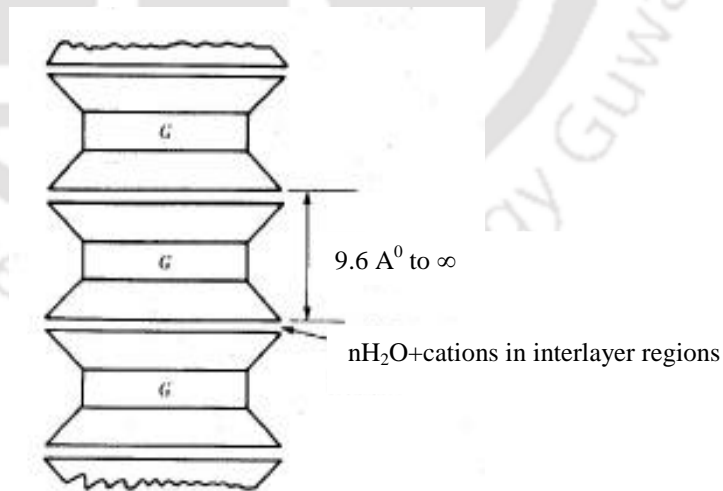


Figure 2.6 Structure of montmorillonite

The montmorillonite is the primary mineral of bentonite. In the dry state a particle of montmorillonite resembles a closed book composed of many thin crystalline sheets held together by weak van der Waal's forces and by cations. Each sheet has charge deficiencies within its crystal structure, and is neutralized by the presence of cations held loosely to the surface of the sheets. When the dry bentonite and water are mixed, water is drawn into the montmorillonite particles to hydrate the surface of the elemental sheets and the cations. For the combination of sodium montmorillonite and freshwater, the fluid that enters the particles forms thick, viscous diffuse ionic layers around the layer, causing the montmorillonite particles to swell, possibly to the extent of complete separation of the sheets. The fabric of freshwater, low salt, sodium bentonite resembles a pile of crumbled paper. For the combination of dry sodium bentonite and a saline solution, less fluid is required to neutralize the negatively charged sheets, and if the ion concentration is large or the valence of the cations are large, the separation distance between sheets will remain small and the montmorillonite particles will remain in the form of closed books. The fabric of bentonite in this case will consist of swollen but intact montmorillonite particles surrounded by thin, viscous diffuse ionic layers, in an arrangement resembling a pile of fallen books. A third case is that of calcium bentonite, an example of bentonite in which dominant exchangeable cations is polyvalent. The calcium cation is very effective in holding together the montmorillonite sheets, and therefore calcium bentonite has small potential to swell, even when mixed with freshwater. Calcium bentonite behaves similarly to sodium bentonite in a high salt state, and its permeability properties are about same.

2.7.3. Swelling Behaviour of Bentonite

The swelling of bentonite takes place in two stages, inner-crystalline swelling and osmotic swelling (Norrish and Quirk, 1954).

2.7.3.1. Inner-crystalline swelling

In inner-crystalline swelling, water molecules enter the interlayer region of the montmorillonite to hydrate the exchangeable cations located there. The cations upon contact with water order themselves on a plane halfway between the clay layers which lead to a widening of the spacing between the layers. The volume of montmorillonite can double in the process of inner-crystalline swelling. Polarity of the water molecule is an important factor in the inner-crystalline swelling of clay. When cations hydrate, the water molecules orient their negative dipoles towards the cation and thus weaken the electrostatic interaction between the negatively charged layers and the interlayer cations. Inner-crystalline swelling, which has also been referred to as Type I swelling, is a process whereby expandable 2:1 phyllosilicates sequentially intercalate one, two, three or four discrete layers of H₂O molecules between the mineral interlayers (Norrish, 1954). In this process the swelling occurs prior to osmotic (Type II) swelling which is associated with longer range electrical diffuse double layer effects. Figure 2.7.a and 2.7.b shows inner-crystalline swelling of sodium montmorillonite.

In inner-crystalline swelling there is a balance between attractive and repulsive forces operating between adjacent interlayer surfaces (Norrish, 1954; van Olphen, 1965; Kittrick, 1969). Electrostatic attraction between the exchange cations and the basal surfaces of the clay dominates the net potential energy of interaction (Laird, 1996 and 2006). The positive charged cations provide links or are like charge bridges between adjacent negatively charged clay layers. On the other hand, the hydration energy of the exchange cations dominates the net

potential energy of repulsion. Net forces of attraction are dominant for unsaturated conditions or saturated conditions with high electrolyte concentrations, while net forces of repulsion are dominant in case of fully saturated conditions of low electrolyte concentration.

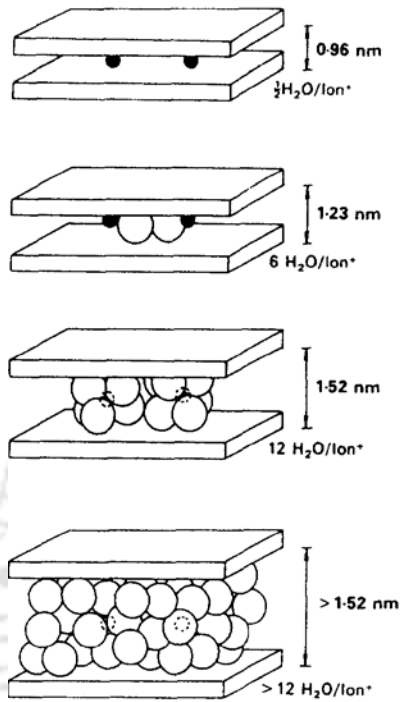


Figure 2.7.a Inner-crystalline swelling of sodium montmorillonite. Given are the layer distances and the maximum number of water molecules per sodium ion (Kraehenbuehl et al., 1987)

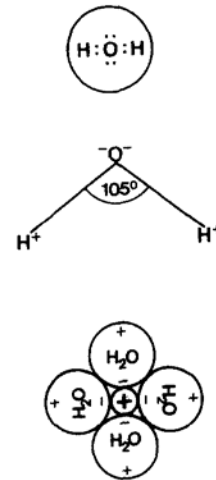


Figure 2.7.b The structure of water molecule

2.7.3.2. Osmotic swelling

The osmotic phase of swelling follows the hydration phase but occurs only when the exchange sites contain monovalent cations (Norrish and Quirk, 1954; Kjellander et al., 1988; McBride, 1994; Prost et al., 1998). The interlayer region retains numerous layers of water molecules during the osmotic phase. The number of layers of water molecules at equilibrium is proportional to the cation concentration in the bulk water (Norrish, 1954; Zhang et al., 1995; Onikata et al., 1999). Accordingly, when the bulk water contains a low concentration of monovalent cations and monovalent cations occupy the exchange sites, a larger fraction of the

total water is bound and less mobile water is available for flow resulting in a lower value of hydraulic conductivity. This condition is commonly observed when sodium-montmorillonite are hydrated and/or permeated with DI water (Lutz and Kemper, 1958; Alther et al., 1985; Gleason et al., 1997; Petrov and Rowe, 1997; Ruhl and Daniel, 1997; Shackelford et al., 2000). When polyvalent cations occupy the exchange sites, only the hydration phase occurs. The interlayer expands until it contains four monolayers of water and then expands no further (Norrish and Quirk, 1954; Posner and Quirk, 1964; Kjellander et al., 1988; McBride, 1994; Prost et al., 1998). There are several explanations for the lack of additional interlayer swelling when polyvalent cations occupy the exchange sites, but consensus does not exist regarding which explanation is correct (McBride, 1994). Nevertheless, absence of the osmotic phase is well documented experimentally in the literature (Norrish and Quirk, 1954; Posner and Quirk, 1964; McBride, 1994; Prost et al., 1998). Lack of an osmotic phase is evident in the free swelling of calcium-montmorillonite (i.e., bentonites where the exchange sites are occupied by Ca^{2+} cations), which typically is about 3 mL/2g even when DI water is the hydrating liquid. In contrast, the free swelling of sodium- montmorillonite typically exceeds 30 mL/2g in dilute monovalent solutions or DI water (Egloffstein, 1995; Lin and Benson, 2000).

In sodium-montmorillonite the swelling can result in the complete separation of the layers. The driving force for the osmotic swelling is the large difference in concentration between the ions electrostatically held close to the clay surface and the ions in the pore water of the rock (Fig. 2.8.a). Irregularities in the crystal lattice are manifested by an excess negative charge, which must be compensated by positive ions close to the surface of the clay. The concentration of positive ions close to the surface is thus extremely high, while that of negative ions is very small. The positive ion concentration decreases with increasing distance from the surface,

whereas the concentration of negative ions increases. The negatively charged clay surface and the cloud of ions form the diffuse electric double layer (Fig. 2.8.b). A high negative potential exists directly at the surface of the clay layer. The value of this potential is reduced, with increasing distance from the surface and reaches zero in the pore water. When two such negative potential fields overlap, they repel each other, and cause the observed swelling in clay. The profile of the potential curves, and therefore the repulsion at a given distance vary with the valence and the radius of the counter-ions in the double layer and with the concentration of electrolytes in the pore water. A transformation of sodium montmorillonite into its calcium form or an increase in the electrolyte concentration in the pore water results in the decrease in the double layer thickness and a reduction in the swelling stress.

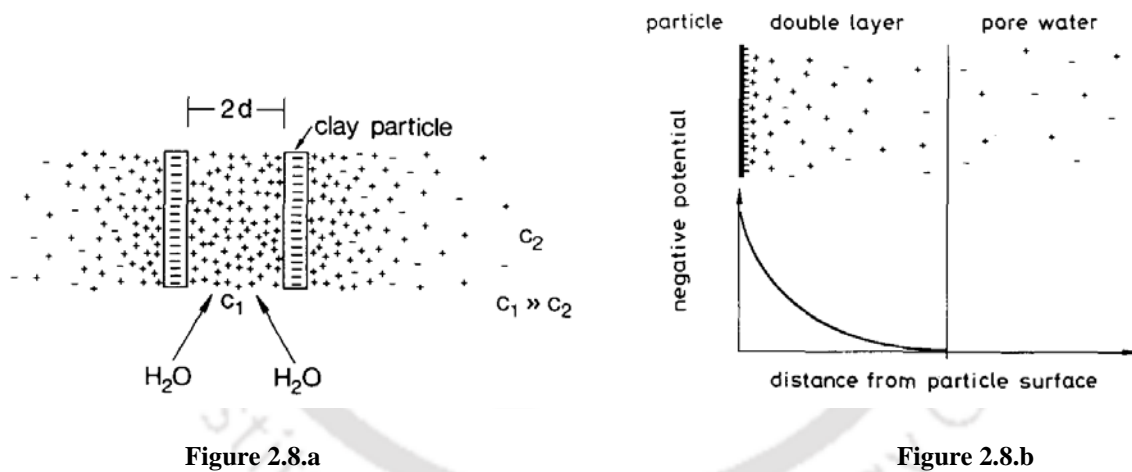


Figure 2.8.a Two negatively charged clay layers with ion cloud. The ion concentration C_1 between the layers is much higher than the ion concentration C_2 in the pore water. An equilibration of the concentration can only be reached through the penetration of water into the space between clay layers, since the interlayer cations are fixed electrostatically by the negative charge of the layers (osmotic swelling)

Figure 2.8.b Negatively charged clay surface, ions in the diffuse double layer and ions in the pore water. The distribution of the negative potential changes with the valence and the radius of the ions in the double layer and with the electrolyte concentration in the pore water

2.8. DIFFUSE DOUBLE LAYER

In dry clay, the negative charge is balanced by exchangeable cations like Ca^{2+} , Mg^{2+} , Na^+ , and K^+ surrounding the particles being held by electrostatic attraction. Cations in excess of those needed to neutralize the electronegativity of the clay particles and associated anions are present as salt precipitates. When water is added, the precipitates can go into solution. The interlayer cations within the clay particles, due to electrostatic attraction of the negatively charged surfaces, pull water molecules because of their hydration energy upon wetting. Highly concentrated cations along the charged surfaces try to diffuse away from the surfaces in order to equalize concentration throughout the clay water solution. The action of two opposing tendencies leads to a specific ion distribution along the clay particles in the clay water suspension. The concentration of the counter ions near the particle surface is high and it decreases with the increase in the distance from the surface. The charged surface and the distributed charge in the adjacent phase are together termed as the diffuse double layer.

Gouy (Gouy, 1910) and Chapman (Chapman, 1913) introduced diffuse double layer model, as shown in Fig. 2.9, in which the potential decreases exponentially away from the clay surface.

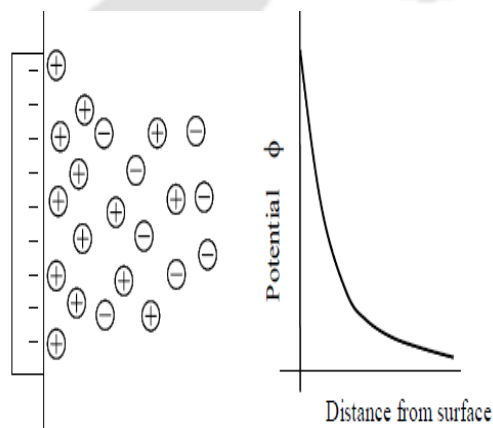


Figure 2.9 Gouy-Chapman diffuse double layer model

2.8.1. Factors affecting diffuse double layer (DDL) thickness

Factors such as electrolyte concentration, ion valence, di-electric constant, temperature, size of hydrated ions, pH and anion adsorption affects the thickness of diffuse double layer.

(i) *Electrolyte concentration*: Thickness of DDL varies inversely to the square root of pore water concentration. An increase in electrolyte concentration decreases the surface potential for the condition of constant surface charge, and the potential decays rapidly with distance. The diffuse layer gets reduced. As concentration increases, the mid-plane concentration and electric potential for interacting parallel plates (clay particles) at a given spacing decrease. Thus, the interparticle repulsive forces decrease.

(ii) *Cation valence*: Thickness of DDL varies inversely to the valency of cation. An increase in valence reduces the mid-plane concentration and potential between interacting plates, thus leading to a decrease in inter-plate repulsion.

(iii) *Di-electric constant*: Thickness of DDL varies directly to square root of the di-electric constant.

(iv) *Size of hydrated ions*: Thickness of DDL varies directly to size of the hydrated cation.

(v) *Temperature*: Thickness of DDL varies directly to square root of the temperature.

2.9. SWELLING PRESSURE

The swelling pressure of a soil is the external pressure that needs to be placed over the soil to prevent its volume to increase. Swelling pressure can also be defined as the pressure required to compress a specimen, which has been soaked and completely swollen under seating pressure, back to its original configuration (i.e. before swelling) (Sridharan et al., 1986a).

Swelling pressure is a helpful index indicating the trouble potential of an expansive soil. When the bentonite contains a significant percentage of montmorillonite, it swells more in presence

of water since larger number of water molecules intercalate in between the clay mineral sheets. Thus a larger pressure is required to prevent volume increase which gives rise to a higher swelling pressure for high swelling bentonites.

Figure 2.10 represents mechanism of swelling pressure of bentonite. Bentonite consists of montmorillonite minerals, non-swelling minerals and voids. Before bentonite imbibes water, the voids are mainly occupied by air and free water. After water gets absorbed into the interlayers of montmorillonite, the mineral present in the bentonite, the volume of montmorillonite increases and thus the volume of compacted bentonite increases until the swelling pressure of the montmorillonite minerals equals the vertical pressure. If the total volume of compacted bentonite is restrained, the montmorillonite minerals swell and fill the voids in the compacted bentonite maintaining the overall constant volume of the bentonite. The volume of montmorillonite minerals cannot change in the compacted bentonite after the voids are filled, and the pressure caused by the swelling of montmorillonite minerals is measured as the swelling pressure of the compacted bentonite.

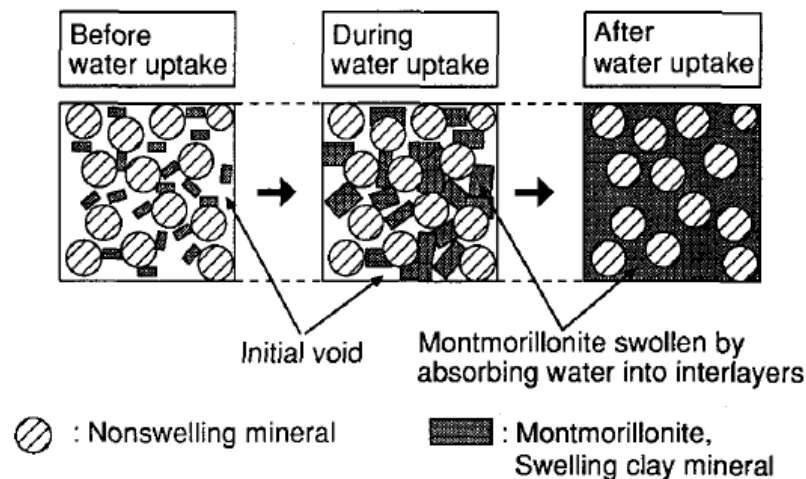


Figure 2.10 Mechanism of the swelling pressure of compacted bentonite (Komine and Ogata, 1996)

2.10. SWELLING POTENTIAL

The swelling potential is defined as the percentage swelling of a compacted, laterally confined sample, which has been soaked in liquid under a surcharge pressure of 4.9 kPa. The ratio of the maximum swell height of a soil sample to the initial height of the sample is defined as the swelling potential of the soil.

The tendency of expansive soils to increase their volume when they come in contact with water is quantified by the swelling potential and swelling pressure parameters (Rao, 2006). The Atterberg limits and swell potentials of clays depend on the quantity of water that clay can imbibe. High swelling soils imbibe greater quantum of water and hence greater would be its swelling potential.

2.11. COMPRESSIBILITY

Similar to the hydraulic conductivity, compressibility is one of the most important properties of clayey soils which need to be studied for settlement analysis. Since the bentonite is a highly compressible material, the liner gets compressed due to the increase in the overburden waste.

The compressibility of the bentonite is controlled by the mechanical and physicochemical effect. High swelling soils develop a larger thickness of diffuse double layer when it interacts with water. When subjected to an overburden pressure, a high swelling soil expels more water resulting in a higher compressibility value. Thus a high swelling bentonite affects its compressibility significantly.

The compressibility of clays under external load is governed by not only the mechanical properties of clay minerals but also the ion concentration, cation valency, dielectric constant and temperature of the pore fluid (Bolt, 1956; Olson and Mesri, 1970; Sridharan and Rao, 1973). The concentration of ions in the pore fluid significantly affects the compressibility

behaviour of clays. According to double layer theory, the double layer is compressed due an increase in ion concentration. The compressibility of clays also depends on the chemical composition of the interstitial liquid or the soil solution. For instance, the replacement of calcium ion in the soil solution of bentonite by sodium ion increases the compression index of the bentonite many times, but the mechanical properties of the solid soil constituents remain unchanged (Salas and Serratoso, 1953). However, the compressibility of clays may be influenced by both mechanical and physico-chemical effects depending on the clay mineralogy, saturating cation and pore fluid. Mechanical effects control the compressibility of kaolinite and illite, whereas, the compressibility of montmorillonite is controlled by physicochemical effects (Robinson and Allam, 1998).

2.12. HYDRAULIC CONDUCTIVITY

The low hydraulic conductivity of the bentonite is due to the accumulation of the water molecules associated with the cations in the interlayer and external surface of the montmorillonite particles, which is manifested as swelling at the macroscale (van Olphen, 1977; Mitchell and Soga, 2005; McBride, 1994). These water molecules are tightly held by electrical forces in the interlayer region (i.e. the water molecules are “bound”) and are hydraulically immobile (van Olphen, 1977; McBride, 1994). When modest confinement exists, the pores containing free (hydraulically mobile) water becomes compressed and more tortuous as bound water accumulates. As a result, lower hydraulic conductivity occurs as the fraction of the bound water increases (Mesri and Olson, 1971b; Mitchell and Soga, 2005; Egloffstein, 1997; Shackelford et al., 2000; Jo et al., 2001; Kashir and Yanful, 2001).

Hydraulic conductivity generally increases when the permeating fluid has a higher unit weight. Similarly, a more viscous fluid will result in a lower hydraulic conductivity. Temperature also

affects hydraulic conductivity as temperature variations can change viscosity. These variations are explicable for coarse grained soils. For clays, other factors such as physico-chemical interactions of clay particles also significantly affect the hydraulic conductivity.

The hydraulic conductivity of the clays depends on a number of factors including soil composition, permeant characteristics, void ratio and structure (Lambe, 1954). The saturated hydraulic conductivity is affected by compaction dry density, temperature, montmorillonite content and type of exchangeable cation. Haug and Leppin (1994) reported that the hydraulic conductivity of a sand-bentonite mixture with 76% montmorillonite was almost 400 times higher than the mixture containing a bentonite with 95% montmorillonite content. Similarly, Martin et al. (1964) concluded from their study that the hydraulic conductivity of soil has a definite relationship with the exchangeable sodium percentage (ESP) at different pH levels.

2.12.1. Influence of salt on hydraulic conductivity of clay

The low hydraulic conductivity of the bentonite is due to imbibing of the water molecules associated with the cations in the interlayer and external surface of the montmorillonite particles, which is manifested as swelling at the macroscale (van Olphen, 1977; Mitchell and Soga, 2005; McBride, 1994). Water in the pores of bentonite is of both mobile and immobile type. Mobile water is the freely flowing bulk water that is free to move under a hydraulic gradient. Immobile water is bound to the external and internal (i.e. interlayer) mineral surfaces by strong electrical forces, and act similar to the solid phase in terms of affecting flow. This immobile water is known as diffuse double layer (DDL). When the DDL in the system increases, the fraction of the pore space comprised of freely flowing bulk water decreases and pathways for flow become smaller and more tortuous. With an increase in the volume of bound water, the swell volume increases and the hydraulic conductivity decreases (McNeal et

al., 1966; Mesri and Olson, 1971b). However, chemicals present in the leachate suppress the thickness of diffuse double layer which in turn shrinks the bentonite. As the bentonite shrink, the flow path becomes open and the hydraulic conductivity increases.

2.12.2. Effect of bentonite waste interaction on hydraulic conductivity

Hydraulic conductivity is a one of the key parameter in the design of landfill liners since leachate from a waste disposal site influence soil properties. The contaminants affect the hydraulic conductivity of the clays in the following three ways;

- a) *Dissolution of soil minerals*- Acids and bases in the contaminant fluids may reduce certain soil minerals into liquid forms by dissolution. For e.g., acids dissolve aluminium and iron, alkali metals, bases dissolve silica in the soils. As a large amount of alumina is present in clay minerals, they get partially dissolved by acids. The solubility of clays in acids depends upon the nature of the acid, the acid concentration, the acid to clay ratio, the temperature and duration of treatment (Grim, 1968). The fines formed by dissolution migrate with the contaminant fluids and cause hydraulic conductivity to decrease due to plugging of the soil pores. However, after a considerable time, this migration of fines may cause increase in hydraulic conductivity due to piping and channel formation within the soil.
- b) *Changes in clay structure*- The clay structure changes due to the changes in its exchange complex or by the replacement of adsorbed water by contaminant fluids. The concentration and valence of cations affect the electrical forces between the clay mineral layer sheets. When cation concentration or valence increases, the net repulsive forces decrease. Thus, a dispersed clay structure changes into flocculated and exhibits an open card house type of structure which increases the hydraulic conductivity. With

an increase in Ca^{2+} concentration, replacement of Na^+ with Ca^{2+} takes place and the clay particles become flocculated. On the other hand, when the Na^+ concentration increases, the clay structure gets dispersed, resulting in a lower hydraulic conductivity. In presence of calcium ions, the increase in hydraulic conductivity can be attributed to a decrease in the DDL thickness due to replacement of the monovalent sodium ions by divalent calcium ions and formation of quasicrystals between exchangeable calcium ions and a pair of opposing siloxane cavities (Sposito, 1984). Among the smectite minerals, more changes occur in montmorillonite because of its greater SSA and CEC. The increase in hydraulic conductivity varies depending upon the quality of bentonite to be used in waste containment systems.

- c) *Precipitation*- The precipitation of heavy metals, salts and carbonates bring changes in hydraulic conductivity. This precipitation blocks the soil pores and decrease the hydraulic conductivity. However, when the pH, solute concentration, temperature changes, the precipitation reverted.

2.13. REVIEW OF LITERATURES ON INTERACTION OF CLAY WITH SALT SOLUTIONS

Quirk and Schofield (1955) had shown that the hydraulic conductivity of soil decreases with increasing the exchangeable sodium percentage (ESP) provided the electrolyte concentration is below a 'threshold level'. They defined the 'threshold level' as the concentration in the percolating solution that would give rise to a 10 to 15% decrease in relative hydraulic conductivity at a given ESP value and demonstrated that the soil hydraulic conductivity can be maintained at a high and stable level provided the salt concentration of the water is above the threshold value.

Mesri and Olson (1971a) studied the consolidation characteristics of montmorillonite on artificially sedimented specimens of Wyoming bentonite by performing one-dimensional consolidation tests on Calcium and Sodium montmorillonite with organic fluids at various electrolyte concentrations. The hydraulic conductivity of the montmorillonite increased significantly when water was replaced as pore fluid by chemical solution and it was observed that bentonite permeated with benzene was more than 10,000 times permeable in comparison to the bentonite permeated with water.

Mesri and Olson (1971b) investigated the effect of water, methyl and ethyl alcohol, benzene and carbon tetrachloride on hydraulic conductivity of three clay minerals, namely, montmorillonite, illite and kaolinite and concluded that the hydraulic conductivity of clays were mainly controlled by two variables, i.e. the mechanical and physico-chemical variables. The mechanical variables included the size, shape and the geometrical arrangement of the clay particles; whereas, the physico-chemical variables included the pore water chemistry. At constant void ratio, hydraulic conductivity reduced from kaolinite to illite to montmorillonite as a result of a reduction in the size of individual flow channels and an increase in the tortuosity of the flow paths. Physico-chemical variables control the tendency of the clay to disperse or to form aggregates.

Sridharan et al. (1986b) studied the mechanisms controlling the Atterberg limits and compressibility characteristics of bentonite homoionised with a series of monovalent, divalent and trivalent cations. They observed that an increase in cationic valency reduces the liquid limit and the compressibility of the bentonite, while an increase in the hydrated ionic radius (for a constant valency) increases the liquid limit and compressibility. The size effect was more pronounced for the monovalent bentonites than for the divalent and trivalent bentonites.

It was observed that the rate of consolidation and hydraulic conductivity were also significantly affected by the valency and size of the adsorbed cations. An increase in the valency of the adsorbed cation leads to quicker rates of consolidation and higher hydraulic conductivity; whereas, for a constant valency, an increase in the hydrated radius of the adsorbed cation results in slower rate of consolidation and lower hydraulic conductivity.

Barbour and Fredlund (1989) demonstrated that the mechanical behaviour of bentonite gets strongly influenced by physicochemical effects when concentrated pore fluids were introduced to the soil. The thickness of diffuse double layer and the net repulsive stress decreases as the concentration of the solution in the pores increases which leads to true effective stress increase, resulting in the contraction of aggregates and shrinkage of the sample.

Rao and Mathew (1995) studied the effect of exchangeable cations on hydraulic conductivity of marine clay and demonstrated a marked influence of valency and hydration radius of the adsorbed cations on the hydraulic conductivity. Lower valency and higher hydrated radii of the exchangeable cations enable the double layer repulsive forces to predominate, thereby increasing dispersion and deflocculation. Results from consolidation tests showed that increase in the valency of the adsorbed cations led to quicker rates of consolidation and higher hydraulic conductivity; whereas, for a constant valency, an increase in the hydrated radius of the adsorbed cations resulted in a lower rate of consolidation and hydraulic conductivity. Sodium saturated clay was found to be approximately six times less permeable than potassium and ammonium clays.

Petrov and Rowe (1997) had shown that the hydraulic conductivity of bentonite increased from $\sim 10^{-11}$ to $\sim 10^{-8}$ m/s with an increase in the NaCl concentration from 0 (i.e. DI water) to 2 N. Ruhl and Daniel (1997) investigated the effects of various leachates on the hydraulic

conductivity of geosynthetic clay liners (GCLs) using a strong acidic, basic and a mix of simulated leachates containing controlled chemical composition and a real-world leachate and concluded that hydraulic conductivity was lowest when the wetting liquid was water rather than the chemical solutions or leachate. The GCLs had a high hydraulic conductivity when permeated directly with simulated MSW leachate that was rich in calcium or a strong acid solution or base solution than the GCLs that were permeated with real MSW leachate which was attributed to presence of higher calcium ions in MSW.

Robinson and Allam (1998) conducted consolidation and hydraulic conductivity tests on kaolinite, illite, montmorillonite and powdered quartz with water and CCl_4 as pore fluids. With water as the pore fluid, hydraulic conductivity (k) and coefficient of volume change (m_v) decreased with increase in the consolidation pressure. They also observed that with an increase in the pressure the coefficient of consolidation (c_v) of the montmorillonite decreases whereas it increases for kaolinite, illite and powdered quartz. It was also concluded that the response of c_v to pressure increase in clays governs by mechanical and physicochemical factors which govern the compressibility.

Shackelford et al. (2000) investigated the hydraulic conductivity of GCLs permeated with non-standard liquids like NaCl , ZnCl_2 , CaCl_2 and reported that permeant solution containing high concentration of monovalent cations as well as low concentration of divalent cations causes significant increase in the hydraulic conductivity.

Jo et al. (2001) studied the hydraulic conductivity and swelling characteristics of non-prehydrated GCLs containing granular bentonite placed between a monofilament-woven geotextile and a staple-fiber nonwoven geotextile and permeated with single species salt solution of NaCl , KCl , LiCl , CaCl_2 , MgCl_2 , ZnCl_2 , CuCl_2 , HCl , and NaOH . From their study

they concluded that the hydraulic conductivity of bentonite increased with the increase in electrolyte concentration and valency of the cations of the pore fluid. They also observed that the swelling was lowest in strong acid but it increased rapidly with increasing the pH of the solution.

Kolstad et al. (2004) studied the influence of multispecies inorganic salt solutions of LiCl, NaCl, CaCl₂ and MgCl₂ salts on swelling and hydraulic conductivity of non-prehydrated GCLs. Results of the free swelling tests showed that swelling is directly related to RMD (ratio of total molarity of monovalent and divalent cations in the permeant solution) and inversely related to the ionic strength. It was observed that RMD has a strong effect on swelling in weaker solutions, and a modest effect in strong solutions. Similar findings were obtained from the hydraulic conductivity tests where the hydraulic conductivity was found to be directly related to ionic strength and inversely related to RMD, with RMD having a greater effect on hydraulic conductivity in weaker solutions.

Lee and Shackelford (2005) studied the differences in hydraulic conductivity for two GCLs containing different qualities of bentonite with the permeant liquids consisting of 5, 10, 20, 50, 100 and 500 mM CaCl₂ and observed that the GCL with higher quality bentonite (GCL-HQB), marked by a higher sodium montmorillonite content, plasticity index and cation exchange capacity compared to the other bentonite (GCL-LQB), possessed a lower value of hydraulic conductivity on permeation with water. They indicated that a change in the amount of sodium montmorillonite in bentonite from 86 to 77% and cation exchange capacity (CEC) from 93 to 64 meq/100 g increased the hydraulic conductivity by three times. However, permeation with the CaCl₂ solution resulted in an increase in hydraulic conductivity of both GCLs relative to

that based on water, with greater increases in hydraulic conductivity occurring for GCL-HQB relative to GCL-LQB.

Singh and Prasad (2007) studied the effect of aluminium hydroxide and acetic acid, which are commonly found in landfill leachate, on bentonite and observed that the differential free swelling with acetic acid and aluminium hydroxide decreased by 47% and 49% respectively in comparison to the DI water. The results showed that on addition of these chemicals the hydraulic conductivity of bentonite decreased by 12% by aluminium hydroxide and 17% by acetic acid. Similarly, the swelling pressure decreased by 82% and 20% due to addition of aluminium hydroxide and acetic acid respectively.

Castellanos et al. (2008) investigated the effects of the salinity of the saturating fluid on the hydro-mechanical properties of the compacted FEBEX bentonite by conducting swelling, compressibility and hydraulic conductivity tests in which DI water and solutions of different concentrations and compositions were used as saturating fluids. It was observed that the swelling capacity of bentonite decreases with the increase in salinity of the pore water, although this difference was less evident for high vertical loads, high densities and very low salinity. The samples saturated with solutions containing high concentration of ions were less deformable and consolidated more rapidly than the samples saturated with low salinity solutions. It was observed that the hydraulic conductivity of the highly compacted FEBEX bentonite increases when high salinity permeants were used, especially for low densities and low stress level.

Mishra et al. (2009) investigated the effect of the various concentrations of NaCl and CaCl₂ on the four different soil-bentonite mixtures. Their results showed that the liquid limit of the mixtures decreases with an increase in the salt concentration. The liquid limit decreased

significantly with an increase in CaCl_2 concentration from 0 to 0.1 N, however, an increase in NaCl concentration from 0 to 0.1 N did not produce any major decrease in the liquid limit, but a further increase in concentration from 0.1 to 1 N decreased the liquid limit significantly. Consolidation tests were carried out on the mixtures to evaluate the effect of mineralogical composition of the bentonite on the hydraulic conductivity (k) of the mixture in the presence of various salts concentrations. The k for the mixtures was found to be decreasing with decrease in the salt concentration. At relatively low salt concentration, Ca^{2+} had a higher effect on the k in comparison to the same concentration of Na^+ solution. However, at 1 N of NaCl and CaCl_2 identical value of k was observed. A comparison of the performance of four bentonites showed that the mixture with bentonite having highest exchangeable sodium percentage (ESP) exhibited the lowest k when permeated with de-ionized (DI) water, however, k increased with an increase in the salt concentration.

John and Evangeline (2009) investigated the effect of acetic acid on the engineering properties of calcium and sodium activated bentonites. For both types of bentonite the liquid limit, plasticity index and swelling were reduced due to reaction with acetic acid. The hydraulic conductivity of the bentonite increased as the concentration of acetic acid increased. The maximum increase in the hydraulic conductivity was obtained for bentonite activated with sodium carbonate with 2 M acetic acid solution. In presence of acetic acid, the properties of calcium bentonite were less altered in comparison to sodium activated bentonites.

Olgun and Yildiz (2010) studied the effect of organic fluids on the consolidation and shear strength parameters of a highly plastic clayey soil consisting of 49 % montmorillonite. Results from the series of tests using four different organic fluids- methanol, ethanol, isopropyl alcohol

and acetic acid concluded that the liquid limit values and consolidation parameters decreased while shear strength values increased with decreasing dielectric constant of the pore fluid.

Thammathiwat and Chimoye (2010) investigated the effect of monovalent (LiCl, NaCl and KCl), divalent (CaCl₂, MgCl₂ and CuCl₂) and trivalent (FeCl₃) salt solutions on swelling volume and hydraulic conductivity of GCLs and observed that at similar concentration, swelling volume was larger with monovalent cations than with divalent and trivalent cation solutions. A higher value of hydraulic conductivity was observed for GCLs permeated with solutions containing divalent or trivalent cations in comparison with monovalent cations or distilled water.

Mishra et al. (2010) studied the influence of bentonite on the consolidation behaviour of soil-bentonite mixtures. Effect of the physical, chemical and mineralogical properties of the bentonites on the various consolidation parameters of the fifteen different soil-bentonite mixtures was evaluated. The compression index (C_c) of the mixtures was found to be increased with the increase in liquid limit, free swelling and clay fraction of the bentonites, as well as with the liquid limit of the soil-bentonite mixtures. The c_v for all the mixtures was found to be increased with the increase in the consolidation pressure, indicating the mixtures gets consolidated at a higher rate under a higher overburden pressure.

Baille et al. (2010) observed the swelling pressures of several compacted saturated bentonite specimens using distilled water as the bulk fluid. A newly developed high pressure oedometer device was used that enabled measurement of swelling pressures of initially unsaturated compacted bentonite specimens (strain-controlled tests). Several initial compaction conditions (i.e., dry density and water content) of the bentonite were considered. The test results showed that both initial water content and compaction dry density influenced the swelling pressure of

the bentonite. At the same water content, the swelling pressure increased with an increase in the dry density. Also, at the same dry density, the swelling pressure was found to decrease with an increase in the water content indicating that the influence of molding water on the fabric of the clay can be quite significant.

Shirazi et al. (2011) investigated on the salinity effect on swelling characteristics of compacted bentonite and concluded that swelling rate depends on the concentration of NaCl more in comparison to initial dry density and loading effect. Their data showed that the liquid limit decreased remarkably from 497 % to 112 % when the testing liquid changed from DI water to 0.5 M NaCl solution, while the plastic limit increased.

Shariatmadari et al. (2011) studied on the effect of three inorganic salts, i.e. NaCl, CaCl₂ and MgCl₂ of varying concentrations on geotechnical properties of mixtures of a commercially available clay soil and bentonite mixed in the proportion of 10 % and 20 % by their dry weight. Results indicated that with increasing the salt concentration and cation valence the swelling volume and liquid limit of the mixtures decreased whereas the hydraulic conductivity increased.

Xue et al. (2012) studied the impact of high concentration solution (MgCl₂, CaCl₂, NaCl and KCl) on hydraulic properties of GCL materials and reported that the GCL hydraulic conductivity increased several times when soaked and permeated with high concentration chemical solutions in comparison to the permeation with DI water. The chemical impact on GCL hydraulic conductivity was found to be in the order CaCl₂> MgCl₂>KCl>NaCl.

Zhu et al. (2013) studied on the influence of salt solutions on the swelling pressure and hydraulic conductivity of compacted bentonite. Swelling pressure and permeability tests were carried out on densely compacted bentonite samples with de-ionized water and NaCl and

CaCl₂ solutions of different concentrations. Results obtained show that the swelling pressure of the bentonite decreased with increasing concentration of infiltrating solutions, while the degree of the impact decreased with the increase of concentrations. Comparison shows that the impact of NaCl solutions on the swelling pressure and hydraulic conductivity was higher than that of CaCl₂ solutions at same concentrations. This may be explained by the impact of cation types on the microstructure of bentonite.

Zhang et al. (2014) observed that the swelling strain, compression index and secondary consolidation coefficient of highly compacted GMZ01 bentonite decreased as the concentration of NaCl solution increased. The hydraulic conductivity increases as the concentration of NaCl solution increases. However, this increase can be prevented if a high confining stress is applied.

2.14. HEAVY METALS

Heavy metals are commonly found in several kinds of wastes, landfill leachates and accounted for much of the contamination found at hazardous waste sites. Concentration of heavy metals ranges from 0 to 100 ppm in municipal solid waste and residual agricultural waste and from 100 to 10000 ppm in sewage sludge, mining waste and industrial wastes (Yong & Di Perno, 1991).

The heavy metals commonly found in landfill leachate include Pb, Cd, Cu, Ni, Fe and Se. Although the actual number and concentration of heavy metals in the leachate varies from one landfill to another, the concentration of most heavy metals are considerably above the allowable concentrations.

Metal species in leachate is of utmost concern because of the dangerous effects of heavy metals on the geo-environment. Heavy metals do not get degraded or destroyed and a small

extent of them generally enters human and animal bodies via food, drinking water, and air. In trace amounts, some heavy metals (e.g., copper, nickel, zinc) are good for all organisms, to accomplish specific catalytic functions. However, when it exceeds the permissible limits, all metals can disturb the metabolism by binding non-specifically to biomolecules and inflicting oxidative damage, due to their ability to catalyze redox reactions, which may result in damage to cellular structures (especially membranes), and DNA modification (mutagenesis). If human beings are exposed to high levels of metals it can cause acute toxicity symptoms, while long-term exposure to lower levels can cause allergies and even cancers.

2.15. REVIEW OF LITERATURES ON INTERACTION OF CLAY WITH HEAVY METALS

When the liner material comes in contact with the heavy metals, the properties of the material may get affected severely. Li and Li (2001) investigated the heavy metal sorption and hydraulic conductivity behaviour of three types of bentonite admixes, such as sand-bentonite, sand-bentonite-forest soil, sand-bentonite-spruce bark, in the presence of Cd, Pb, and Cu and reported that the forest soil admix exhibited the greatest heavy metal retention capacity. They also concluded that the mobility of Cd was 4.5 times higher than that of Pb, whereas, Cu was 2.5 times more mobile than Pb.

Abollino et al. (2001) reported on the adsorption of heavy metals on Na-montmorillonite as a function of pH. They found that the adsorption of metal ions decreases with decreasing the pH. At low pH (i.e. 2.5 to 3.5), the hydrogen ion competes with the heavy metals towards the superficial sites and also the Si-O and Al-O groups are less deprotonated and they form complexes with bivalent and trivalent ions in solution with greater difficulty.

Li (2003) examined the adsorptivity of different combinations of lead, copper and cadmium ions onto the kaolinite. Results of single Pb^{2+} , Cu^{2+} and Cd^{2+} solutions were compared with those of binary $Pb^{2+} + Cu^{2+}$, $Pb^{2+} + Cd^{2+}$, $Cu^{2+} + Cd^{2+}$ and ternary $Pb^{2+} + Cu^{2+} + Cd^{2+}$ solutions. Results indicated that the adsorptivity of heavy metal ions was slightly lower in binary and ternary solutions than for single ion species in the solution. Lo et al. (2004) studied the migration of heavy metals in saturated sand and bentonite / soil admixture using batch sorption and column tests and observed that the permeability of the compacted sand to be of six orders of magnitude higher than that of bentonite soil admixture when permeated with metal solutions of Pb, Zn, and Cd under an effective stress of 34.5 kPa. Nakano et al. (2008) investigated the lead retention mechanisms and hydraulic conductivity behaviour of three Japanese and one US bentonite where the bentonites were exposed to batch adsorption test, selective sequential extraction and consolidation tests. Their test results indicated that carbonate plays a major role at low Pb solution concentration and precipitate as $PbCO_3$. They also observed that the hydraulic conductivity for US bentonite was lowest in comparison to the Japanese bentonite due to its highest montmorillonite content and swelling capacity.

Du et al. (2015) conducted consolidation tests to evaluate the compressibility and hydraulic conductivity of clayey soil/calcium-bentonite backfills exposed to different levels of lead (Pb) contamination. It was observed that the Pb contaminated backfills exhibit a fifty fold increase in hydraulic conductivity when compared to clean backfills. The liquid limit, compression index and pH decreased as the Pb concentration increased. The changes in the liquid limit, compression index and hydraulic conductivity of the backfills with respect to the Pb concentration were attributed to the contraction of diffuse double layer of bentonite

2.16. SUMMARY AND CRITICAL APPRAISAL OF LITERATURE REVIEW

A reviewed of the literatures highlighted that liners are the most important component of a landfill system as it prevents the migration of harmful contaminants to the underlying hydrogeological environment. The leachates affect the hydraulic conductivity and swelling behaviour of the clay liner and amount of impact depends upon the clay mineralogy and the constituents of the leachate. The chemicals on permeation affect the soil fabric and porosity owing to the change in ion concentration, ion exchange, anion adsorption and dissociation. In addition to the contaminant solution, a change in the mineralogical composition such as montmorillonite content, cation exchange capacity, specific surface area, exchangeable sodium percentage of the bentonite also significantly influences its swelling and consequently the hydraulic conductivity behaviour. Since bentonite is a naturally occurring material, these mineralogical properties may vary to a great extent depending upon the source of its origin.

Very few of the past studies have focussed on the effect of the salt solution and mineralogical parameters on the swelling and consequently on the hydraulic conductivity and compressibility behaviour of bentonite together; where, most of the previous investigations mostly focused only on the study of the hydraulic conductivity of bentonite (Quirk and Schofield, 1955; Lee and Shackelford, 2005) or soil-bentonite mixtures (Mishra et al., 2009).

Similarly, up to date, most of the studies focused on the effect of a single species of ion on the behaviour of bentonite. However in reality, leachate generated from wastes consists of combination of various ions. Similarly, no study has been carried to compare the effect of the quality of the bentonite, which is marked by its swelling capacity, on the swelling and hydraulic behaviour in the presence of combination of inorganic salts and heavy metals.

Generally to achieve a lower value of hydraulic conductivity, bentonite is compacted at optimum moisture content (OMC) and maximum dry density (MDD) in the field. However, due to evaporation the compacted bentonite may lose some of its initial moisture which may affect its swelling and consequently its hydraulic behaviour. However, no study has been carried out to investigate the effect of the variation of the initial moisture content on the swelling, hydraulic and compressibility behaviour of compacted bentonite in the presence of salt solution.

2.17. OBJECTIVES OF THE PRESENT STUDY

The reviewed literature highlighted that there are considerable changes in the engineering properties of landfill liners when exposed to salts present in leachate. Studies on clay-pore fluid interactions are of utmost importance in assessing the quality and suitability of a liner material. Very few of the previous studies have focussed on the behavioural attributes such as swelling, hydraulic conductivity and consolidation behaviour of bentonites of different mineralogical properties in presence of chemicals and heavy metals ions of various concentrations. Hence, the primary objectives of the present study are;

- i) To investigate the effect of inorganic salts and heavy metals of various concentrations on the free swelling, Atterberg limits, swelling potential, swelling pressure, hydraulic conductivity of two bentonites with varying mineralogical composition and swelling capacity.
- ii) To investigate the effect of initial compaction conditions varying in their initial water content on the two bentonites in the presence of inorganic salts and heavy metals.
- iii) To investigate the effect of inorganic salts and heavy metals on various consolidation parameters such as; coefficient of volume change (m_v), coefficient of consolidation (c_v), time for 90% of consolidation (t_{90}), and compression index (C_c) of the bentonites.

iv) To investigate the combined effect of inorganic salt and heavy metals on the free swelling, Atterberg limits, swelling potential, swelling pressure, hydraulic conductivity and consolidation parameters of the bentonites.

2.18. SIGNIFICANCE OF THE STUDY

The anticipated significance of the study will be especially useful for the engineers who are involved in the design of the landfill liners, surface impoundment liners and vertical clay barriers. Since bentonite is widely used as a liner material at waste disposal sites, the results of this study may provide a general guideline for choosing the bentonite type for the liner application. This research will provide guidance for rational design of a proper containment system and will contribute to environmental geo-technology for prevention of pollutant migration. The result of the proposed study will be useful globally for industrialized countries and for the developing countries as a reference to prevent migration.

3.1. GENERAL

This chapter deals with the details about the materials and experimental methodology used to carry out this study. The methods of determining hydraulic conductivity and swelling pressure from one dimensional consolidation tests have also been discussed.

3.2. MATERIALS USED IN THE STUDY

3.2.1. Bentonite

Bentonites used in this study were procured from Rajasthan state of India and was in powdered form. The properties of bentonites are listed in Table 3.1. The data in the Table 3.1 shows that the Bentonite-B, which has a higher liquid limit, plasticity index, clay content, CEC, ESP, and SSA, is expected to swell more and exhibit a lower value of hydraulic conductivity (Mishra et al., 2011) in comparison to Bentonite-A and termed as a high quality bentonite.

3.2.2. Permeant liquids

Since Na^+ and Ca^{2+} are commonly found in waste leachates as well as in industrial process waters, they were chosen for the study. Solutions of 0 (i.e. De-ionized (DI) water), 0.01, 0.1 and 1 N concentrations were prepared by dissolving salt of NaCl and CaCl_2 (powdered with purity grade greater than 95%) in 1 L of DI water. Of the various metal species detected in leachate, Cu, Zn and Pb are the major pollutants causing health hazards and thus chosen for this study. Since it has been observed from the literature that the maximum concentration of the heavy metals present in a leachate is 1000 ppm (Prudent et al., 1996), the study was carried out up to 1000 ppm of these heavy metals.

Table 3.1 Properties of bentonites used in this study

Property	Bentonite-A	Bentonite-B
Liquid limit	218.0%	560.0%
Plastic limit	35.5%	36.0%
Plasticity index	182.5	524.0
Shrinkage limit	16.3%	19.7%
Specific gravity	2.8	2.82
Clay content	57.0%	68.0%
Silt content	43.0%	32.0%
Cation exchange capacity (CEC) (meq/100gm)	27.2	44.6
Na ⁺	10.5	24.2
K ⁺	3.4	1.9
Ca ²⁺	10.8	16.9
Mg ²⁺	2.5	1.6
Exchangeable sodium percentage (ESP)	38.8%	54.2%
Specific surface area (m ² /g)	339.2	456.1
Optimum moisture content (OMC)	33.1%	32.1%
pH	8.8	9.7
Maximum dry density (MDD) g/cc	1.23	1.28

3.3. TESTING METHODOLOGY

3.3.1. Atterberg limits

Atterberg limits were determined according to ASTM D 4318 (2000). Casagrande apparatus was used to determine the liquid limit (Fig. 3.1). The plastic limit was determined with the thread-rolling method.

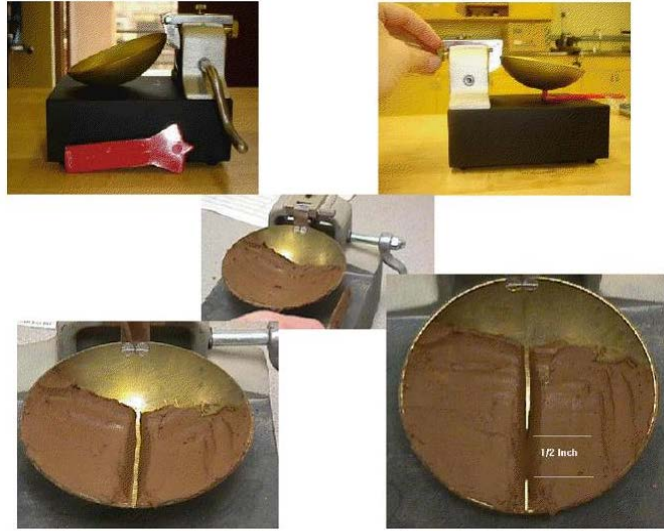


Figure 3.1 Casagrande apparatus for determination of liquid limit

3.3.2. Free Swelling test

Free swelling tests for the bentonites were conducted according to ASTM D5890 (2001). Approximately 90 ml of DI water or various concentrations of salt solutions, heavy metals were poured into a 100 ml graduated cylinder. Two grams of dry bentonite was put into the cylinder and the respective DI water or solution was used to rinse down any bentonite particles adhering to the sides of the cylinder and then it was filled up to the 100 ml mark. The swollen volume of the bentonite was measured after 24 hour of exposure. Figure 3.2 represents free swelling test carried out in the laboratory.

3.3.3. Compaction test

The compaction characteristic of bentonites, i.e. maximum dry density (MDD) and optimum moisture content (OMC), were determined as per as ASTM D698 (2012).

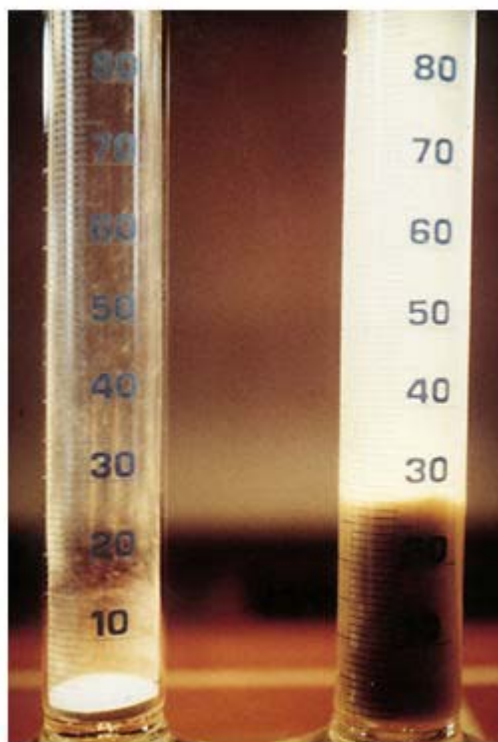


Figure 3.2 Free swelling test

3.3.4. Cation Exchange Capacity (CEC)

The cation exchange capacity (CEC) is the quantity of exchangeable cations required to balance the negative charge on the surface of the clay particles. CEC is expressed in milliequivalent per 100 grams of dry clay. The cation exchange capacity (CEC) and exchangeable cations of the bentonites were determined by the ammonium acetate method as described by Chapman (1965) and Pratt (1965) respectively. 125 ml of 1 M ammonium acetate (NH_4OAc) was added to 25 g of soil and allowed to stand 16 hours. The soil was washed 4 times with 25 ml additions of NH_4OAc , allowing each addition to filter through but not allowing the soil to crack or dry. Exchangeable cations were determined on the leachate after diluting it to 250 ml.

3.3.5. Specific Surface Area (SSA)

Specific surface is the ratio of the surface area of a material to its mass and expressed in m^2/gm . Smaller the particle size higher is the specific surface area. Higher is the specific surface area, higher is the amount of charge on its surface and higher will be the amount of water or contaminant it can adsorb. The specific surface area of the bentonites was determined by the method described by Cerato and Lutenegeger (2002). This test involved saturating a soil sample with ethylene glycol mono-ethyl ether (EGME) and then removing the excess EGME in a vacuum desiccator, until the EGME forms a monomolecular layer on the soil surface. One gram of oven dried soil was placed in a glass tare and mixed with 3 ml of EGME. The tare was placed into a vacuum desiccator and it was evacuated by a vacuum pump using a vacuum of atleast 635 mm Hg. The weight of the mixture was taken at regular intervals till the weight did not vary more than 0.001 g between two successive readings. SSA was calculated according to

$$\text{Specific Surface Area (SSA)} = \frac{W_a}{0.000286W_s}$$

Where,

W_s = Weight of soil added initially (g)

W_a = Weight of EGME retained by the sample in grams (final slurry weight - W_s)

0.000286 = Weight of EGME required to form a monomolecular layer on a square meter

3.3.6. X-ray diffraction (XRD) method

In XRD method the material is exposed to a filtered X-ray beam. The beam passes into the material and cause the electron in the atoms of the minerals to vibrate and reflect the beams through successive planes. The method involves increasing of incidence angle and monitoring the intensity of the diffracted X-radiation until a maximum value of the

diffracted intensity is achieved. The X-ray diffraction maximum is detected whenever the following equation is satisfied;

$n\lambda = 2d \sin \theta$, $n = 1, 2, 3, \dots$, λ = wave length, d = space between the diffracting planes, θ = angle of diffraction. Figure 3.3 and 3.4 shows X-ray diffraction patterns of Bentonite-A and -B

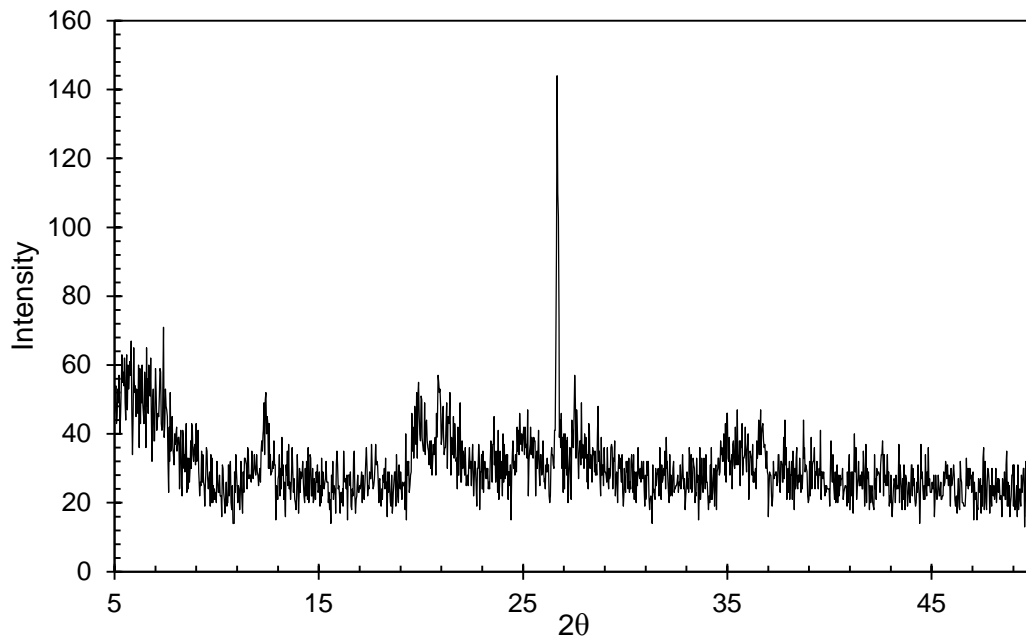


Figure 3.3 X-ray diffraction result of Bentonite-A

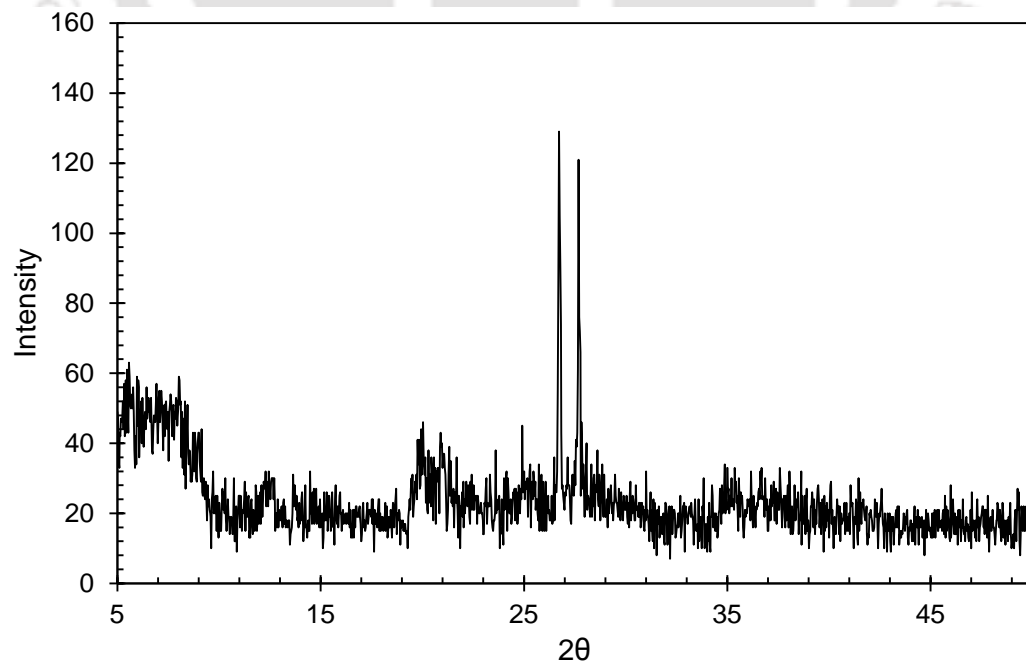


Figure 3.4 X-ray diffraction result of Bentonite-B

3.3.7. Consolidation test

In order to assess the hydraulic conductivity and compressibility, consolidation test was carried out. Figure 3.5 shows the oedometer test set up used in carrying out consolidation test. Indirect determination of the hydraulic conductivity from consolidation test has several advantages and disadvantages over permeability tests, which are as follows;

- (1) can apply vertical pressure simulating those in field;
- (2) can measure vertical deformations;
- (3) can test sample under a range of vertical stresses;
- (4) thin samples permit short testing time;
- (5) cost effective method for obtaining hydraulic conductivity data over a range sample states;

However it has also some disadvantages over other methods. These are,

- (1) Some soil types may be difficult to trim into consolidation ring;
- (2) Thin samples may not be representative;
- (3) Potential for side wall leakage;

Despite of some disadvantages, the consolidation permeability test is potentially the most useful among the other methods viz. rigid wall permeameter and flexible wall (triaxial) permeameter because of the flexibility which it offers for testing specimens under a range of confining stresses and for accurate determination of the change in sample thickness as a result of both seepage forces and chemical influence on the soil structure. Pore fluid replacement can be achieved in short time as in this method the sample thickness is thin compared to other test.

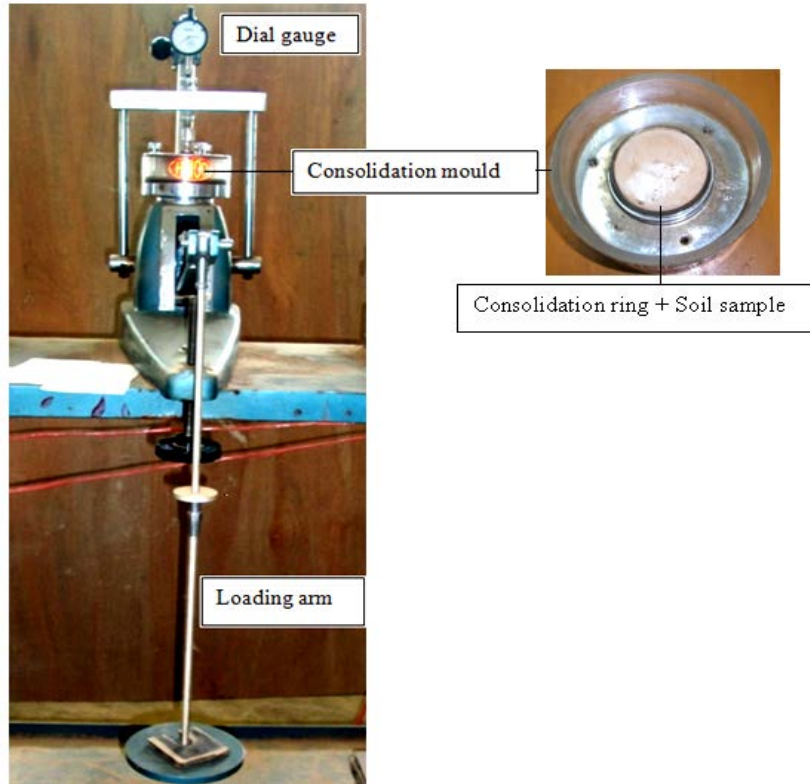


Figure 3.5 Oedometer test set up

3.3.7.1. Determination of hydraulic conductivity and compressibility

Consolidation test was carried out in a standard consolidometer of 60 mm in diameter and 15 mm in thickness sample according to ASTM D 2435 (1996). To attain the moisture equilibrium bentonites were kept in humidity controlled desiccators for 24 hours after mixing at their respective OMC. The moisture-equilibrated specimens were then statically compacted to its MDD in oedometer rings of a diameter of 60 mm to a thickness of 15 mm to an initial porosity of 55.9 % and 54.7 % and degree of saturation of 75.1 % and 76.1 % for Bentonite-A and -B, respectively. Then entire assembly was placed in a consolidation cell and positioned in the loading frame and inundated in DI water or respective salt solutions under a nominal pressure of 4.9 kPa and allowed to swell. Once the swelling was completed, the samples were

consolidated by increasing the pressure gradually by an increment ratio of 1 (i.e. increased by 4.9, 9.8, 19.6 kPa at each step) to a maximum pressure of 784.5 kPa. For each pressure increment the change in the thickness of soil sample was measured from the dial gauge readings. The change in the void ratio corresponding to the increase in the overburden pressure was calculated as,

$$\Delta e = \Delta H(1+e_0)/H \quad (\text{Eq. 3.1})$$

where,

ΔH is the change in the thickness of sample due to increase in pressure

H is the initial thickness of the sample; e_0 is the initial void ratio

From the consolidation test result, a time-settlement curve was obtained at each pressure increment. The coefficient of consolidation (c_v) was obtained using Taylor's square root time (\sqrt{T}) method (Taylor, 1948).

The coefficient of volume change was calculated as,

$$m_v = -\frac{\Delta\sigma}{\Delta e} \times (1+e_0) \quad (\text{Eq. 3.2})$$

$\Delta\sigma$ is the change in pressure

Δe is the change in void ratio

The hydraulic conductivity (k) was calculated by fitting Terzaghi's theory of consolidation (Terzaghi, 1943) for various pressure increments using the c_v and m_v as,

$$k = c_v m_v \gamma_w \quad (\text{Eq. 3.3})$$

where,

γ_w is the unit weight of the pore fluid

Coefficient of consolidation (c_v) was determined by the square root of time fitting method given by Taylor (1942) as shown in Fig. 3.6.

$$c_v = \frac{D^2 T_v}{t_{90}} \quad (\text{Eq. 3.4})$$

t_{90} = Time at 90% degree of consolidation (U)

U = Degree of consolidation

$D = H/2$ for double drainage

= H for single drainage

T_v = Time factor (0.848 for 90 % of consolidation).

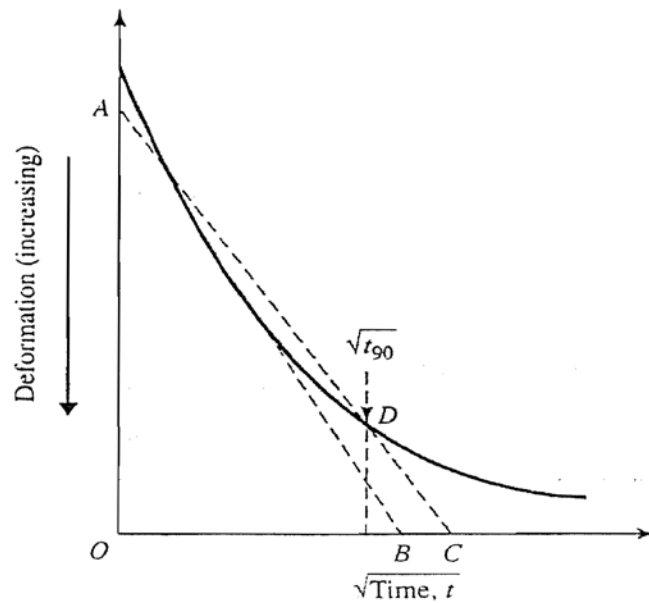


Figure 3.6 Taylor's square root-of time fitting method (Das, 2006)

Compression index (C_c) for the samples was calculated as the slope of the straight line portion of virgin void ratio (e) - log pressure (P) curve as;

$$C_c = - \frac{e_i - e_j}{\log \frac{P_i}{P_j}} \quad (\text{Eq. 3.5})$$

where,

e_i and e_j are the void ratio corresponding to the consolidation pressure of P_i and P_j at i^{th} and j^{th} steps of loading respectively

3.3.7.2. Determination of swelling potential and swelling pressure

A conventional oedometer apparatus was used for the determination of the swelling potential and swelling pressure of compacted bentonite sample. A surcharge load of 4.9 kPa was applied, then the specimen was inundated with saturating liquid and the values of swelling with time were recorded. The measurements continue until the swelling increment reach negligible values. At this point a standard consolidation test was conducted by applying incremental loads starting with 4.9 kPa and ending with 784.5 kPa. The pressure required to revert the specimen to its initial void ratio was determined as the swelling pressure, which is defined as the value of pressure required to keep the sample at zero swelling after saturating it with saturating fluid. The swelling potential is defined as the percentage swelling of the soil. The details of this method have been described by Sridharan et al. (1986a). The point SP in Fig. 3.7 corresponds to swelling pressure of the compression curve

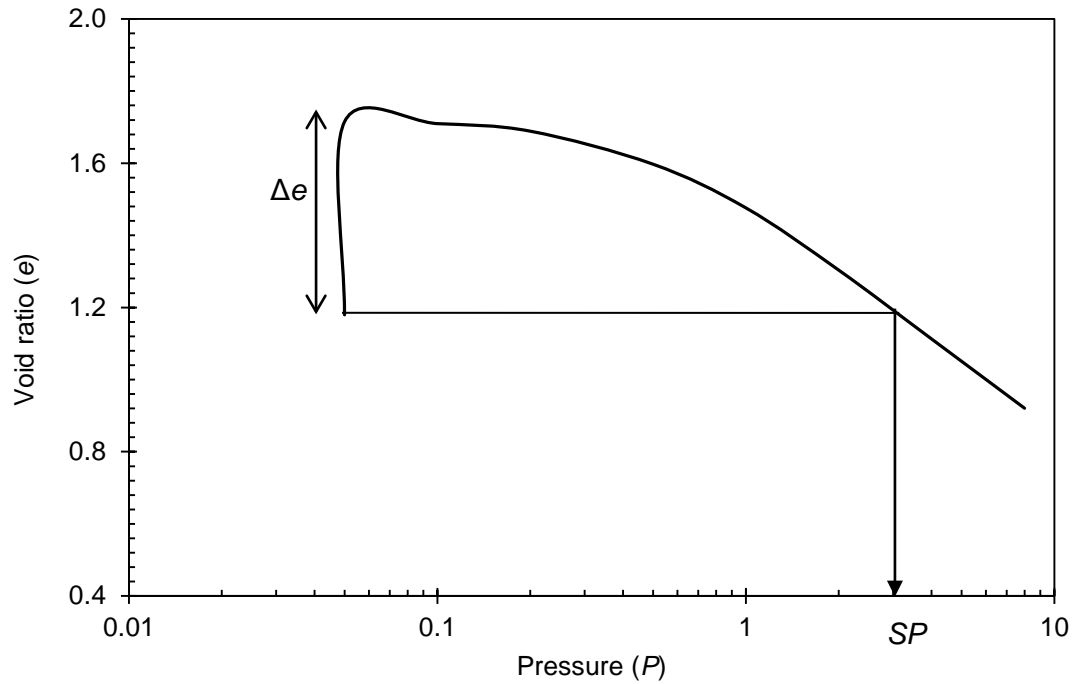


Figure 3.7 Determination of swelling pressure and swelling potential

Swelling potential (SP) for the samples was calculated as;

$$\text{Swelling Potential (SP)} = \frac{\Delta e}{1 + e_0} \quad (\text{Eq. 3.6})$$

where,

Δe is the change in the void ratio of the sample due to swelling and e_0 is the initial void ratio before swelling.

EFFECT OF INORGANIC SALTS ON THE BEHAVIOUR OF BENTONITES

4.1. INTRODUCTION

Due to its high swelling and low hydraulic conductivity, bentonite is widely used as a liner material at the waste disposal site (Daniel, 1984). However, chemicals present in the leachate suppress the thickness of diffuse double layer which in turn shrinks the swollen bentonite (Norrish and Quirk, 1954) and increases the hydraulic conductivity (Quirk and Schofield, 1955; Madsen and Mitchell, 1989). Hence, in order to design a clay liner it is quite essential to study the behaviour of bentonite in the presence of various chemicals present in the leachate.

Many studies have been carried out in the past to investigate the effect of chemicals on the behaviour of bentonite (Mesri and Olson, 1971b; Shackelford et al., 2000; Thammathiwat and Chimoye, 2010; Shirazi et al., 2011) which has been discussed in Chapter 2. However, very few of the previous studies have focused on the effect of the mineralogical parameters on the swelling and consequently on the hydraulic conductivity of bentonite. Quirk and Schofield (1955) concluded that the hydraulic conductivity of soil decreases with increasing the exchangeable sodium percentage (ESP), whereas, Martin et al. (1964) had shown that the hydraulic conductivity of soil has a definite relationship with the ESP at different pH levels.

Since bentonites with different mineralogical composition may behave differently in the presence of salt solution, it is quite essential to study the behaviour of different bentonite in the presence of salt solution. Lee and Shackelford (2005) studied the differences in hydraulic conductivity for two GCLs containing different qualities of bentonite and concluded that GCL with a higher quality of bentonite is more susceptible to chemical attack in comparison to the GCL with lower quality bentonite. From their studies Mishra et

al. (2009) concluded that the salt affect the hydraulic conductivity significantly of the mixture containing higher quality of bentonite characterized by a higher ESP, swelling and liquid limit.

Similar to the hydraulic conductivity, compressibility is one of the most important properties which help in evaluating the settlement of the liner material due to the overburden weight of waste at the waste disposal site (Mishra et al., 2010). The compressibility behaviour of the bentonite is controlled by both mechanical and physico-chemical factors (Bolt, 1956). The short-range particle interaction controlled by the physical properties such bending, sliding, rolling, and crushing of soil particles controls the mechanical effect of the compressibility of bentonite, whereas, physico-chemical interactions between particles depend on long-range interaction between the particles through the diffuse double layer (Sridharan and Rao, 1973; Sridharan and Jayadeva, 1982; Mitchell and Soga, 2005).

Due to their importance on the compressibility behaviour various parameters of the compressibility such as, compression index (C_c), coefficient of volume change (m_v), coefficient of consolidation (c_v) and time to complete 90% of the consolidation (t_{90}) has attracted much attention among the researchers.

Limited studies have been carried out in the past to investigate the effect of mineralogical and chemicals factors on the compressibility and consolidation behaviour of bentonite. From a series of experiments Salas and Serratos (1953) concluded that the compressibility of monovalent bentonites decreased in the order lithium bentonite > sodium bentonite > potassium bentonite. Sridharan et al. (1986b) studied the compressibility characteristics of bentonites homoionized with a series of monovalent, divalent and trivalent cations and concluded that a decrease in the cation valence and increase in hydrated cationic radius increases the compressibility. They also concluded that the size of the hydrated cation is

more pronounced for monovalent cations in comparison to divalent and trivalent cation. Study by Robinson and Allam (1998) on kaolinite, illite, montmorillonite clay concluded that the mineralogy of clay plays a significant role in consolidation behaviour. Mishra et al. (2010) studied the influence of bentonite on the consolidation behaviour of soil-bentonite mixtures and concluded that C_c of the mixtures increase with the increase in the liquid limit, free swelling and clay fraction of the bentonites, whereas, the c_v increases with the increase in the consolidating pressure. Shariatmadari et al. (2011) studied the effect of three inorganic salts, i.e. NaCl, CaCl₂, and MgCl₂ on compressibility behaviour of mixtures of Iranian clay and bentonite mixed in various proportions and observed that C_c of the mixtures decreases with the increase in the salt concentration. From their experiments on the mixture of sand and polymerized bentonites mixed in various proportions, Bohnhoff and Shackelford (2014) concluded that with the increase in the pressure m_v decreases and c_v increases.

This chapter deals with the study to investigate the effect of inorganic salts of NaCl and CaCl₂ of different concentrations on the Atterberg limits, free swelling, hydraulic conductivity, swelling potential, swelling pressure and various consolidation parameters such as C_c , c_v , m_v , & t_{90} of two bentonites of varying mineralogical composition and swelling capacity at two different compaction conditions.

4.2. RESULTS AND DISCUSSION

4.2.1. Atterberg limits

The Atterberg limits have been shown to be useful indicators of clay behaviour (Jefferson and Rogers, 1998). The effect of salt solutions on the Atterberg limits of Bentonite-A and Bentonite-B is shown in Fig. 4.1. The data shows that the liquid limits of both the bentonites decreased with an increase in the salt concentrations. The liquid limit of Bentonite-A, which has a lower cation exchange capacity (CEC), specific surface area

(SSA) and ESP, decreased from 218.0 % with DI water to 94.9 % and 90.0 % with 1 N concentration of NaCl and CaCl₂ solution, respectively. In contrast, the liquid limit of Bentonite-B, which had a higher CEC, SSA and ESP, decreased from 560.0 % with 0 N (i.e. DI water) to 112.0 % and 107.0 % with 1 N concentration of NaCl and CaCl₂ solution, respectively. Interparticle forces have a more prominent role in determining the liquid limit. The distance between particles, or between structural units of particles, is such that the forces of interaction between the clay particles become sufficiently weak to allow easy movement of particles relative to each other. In high-swelling clays such as bentonite, the dominant interparticle force is one of repulsion. This force of repulsion determines the distances between particles. The increase in the salt concentration and the cation valency decreases the inter-particle repulsion which leads the particles to become free to move at lower water contents or lower inter-particle distances, resulting in a decrease in the liquid limit (Warkentin, 1961; Sridharan and Rao, 1975).

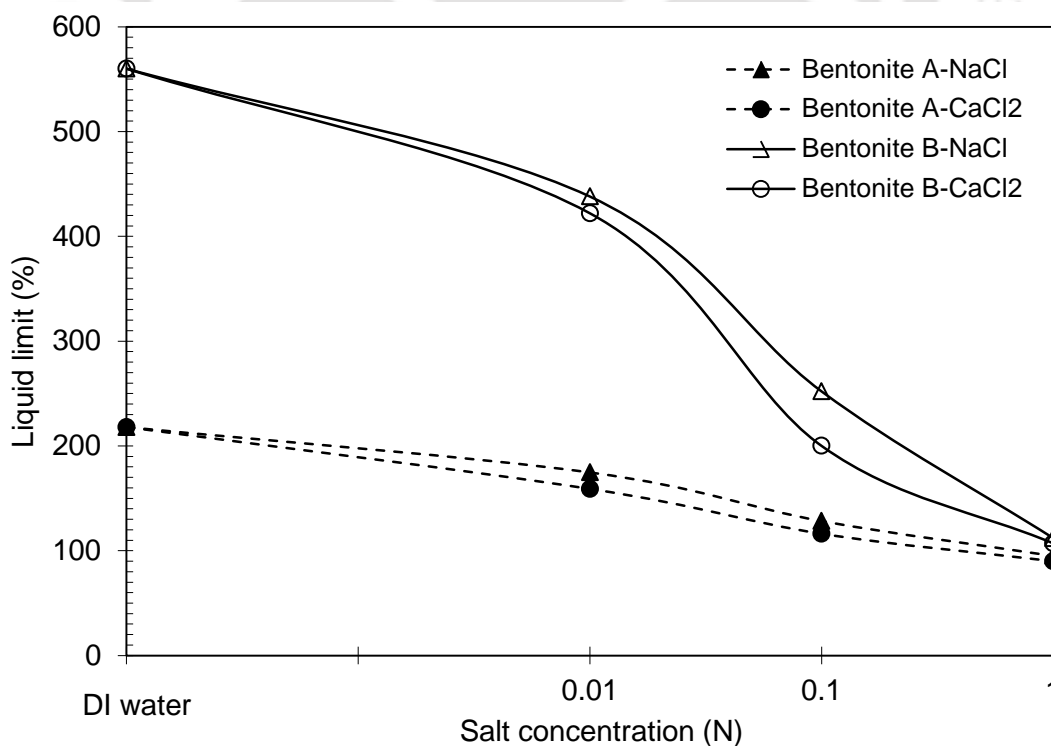


Figure 4.1 Plots for the liquid limit of Bentonite -A and -B at various concentrations of NaCl and CaCl₂ solution

The data also shows that for any given concentration, bentonite with NaCl solution exhibited a higher value of liquid limit in comparison to CaCl₂ solution. This can be attributed to the formation of a relatively large diffuse double layer thickness in the presence of NaCl solution in comparison with the same concentration of CaCl₂ solution. However, the difference in the liquid limit for the two salts decreased with the increase in the salt concentration and reached to an almost identical value at 1 N. Since the diffuse double layer thickness decreases significantly at 1 N concentration of both NaCl and CaCl₂ solution (Norrish and Quirk, 1954), almost an equal value of liquid limit was observed at 1 N concentration for both the bentonites.

A comparison between the values of liquid limits for the two bentonites at the same concentration indicated that Bentonite-B, with a higher CEC, ESP and SSA value, exhibited a higher value of liquid limit in comparison to Bentonite-A. The plot shows that the liquid limit of the Bentonite-B decreased more significantly in comparison to the Bentonite-A, where, the liquid limit of Bentonite-B was decreased from 560.0 % to 107.0 % in comparison to a decrease from 218.0 % to 90.0 % for Bentonite-A due to an increase in the concentration from 0 to 1 N of CaCl₂ solution. This decrease in liquid limit was more significant at salt of 0.1 N or higher concentration. Similarly, the plot also shows that the CaCl₂ solution decreased the liquid limit of bentonite more significantly in comparison to similar concentration of NaCl solution.

Plastic limit of clay is the lower boundary of water content at which clay still exhibits plastic properties. In plastic state, in order to take up a new position the soil particles should be able to move or slide past one another and retain this new equilibrium position; however, the cohesion between the particles should be low enough to permit this movement of the particles and strong enough to hold the particles in its new equilibrium position (Yong and Warkentin, 1975). The plot between the salt concentration and plastic

limit in Fig. 4.2 shows that the plastic limit of both the bentonites increased marginally due to increase in the salt concentration indicating that plastic limit is very much insensitive to change in pore water chemistry. The marginal increase in the plastic limit could be due to development of more flocculated structure which would require more water to fill its void (Barbour and Yang, 1993).

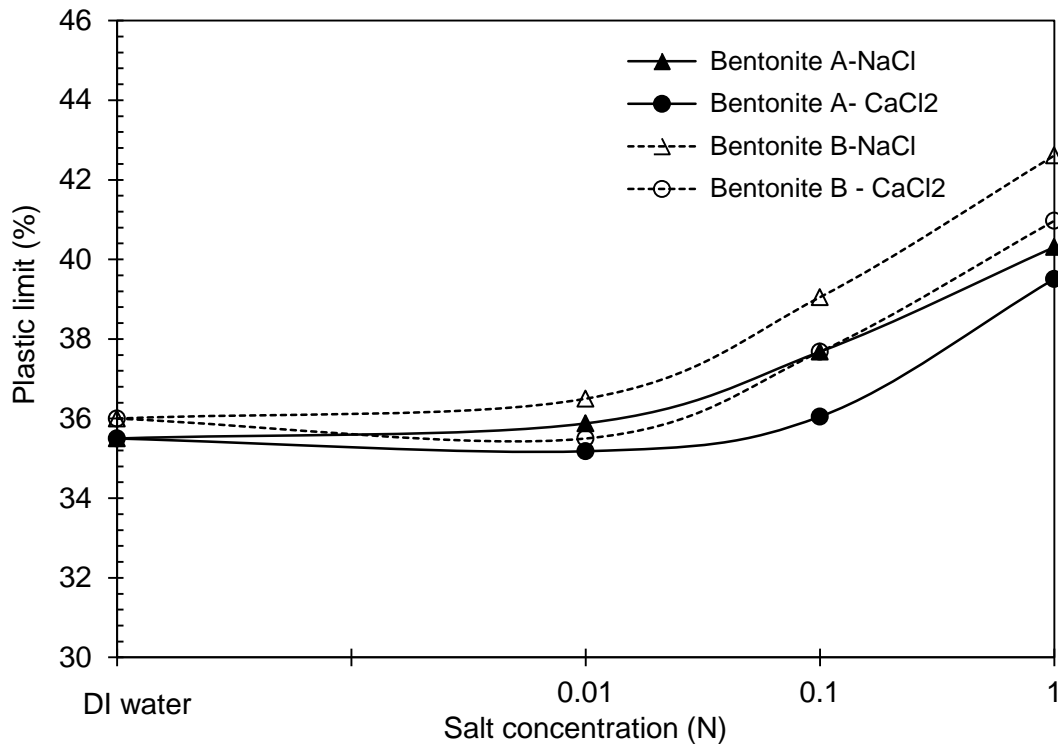


Figure 4.2 Plots for the plastic limit of Bentonite-A and -B at various concentrations of NaCl and CaCl₂ solution

4.2.2. Free swelling

Free swelling of bentonite is defined as the increase in the volume of the bentonite due to imbibing of water in the absence of any external overburden pressure. The effect of various concentrations of NaCl and CaCl₂ on free swelling of the bentonites is shown in Fig. 4.3. The plot in the figure shows that the free swelling decreased with increasing the concentration of NaCl and CaCl₂ solution. A higher swelling was observed with NaCl solutions in comparison to the same concentration of CaCl₂ solutions. Since osmotic as well as inner-crystalline swelling takes place with NaCl solution, which allows the

interlayer spacing to become large, a higher swelling was observed for NaCl solution. In contrast to this, the amount of osmotic swelling decreases in the presence of CaCl₂ solution, resulting in a reduction in the swelling of bentonite (Norrish and Quirk 1954; Zhang et al., 1995).

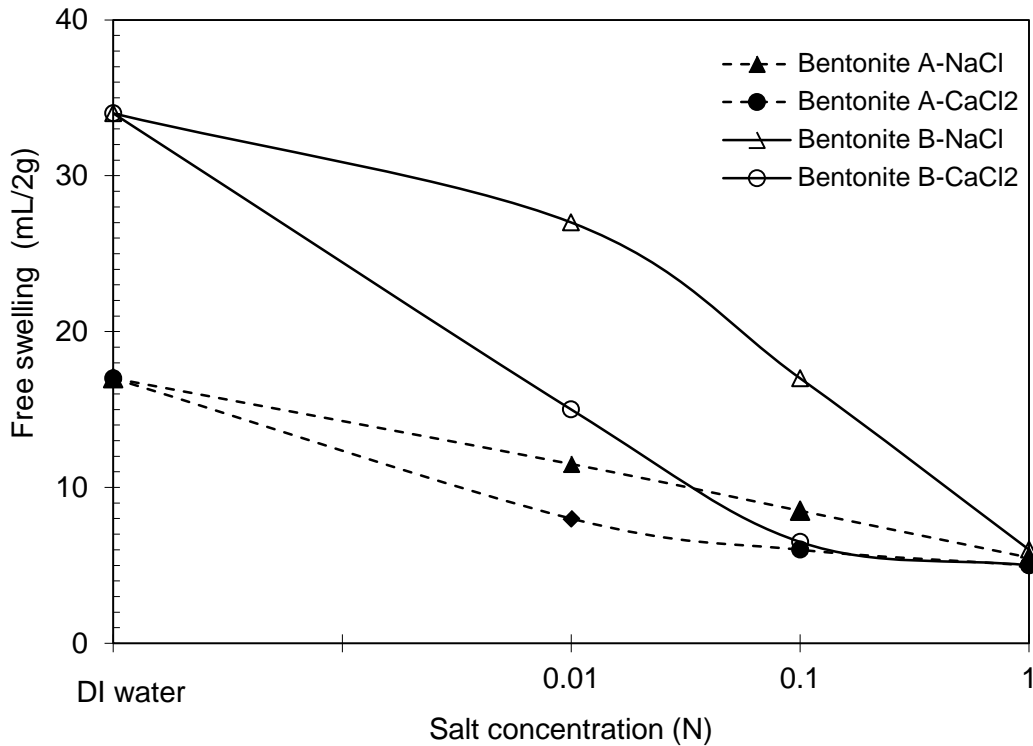


Figure 4.3 Plots for the free swelling of Bentonite -A and -B at various concentrations of NaCl and CaCl₂ solution

Similar to the liquid limit, almost an identical value of free swelling was observed at 1 N concentration of both NaCl and CaCl₂ solution. The free swelling of Bentonite-B was found to decrease significantly due to the increase in the salt concentration in comparison to Bentonite-A. However, a non-uniform decrease in the free swelling with salt concentration was observed. With an increase in the concentration from 0 to 0.01 N of NaCl solution the free swelling decreased from 34 mL/2g to 27 mL/2g for Bentonite-B and from 17 mL/2g to 11 mL/2g for Bentonite-A. A further increase in the concentration from

0.01 to 1 N of NaCl decreased the free swelling from 27 mL/2g to 6 mL/2g for Bentonite-B and from 11 mL/2g to 5 mL/2g for Bentonite-A. In contrast to this, the trend for the decrease in the free swelling with increase in the concentration of CaCl₂ solution was quite different to that for NaCl solution. With an increase in the concentration from 0 to 0.01 N of CaCl₂ solution the free swelling decreased from 34 mL/2g to 15 mL/2g for Bentonite-B and from 17 mL/2g to 8 mL/2g for Bentonite-A. However, a further increase in the concentration from 0.01 to 1 N of CaCl₂ decreased the free swelling only from 15 mL/2g to 5 mL/2g for Bentonite-B and from 8 mL/2g to 5 mL/2g for Bentonite-A. The plot also shows that Bentonite-B gets affected significantly due to increase in the concentration from 0 to 1 N of both NaCl and CaCl₂ solution in comparison to Bentonite-A. A higher reduction in the free swelling of Bentonite-B can be attributed to the significant reduction in the DDL thickness due to the addition of salt solutions.

4.2.3. Time swelling relationship

The swelling in bentonites is a result of changes of the interlayer structure within the expansive clay minerals, i.e. particle–water–cation interactions. Figures 4.4 to 4.7 show the relationship between the swelling of bentonite expressed in percentage and elapsed time for the samples in the presence of various concentrations of NaCl and CaCl₂ solution and compacted at two different compaction conditions. Swelling of the bentonite at any time was calculated as the ratio between the total increase in the height at that time to the initial height of sample and expressed in percentage. Irrespective of their initial compaction condition and type of saturating fluid, the time-swelling curve followed a “S” shape in which initially the bentonite swelled slowly, then the swelling increased steeply and reached to an asymptotic value. The plots show that the sample swells in three stages and named as initial, primary and secondary swelling (Rao et al., 2006; Mishra et al., 2008). In the first stage of swelling, termed as initial swelling, a marginal increase in swelling was

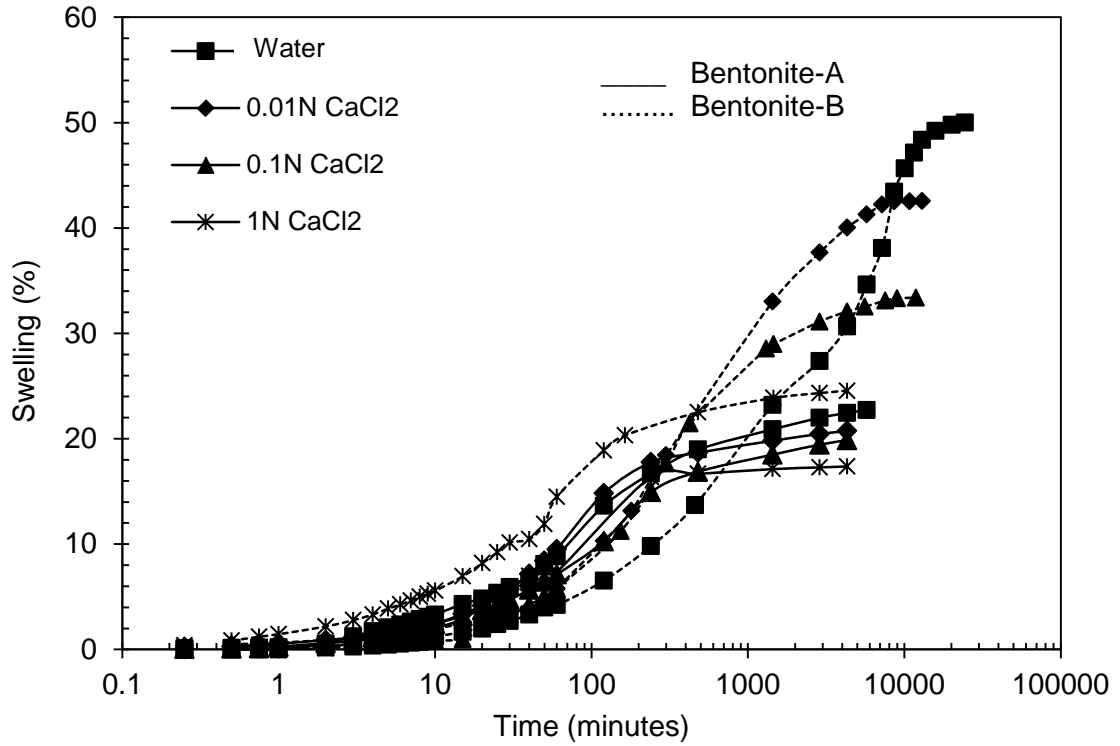


Figure 4.4 Time–swelling plot at different concentrations of CaCl₂ solution for Bentonite-A and -B compacted at MDD-OMC

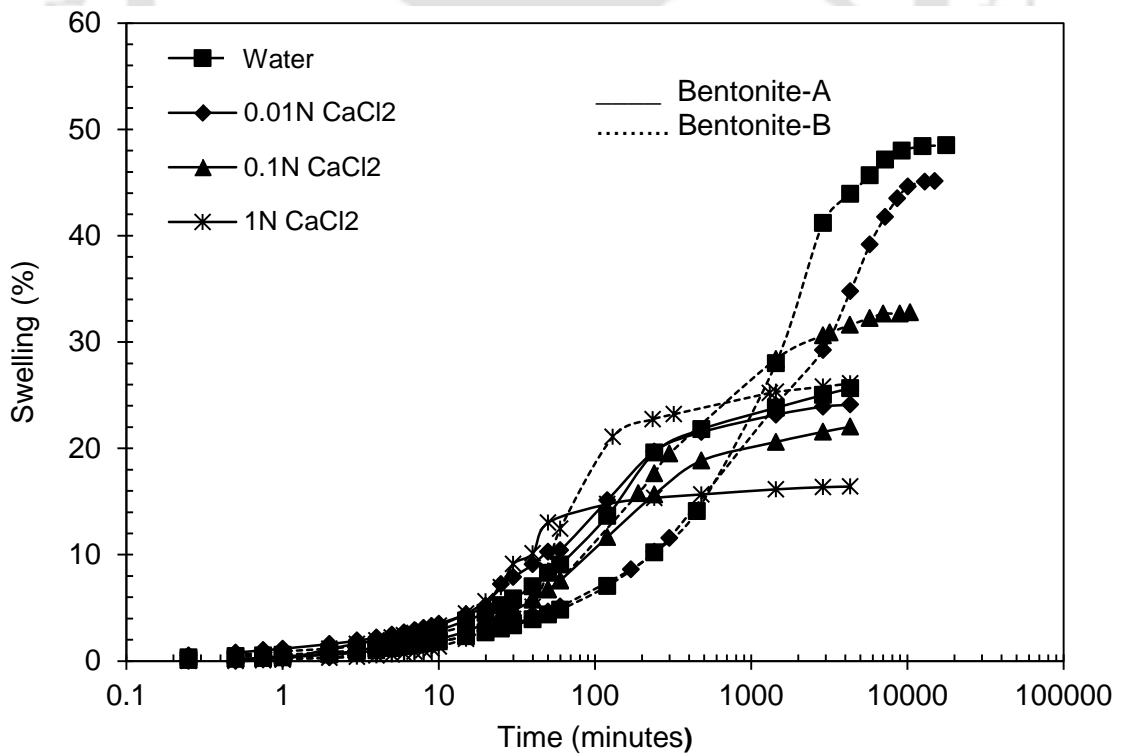


Figure 4.5 Time–swelling plot at different concentrations of CaCl₂ solution for Bentonite-A and -B compacted at MDD-5% dry of OMC

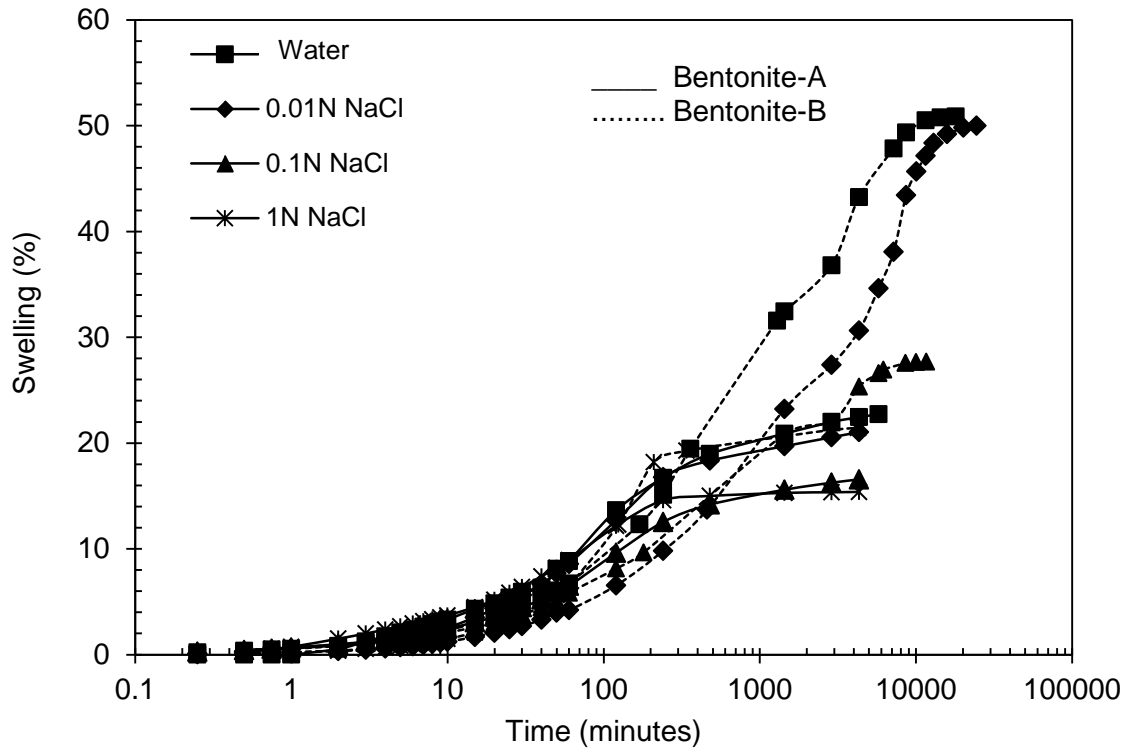


Figure 4.6 Time–swelling plot at different concentrations of NaCl solution for Bentonite-A and -B compacted at MDD-OMC

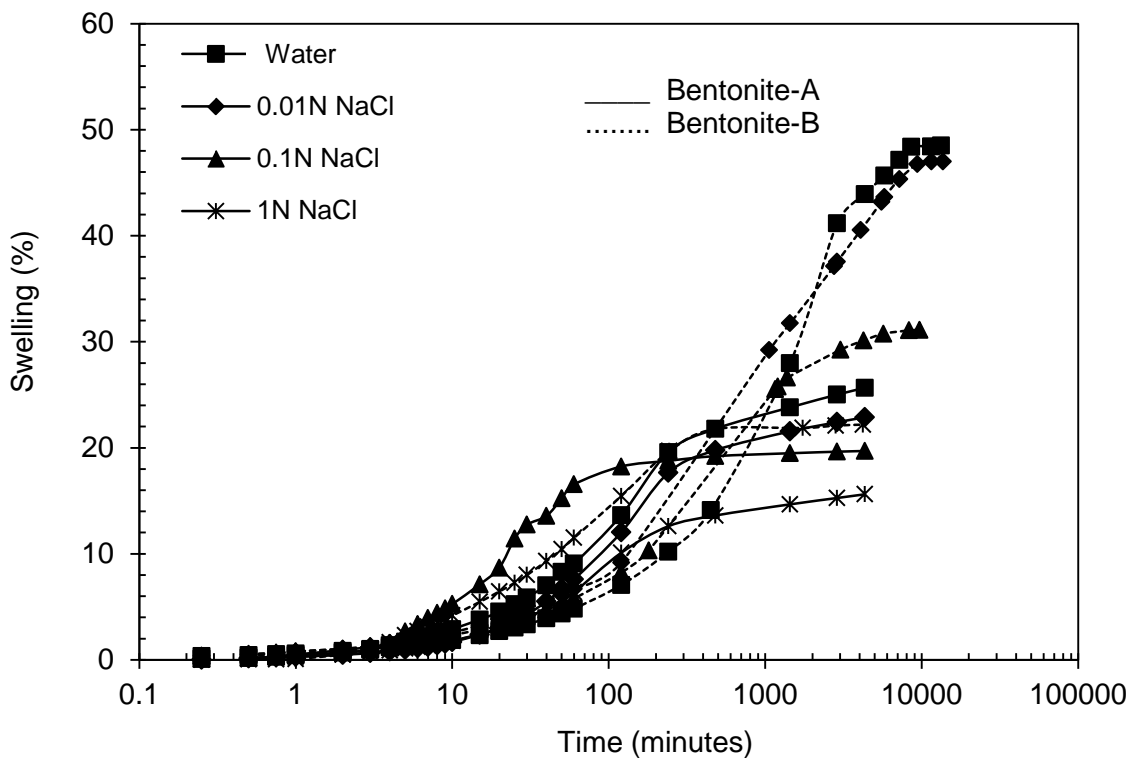


Figure 4.7 Time–swelling plot at different concentrations of NaCl for Bentonite-A and -B compacted at MDD-5% dry of OMC

observed for all the samples irrespective of their initial compaction condition and type of saturating liquid. In the second stage of swelling, termed as primary swelling, a significant amount of swelling was observed for all the samples. In the final stage of swelling, termed as the secondary swelling, again a marginal swelling was observed for all the samples. Primary swelling develops relatively rapidly, as it is linked to the rate of matric suction dissipation. Furthermore, the dependence of primary swelling duration on the rate of matric suction dissipation causes the primary swelling durations to be independent of salt concentrations. Since the secondary swelling is controlled by diffusion of salts it develops more slowly. A longer period is also needed to complete secondary swelling, perhaps because ionic diffusion is affected by adsorption–desorption reactions (Shackelford & Daniel, 1991).

A comparison between the two bentonites in Figs. 4.4 to 4.7 showed that at the same time elapsed, the percentage of swelling was more for Bentonite-B, which possess a higher CEC, ESP and SSA value, in comparison to Bentonite-A. Irrespective of the bentonite quality, swelling was least in presence of high concentration solutions. Samples compacted at dry side of OMC exhibited a higher percentage of swelling in comparison to the samples compacted at OMC.

4.2.4. Swelling potential

The swelling potential is defined as the percentage of swelling of a compacted, laterally confined sample, which has been soaked in a saturating liquid under a surcharge pressure of 4.9 kPa. Figure 4.8 shows the effect of salt concentration, salt type and initial water content on the swelling potential of the two bentonites. Irrespective of initial water content the swelling potential of bentonite decreased with increase in the salt concentration. The reduction in the swelling potential with increase in the salt is attributed to the decrease in the diffuse double layer thickness. A comparison between the two bentonites showed that

the swelling potential of Bentonite-B was affected significantly due to the increase in the concentration of the salt solution. Due to increase in the concentration from 0 to 1 N of NaCl solution the swelling potential for Bentonite-B compacted at OMC-MDD decreased from 48.4 % to 24.5 %; whereas, it decreased from 21.1 % to 13.5 % for Bentonite-A. Similarly, due to increase in the concentration from 0 to 1 N of CaCl₂ solution the swelling potential for Bentonite-B compacted at OMC-MDD decreased from 48.4 % to 21.4 %, whereas, it decreased from 21.1 % to 13.7 % for Bentonite-A.

In addition to this, the decrease in the swelling potential with increase in salt concentration was found to follow different trends for different concentrations of NaCl and CaCl₂ solution. An increase in the concentration from 0 to 0.01 N solution decreased the swelling potential of both the bentonites marginally, whereas, a further increase in the concentration the swelling potential decreased significantly. The swelling potential of Bentonite-B compacted at OMC-MDD decreased marginally from 48.4 % to 48.2 % with an increase in the concentration from 0 to 0.01 N of NaCl solution, however, with a further increase in the concentration from 0.01 to 1 N the swelling potential decreased significantly from 48.2 % to 24.5 %. Similarly, the swelling potential of Bentonite-B compacted at OMC-MDD decreased from 48.4 % to 42.2 % with an increase in the concentration from 0 to 0.01 N of CaCl₂, however, a further increase in the concentration from 0.01 to 1 N the swelling potential decreased significantly from 42.2 % to 21.4 %.

Figure 4.8 also shows that, irrespective of the salt concentration, samples compacted on the dry side of the OMC possessed a higher value of swelling potential in comparison to the samples compacted at OMC. Samples compacted on the dry side of OMC possessed a higher suction values (Chen, 1975) resulting in a higher swelling potential. Plot shows that the initial moisture content has more influence on the swelling potential for the pore fluid of low concentration.

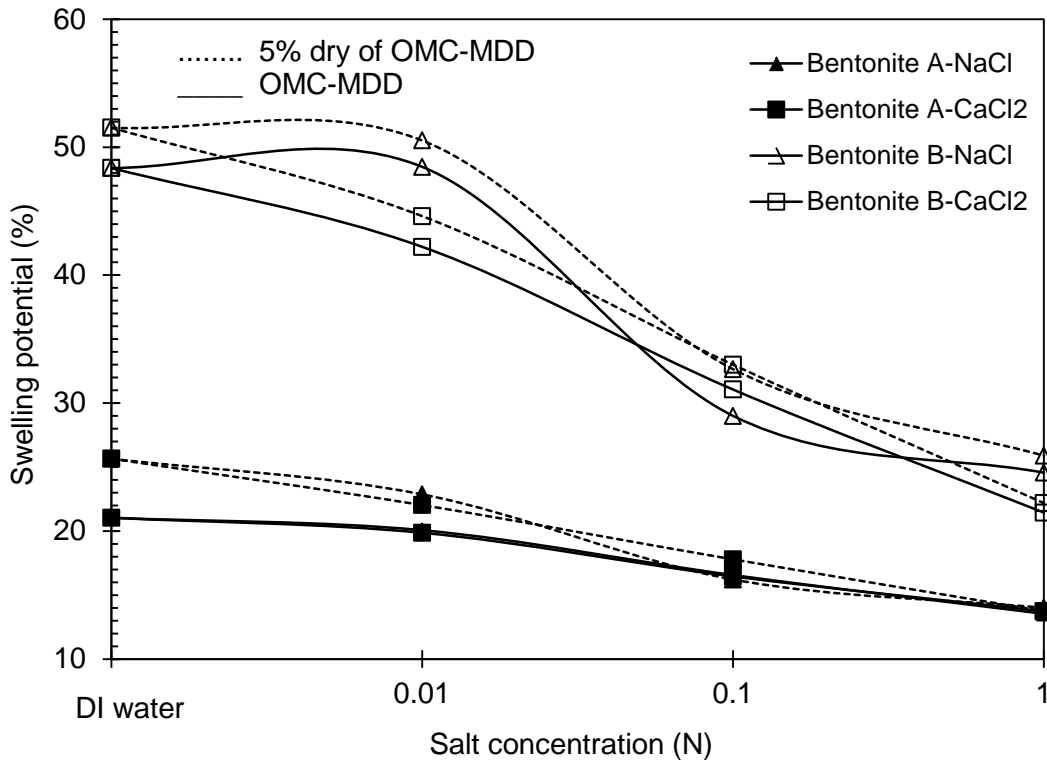


Figure 4.8 Effect of salt concentrations on swelling potential of Bentonite-A and -B at different compaction conditions

4.2.4.1. Relationship of the swelling potential with free swelling and liquid limit

Further to study the influence of free swelling and liquid limit on the swelling potential of bentonite, graphs were plotted between these parameters. Figure 4.9 shows the relationship between swelling potential and free swelling for the bentonites. From Fig. 4.9 it can be concluded that swelling potential increases with an increase in the free swelling of bentonite. Irrespective of the bentonite quality, samples with CaCl_2 solution exhibited higher increase in swelling potential with an increase in free swelling in comparison to NaCl solution. The increase in swelling potential was higher for Bentonite-B in comparison to Bentonite-A. For Bentonite-A, in presence of NaCl solution and compacted at OMC-MDD, with an increase in free swelling from 5 mL/2g to 17 mL/2g the swelling potential increased from 13.5 % to 21.1 %, however for Bentonite-B, with an increase in free

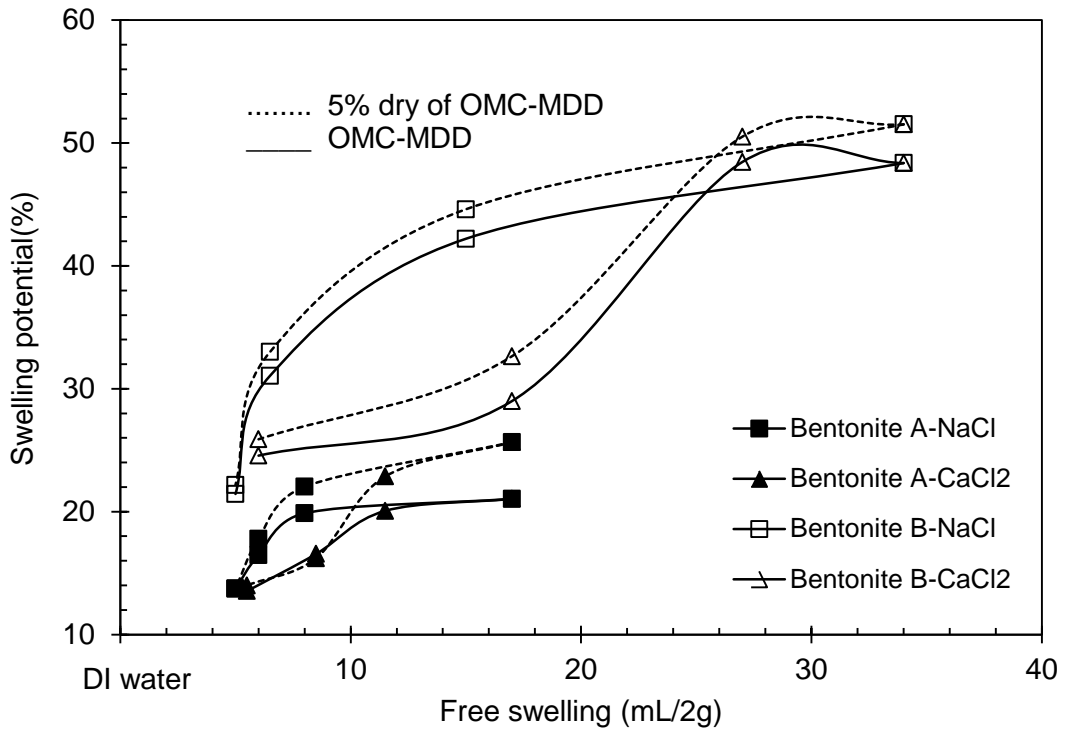


Figure 4.9 Swelling potential versus free swelling plot for Bentonite-A and -B

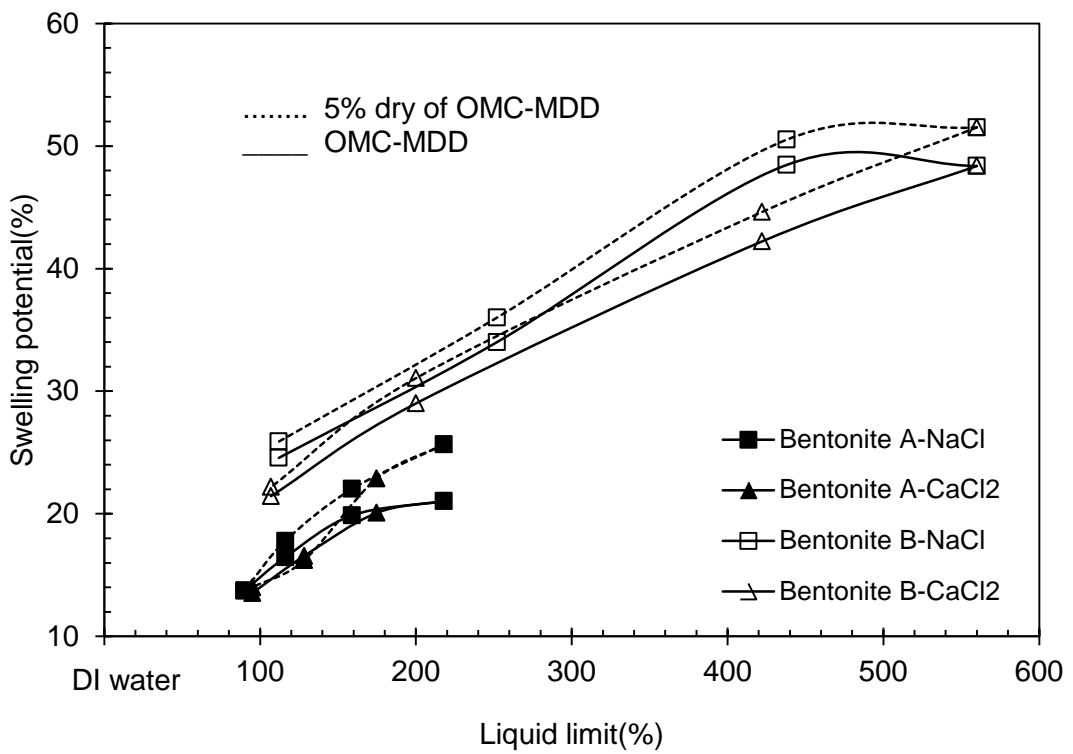


Figure 4.10 Swelling potential versus liquid limit plot of Bentonite-A and -B

swelling from 6 mL/2g to 34 mL/2g the swelling potential increased from 24.5 % to 48.4 %. Similarly for Bentonite-A, in presence of CaCl_2 solution and compacted at OMC-MDD, with an increase in free swelling from 5 mL/2g to 17 mL/2g the swelling potential increased from 13.7 % to 21.1 %, however for Bentonite-B, with an increase in the free swelling from 5 mL/2g to 34 mL/2g the swelling potential increased from 21.4 % to 48.4 %.

Similarly, Fig. 4.10 shows that the swelling potential increased with an increase in liquid limit of bentonite. The increase in swelling potential was more prominent for Bentonite-B in comparison to Bentonite-A. For Bentonite-A, in presence of NaCl and compacted at OMC-MDD, with an increase in liquid limit from 94.9 % to 218.0 % the swelling potential increased from 13.5 % to 21.1 %, but for Bentonite-B, with an increase in liquid limit from 112.0 % to 560.0 % the swelling potential increased from 24.5 % to 48.4 %. Similarly for Bentonite-A, in presence of CaCl_2 and compacted at OMC-MDD, with an increase in liquid limit from 90.0 % to 218.0 %, the swelling potential increased from 13.7 % to 21.1 %; but for Bentonite-B, with an increase in liquid limit from 107.0 % to 560.0 %, the swelling potential increased from 21.4 % to 48.4 %.

4.2.5. Swelling pressure

Swelling pressure is defined as the pressure required to compress the specimen, which has been soaked and completed swelling under a pressure of 4.9 kPa, back to its original volume (Sridharan et al., 1986a). It is also defined as the pressure required to maintain a constant void ratio of an unsaturated expansive soil specimen during the hydration process (Sridharan et al., 1986a). The quantification of swelling pressure during hydration of compacted specimens is required for the safe design of liners at the waste disposal site.

The plot in Fig. 4.11 shows the effect of the salt concentration on the swelling pressure of the bentonites compacted at OMC-MDD and 5% dry of OMC-MDD. The plot shows that

the swelling pressure of the bentonite decreased with the increase in the salt concentration. Similar to the liquid limit, free swelling and swelling potential, the decrease in the swelling pressure with the increase in salt concentration was different for different range of concentration. For Bentonite-A, the swelling pressure decreased significantly with the increase in the concentration from 0 to 0.1 N of both NaCl and CaCl₂ solution, where it decreased from 267.7 kPa for 0 N concentrations to 186.3 kPa and 176.5 kPa for 0.1 N concentration of NaCl and CaCl₂, respectively. A further increase in the concentration from 0.1 to 1 N decreased the swelling pressure marginally to 157.9 kPa and 156.9 kPa for NaCl and CaCl₂, respectively. Similarly, for Bentonite-B the decrease in swelling pressure was relatively higher for increase in concentration from 0 to 0.1 N. For the Bentonite-B compacted at OMC-MDD and permeated with NaCl solution, the swelling pressure decreased marginally from 708.0 kPa to 686.4 kPa due to increase in the concentration from 0 to 0.01 N, however, it decreased significantly from 686.4 kPa to 418.7 kPa and again from 418.7 kPa to 300.0 kPa when the concentration increased from 0.01 to 0.1 N and 0.1 to 1 N, respectively.

In comparison to the CaCl₂ solution, for any given concentration a higher value of swelling pressure was observed for NaCl solution. This can be attributed to a higher value of diffuse double layer thickness in NaCl solution in comparison to CaCl₂ solution of same concentration. However, the difference in swelling pressure was decreased with the increase in the concentration.

A comparison between the two bentonites showed that the salt has a significant effect on the swelling pressure of Bentonite-B in comparison to Bentonite-A. The swelling pressure of Bentonite-B, which has a high liquid limit, high SSA, CEC and ESP, decreased significantly due to increase in the salt concentration. A comparison of the initial compaction condition on the swelling pressure shows that initial water content has a

marginal effect on the swelling pressure irrespective of the permeating liquid. Similar observation was also made by Holtz and Gibbs (1956), Seed et al. (1962) and Chen (1975).

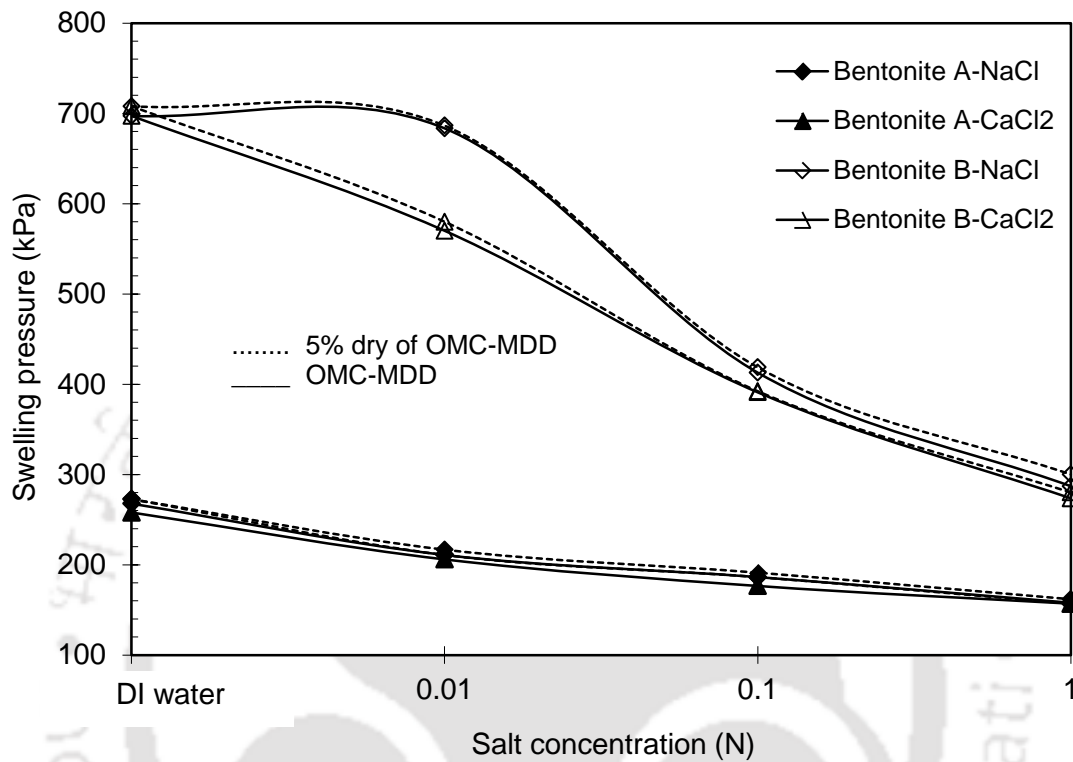


Figure 4.11 Effect of salt concentrations on swelling pressures of Bentonite-A and -B at different compaction conditions

4.2.5.1. Relationship of the swelling pressure with free swelling and liquid limit

From Fig. 4.12 and 4.13 it can be observed that swelling pressure of the bentonite increased with an increase in the free swelling and liquid limit value. For Bentonite-A, in presence of NaCl and compacted at OMC-MDD, with an increase in free swelling from 5 mL/2g to 17 mL/2g, the swelling pressure increased from 157.9 kPa to 267.7 kPa, however for Bentonite-B, with an increase in free swelling from 6 mL/2g to 34 mL/2g, swelling pressure increased from 300.0 kPa to 708.0 kPa. Similarly for Bentonite-A, in presence of CaCl₂ and compacted at OMC-MDD, with an increase in free swelling from 5 mL/2g to 17 mL/2g, the swelling pressure increased from 156.9 kPa to 267.7 kPa; but for Bentonite-B,

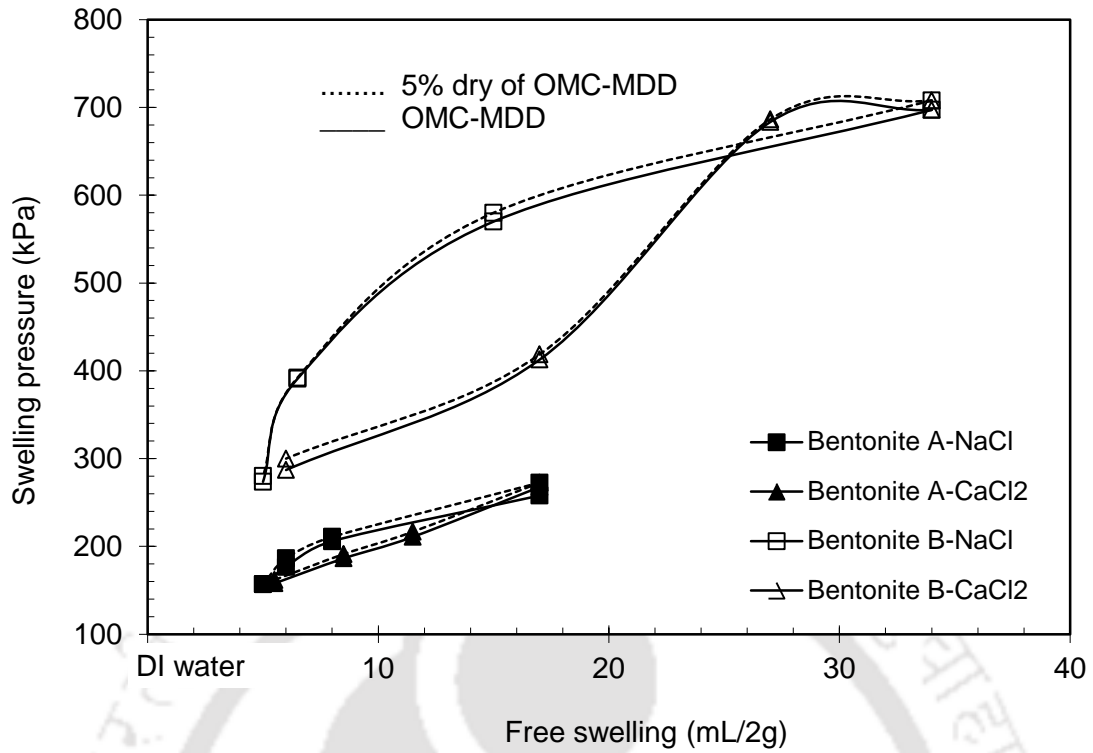


Figure 4.12 Swelling pressure versus free swelling plot of Bentonite-A and-B

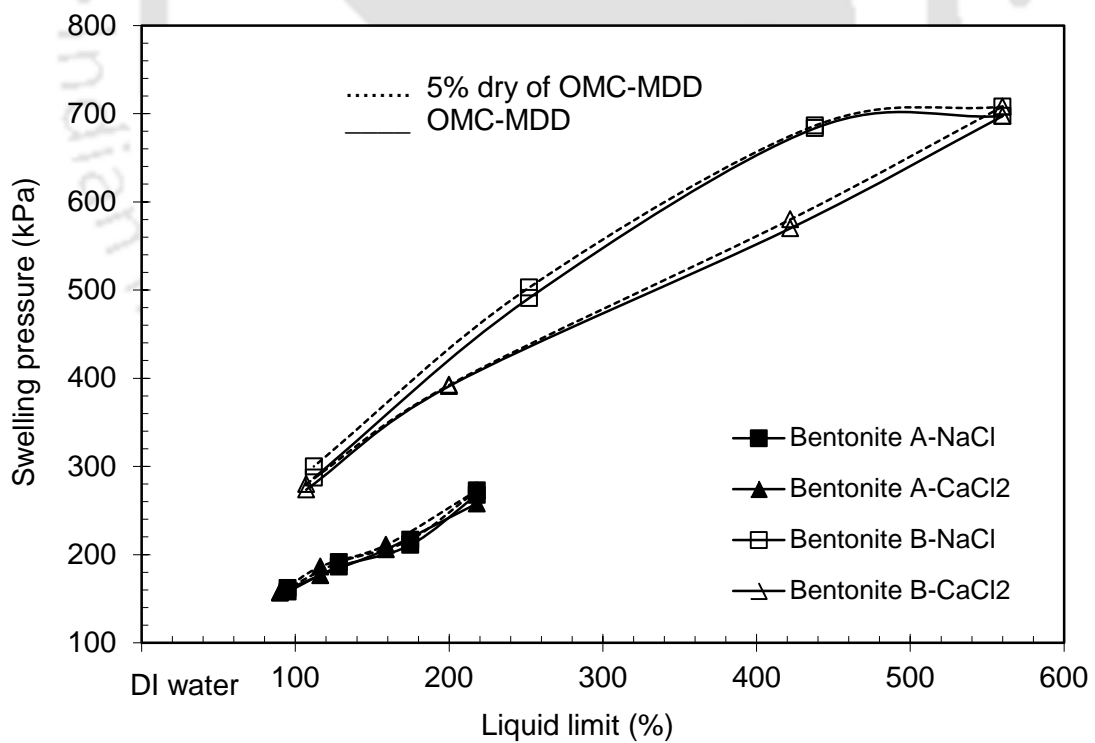


Figure 4.13 Swelling pressure versus liquid limit plot of Bentonite-A and-B

with an increase in free swelling from 5 mL/2g to 34 mL/2g, swelling pressure increased from 273.5 kPa to 708.0 kPa. Similarly for Bentonite-A, in presence of NaCl and compacted at OMC-MDD, with an increase in liquid limit from 94.9 % to 218.0 % the swelling pressure increased from 157.9 kPa to 267.7 kPa, however, for Bentonite-B, with an increase in liquid limit from 112.0 % to 560.0 %, swelling pressure increased from 300.0 kPa to 708.0 kPa. For the Bentonite-A samples saturated with CaCl₂ solution and compacted at OMC-MDD, with an increase in liquid limit from 90.0 % to 218.0 %, the swelling pressure increased from 156.9 kPa to 267.7 kPa, whereas, for Bentonite-B, with an increase in liquid limit from 107.0 % to 560.0 %, swelling pressure increased from 273.5 kPa to 708.0 kPa.

4.2.6. Hydraulic conductivity

Hydraulic conductivity is the key parameter affecting performance of liners and cover of a waste disposal site (Daniel, 1984; Daniel and Benson, 1990). Many environmental protection agencies have stipulated a minimum hydraulic conductivity of less than 1×10^{-7} cm/sec as design criteria for compacted soil liner (Daniel, 1984). The relationship between hydraulic conductivity and void ratio at different salt concentrations of NaCl and CaCl₂ is shown in Figs. 4.14 to 4.17. The plots show that irrespective of the initial compaction condition, the hydraulic conductivity of the bentonite increased with an increase in the salt concentration. The increase in the hydraulic conductivity with salt concentration was more prominent at higher salt concentrations. The effect of salt concentration was found to be more prominent for the concentration of 0.1 N and above of both NaCl and CaCl₂ solution. The pores of bentonite contain both mobile and immobile water; where the mobile water is free to move under the hydraulic gradient whereas, the immobile water is bound to the bentonite surface. Salt concentrations reduce the electrical potential between the clay platelets and the pore water, causing a reduction in double layer thickness.

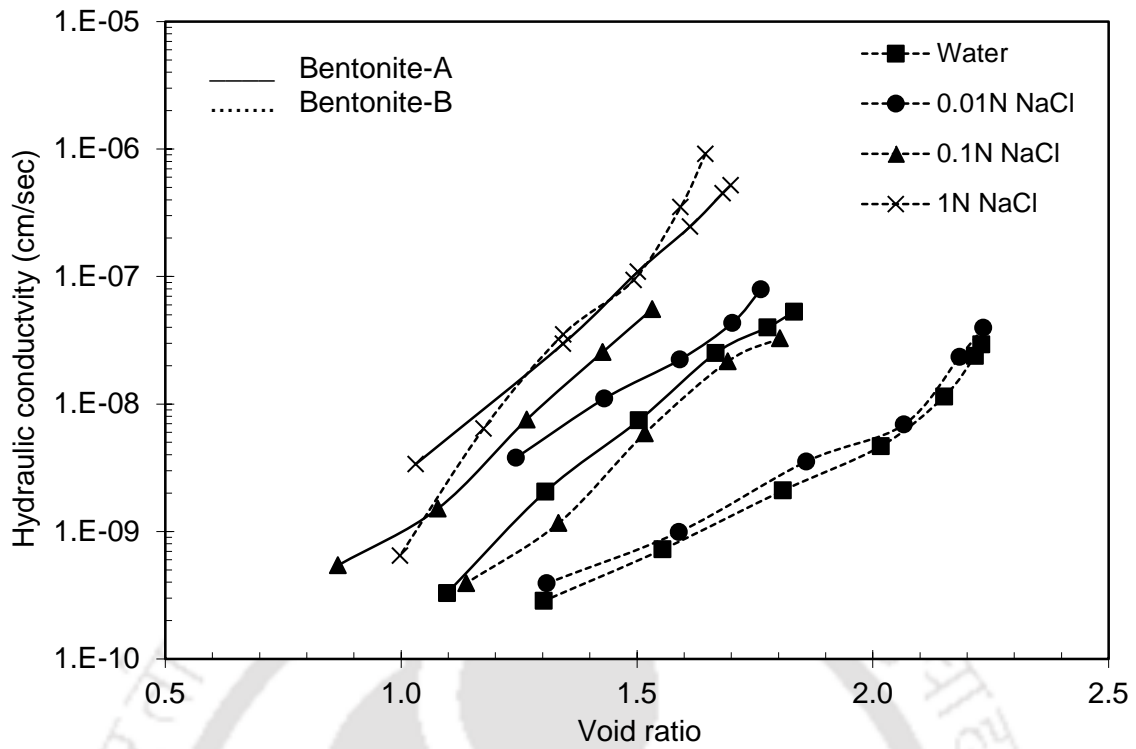


Figure 4.14 Void ratio-hydraulic conductivity plots of Bentonite-A and -B compacted at MDD-5% dry of OMC at various concentrations of NaCl

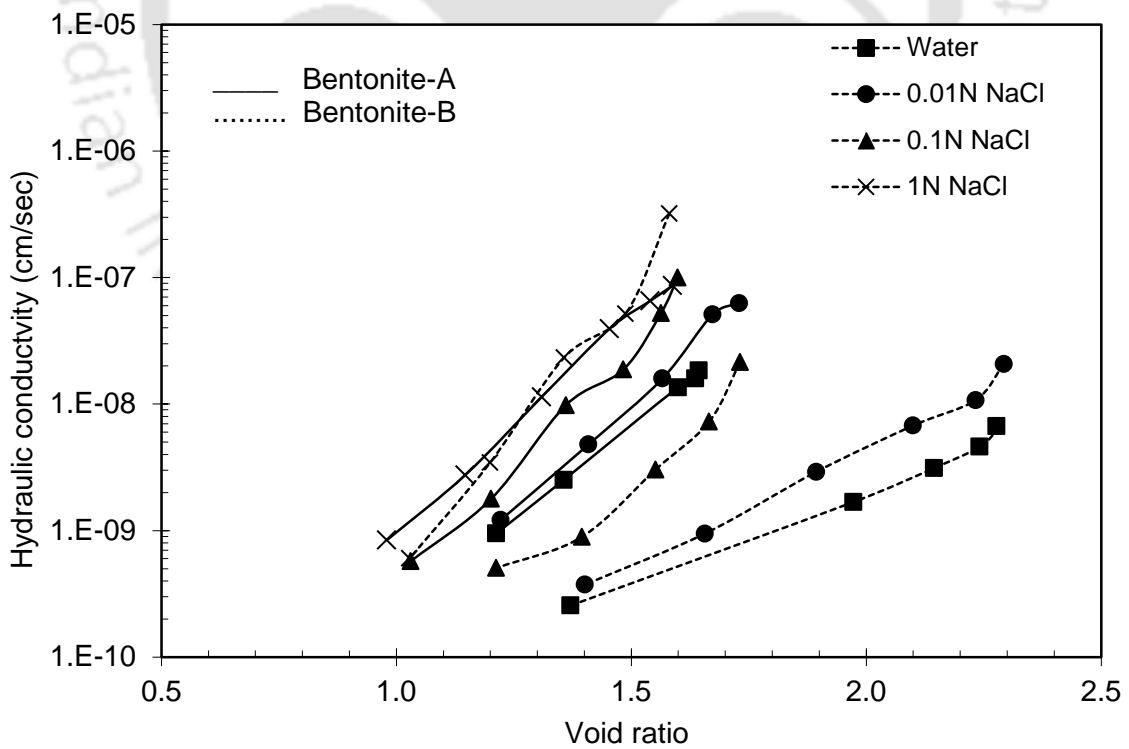


Figure 4.15 Void ratio-hydraulic conductivity plots of Bentonite-A and -B compacted at MDD-OMC at various concentrations of NaCl solution

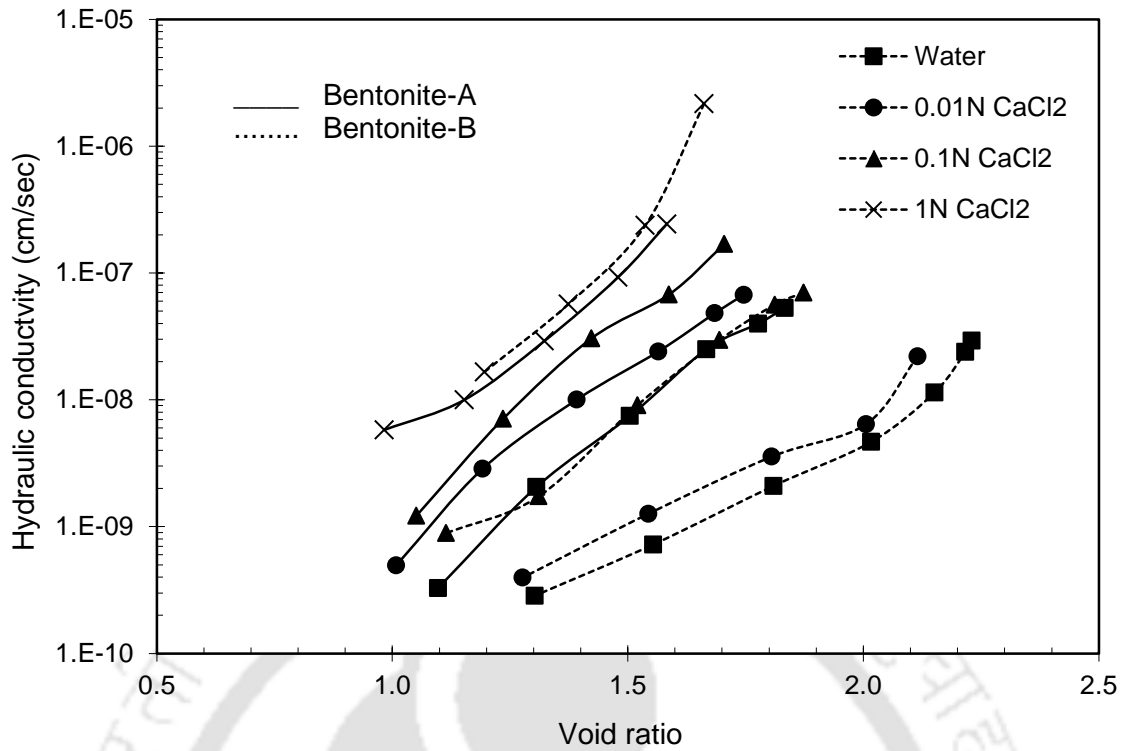


Figure 4.16 Void ratio-hydraulic conductivity plots of Bentonite-A and -B compacted at MDD-5% dry of OMC at various concentrations of CaCl₂ solution

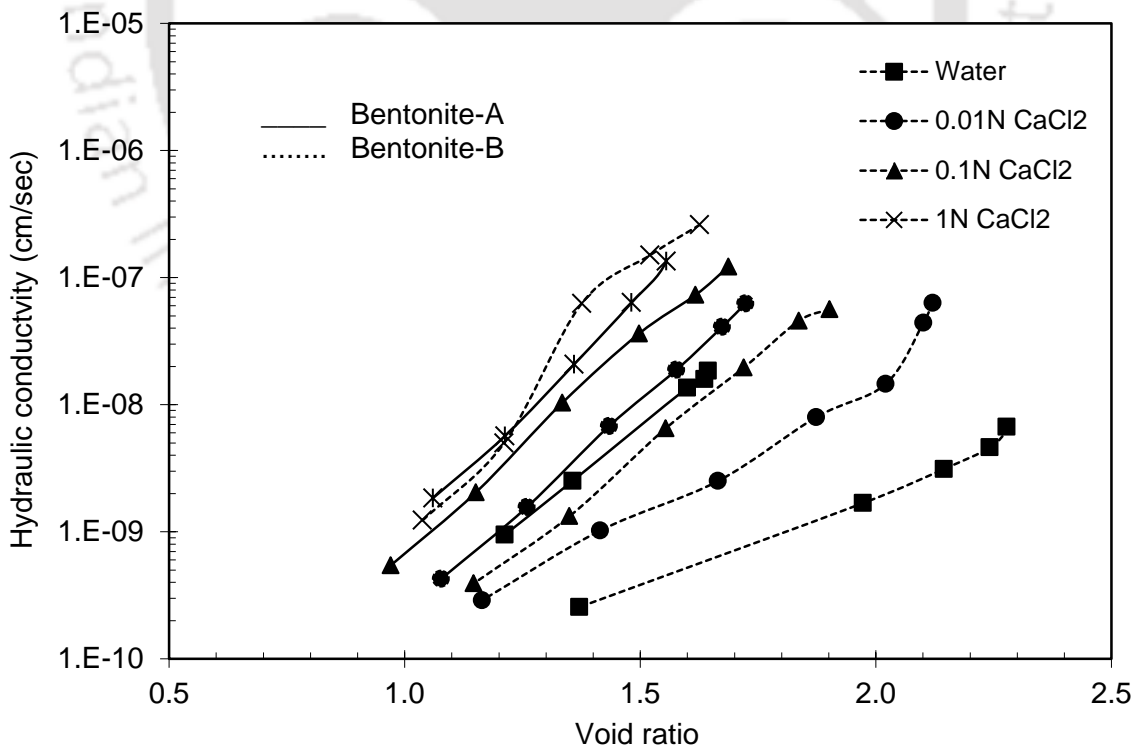


Figure 4.17 Void ratio-hydraulic conductivity plots of Bentonite-A and -B compacted at MDD-OMC at various concentrations of CaCl₂ solution

With an increase in thickness of the diffuse double layer the amount of immobile water in the pore increases resulting in a decrease in the hydraulic conductivity. Since the amount of immobile water depends upon the thickness of the diffuse double layer, any change in the diffuse double layer thickness also influences the amount of immobile water held by the bentonite. When the bentonite comes in contact with the salt solution the thickness of the diffuse double layer decreases and the flow channel becomes more open resulting in an increase in the hydraulic conductivity (Quirk and Schofield, 1955; Mesri and Olson, 1971b; Madsen and Mitchell, 1989). Plots in Figs. 4.14 to 4.17 show that the samples compacted at 5% dry of OMC-MDD and permeated with 1 N of NaCl and CaCl₂ solution possessed a hydraulic conductivity higher than 10⁻⁷ cm/sec, the limiting criteria for the landfill liner, at higher void ratios. However, with an increase in the overburden pressure the void ratio decreases and the hydraulic conductivity value became lower than 10⁻⁷ cm/sec.

A comparison between the samples compacted at OMC-MDD and 5% dry of OMC-MDD shows that samples compacted at 5% dry of OMC exhibited a higher value of hydraulic conductivity in comparison to bentonite compacted at OMC for same salt concentration. Since samples compacted at 5% dry of OMC have flocculated structure (Lambe, 1958a) the flow channel becomes more open resulting in an increase in the hydraulic conductivity (Lambe, 1958b; Daniel and Benson, 1990).

In order to compare the hydraulic conductivity of all the samples with different concentration of salts, hydraulic conductivity value corresponding to a void ratio of 1.5 was determined from the Figs. 4.14 to 4.17 and compared. The data in Table 4.1 shows the ratio between the hydraulic conductivity with salt solution (k_{salt}) to DI water (k_{water}) at a void ratio of 1.5 for a particular bentonite with the similar initial compaction condition.

Table 4.1 $k_{\text{salt}}/k_{\text{water}}$ for Bentonite-A and-B at a void ratio of 1.5

Salt type and concentration	Bentonite-A		Bentonite-B	
	$k_{\text{salt}}/k_{\text{water}}$ at $e = 1.5$		$k_{\text{salt}}/k_{\text{water}}$ at $e = 1.5$	
	OMC-MDD	5% Dry of OMC-MDD	OMC-MDD	5% Dry of OMC-MDD
NaCl				
0 N (DI water)	1.0	1.0	1.0	1.0
0.01 N	1.5	1.9	1.4	1.2
0.1 N	3.3	6.1	5.3	8.8
1 N	7.7	12.9	182.2	185.6
CaCl ₂				
0 N (DI water)	1.0	1.0	1.0	1.0
0.01 N	1.8	2.1	3.7	1.9
0.1 N	5.8	5.5	12.2	13.0
1 N	11.4	16.4	376.3	301.9

The data shows that the effect of CaCl₂ on the hydraulic conductivity was more significant in comparison to NaCl solution. Since the cation replacing capacity of Ca⁺² is higher in comparison to Na⁺ (Sposito, 1981) a large decrease in the diffuse double layer takes place at the same concentration of CaCl₂ solution in comparison to NaCl solution resulting in a higher decrease in the value of hydraulic conductivity. The hydraulic conductivity of Bentonite-A compacted at OMC-MDD was increased from 6.81x10⁻⁹ cm/sec to 7.79x10⁻⁸ cm/sec (i.e. 11.4 times) due to an increase in the concentration from 0 to 1 N of CaCl₂ solution in comparison to an increased from 6.81x10⁻⁹ cm/sec to 5.32x10⁻⁸ cm/sec (i.e. 7.7 times) for the same increase in NaCl solution. Similarly, the hydraulic conductivity of Bentonite-B was increased from 3.81x10⁻¹⁰ cm/sec to 1.43x10⁻⁷ cm/sec (i.e. 376.3 times) due to increase in the concentration from 0 to 1 N of CaCl₂ solution in comparison to increase from 3.81x10⁻¹⁰ cm/sec to 6.85x10⁻⁸ cm/sec (i.e. 182.2 times) for the similar increase in NaCl solution. Similar trend was also observed for samples compacted at 5% dry of OMC-MDD. A comparison between the two bentonites for a given concentration and compaction condition shows that salt had a significant impact on Bentonite-B in comparison to Bentonite-A and the effect was more prominent at higher concentration. Due

to increase in the concentration from 0 to 1 N of NaCl, the hydraulic conductivity of Bentonite-B was increased by 182.2 times in comparison to 7.7 times for Bentonite-A for the corresponding increase in the concentration. Similarly, due to increase in the concentration from 0 to 1 N of CaCl₂, the hydraulic conductivity of Bentonite-B was increased by 376.3 times in comparison to 11.4 times for Bentonite-A for the corresponding increase in the concentration. A higher effect of salt solution on Bentonite-B can be attributed to the presence of a higher amount of exchangeable sodium ion on its exchange site in comparison to Bentonite-A (Quirk and Schofield, 1955). Since the diffuse double layer thickness decreases significantly at 1 N concentration of both NaCl and CaCl₂ solution (Norrish and Quirk, 1954), both the bentonites exhibited almost identical value of the hydraulic conductivity at 1 N concentration of NaCl and CaCl₂ solution irrespective of the initial value with DI water. Similar behaviour was also observed for the liquid limit and free swelling of both the bentonites.

4.2.6.1. Hydraulic conductivity ratio versus free swell ratio and liquid limit ratio

Figure 4.18 shows the relationship between hydraulic conductivity ratio and free swell ratio for the hydraulic conductivity value corresponding to a void ratio of 1.5. From the plot it was observed that the $k_{\text{salt}}/k_{\text{water}}$ ratio decreased with the increase in the $\text{FS}_{\text{salt}}/\text{FS}_{\text{water}}$ ratio. The decrease was higher for Bentonite-B in comparison to Bentonite-A. For Bentonite-A in presence of NaCl and compacted at MDD-OMC, with an increase in $\text{FS}_{\text{salt}}/\text{FS}_{\text{water}}$ from 0.3 to 1.0 the $k_{\text{salt}}/k_{\text{water}}$ ratio decreased from 10.7 to 1.0. Similarly, for Bentonite-B with the increase in $\text{FS}_{\text{salt}}/\text{FS}_{\text{water}}$ from 0.2 to 1.0 the $k_{\text{salt}}/k_{\text{water}}$ decreased from 182.2 to 1. Similar observation was made for the bentonite permeated with CaCl₂ solution.

From Fig. 4.19 it was observed that the ratio $k_{\text{salt}}/k_{\text{water}}$ decreased with the increase in the $\text{LL}_{\text{salt}}/\text{LL}_{\text{water}}$ ratio. The decrease was more for Bentonite-B in comparison to Bentonite-A.

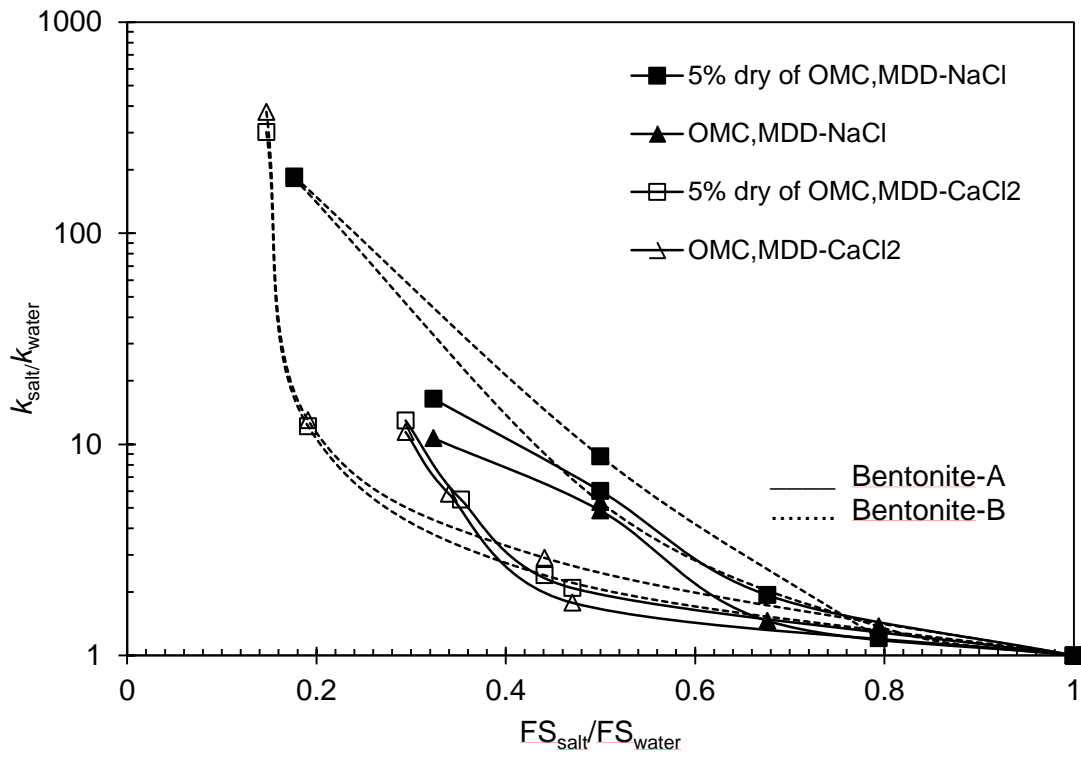


Figure 4.18 Hydraulic conductivity ratio versus free swell ratio plot for Bentonite-A and -B

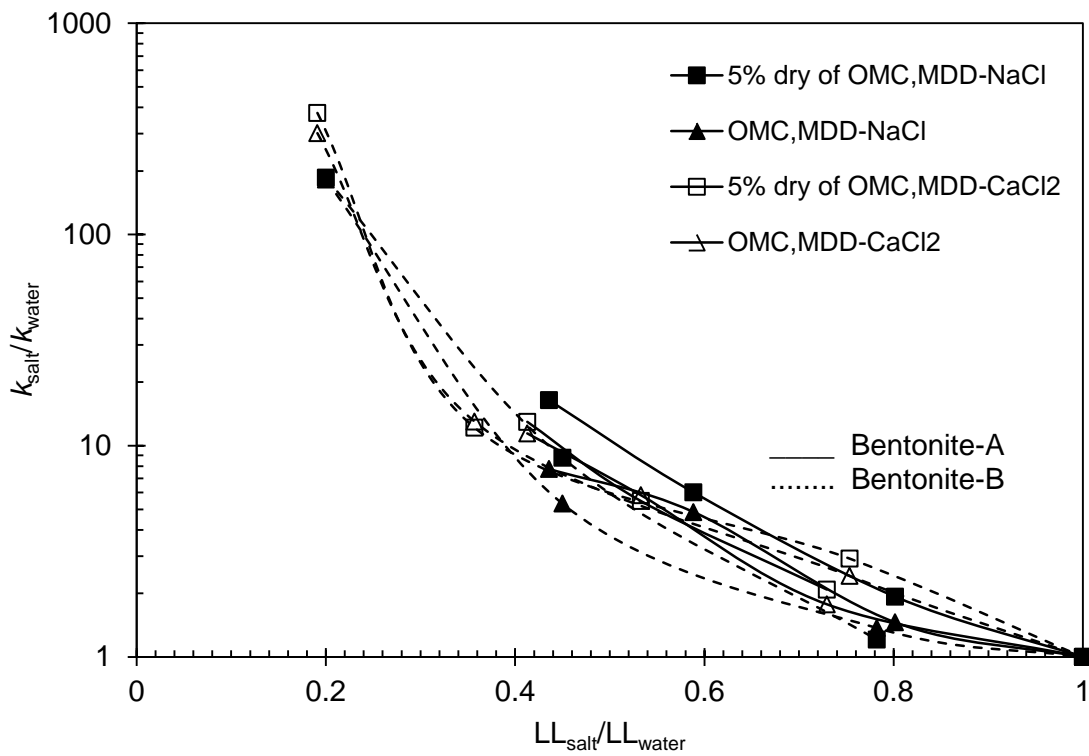


Figure 4.19 Hydraulic conductivity ratio versus liquid limit ratio plot for Bentonite-A and -B

For Bentonite-A, in presence of NaCl and compacted at MDD-OMC, with the increase in $LL_{\text{salt}}/LL_{\text{water}}$ from 0.4 to 1, the $k_{\text{salt}}/k_{\text{water}}$ decreased from 7.7 to 1.0. For Bentonite-B in presence of NaCl compacted at MDD-OMC, with the increase in $LL_{\text{salt}}/LL_{\text{water}}$ from 0.2 to 1.0, the $k_{\text{salt}}/k_{\text{water}}$ decreased from 182.2 to 1.0. Similar observation was made for the bentonite permeated with CaCl_2 solution.

4.2.6.2. Hydraulic conductivity versus swelling pressure

Figure 4.20 shows the relationship between the hydraulic conductivity and swelling pressure for the two bentonites. The hydraulic conductivity of the bentonites was found to decrease with increase in the swelling pressure of the bentonites. The decrease in the hydraulic conductivity with increase in the swelling pressure was quite steep in the beginning and gradually decreased thereafter.

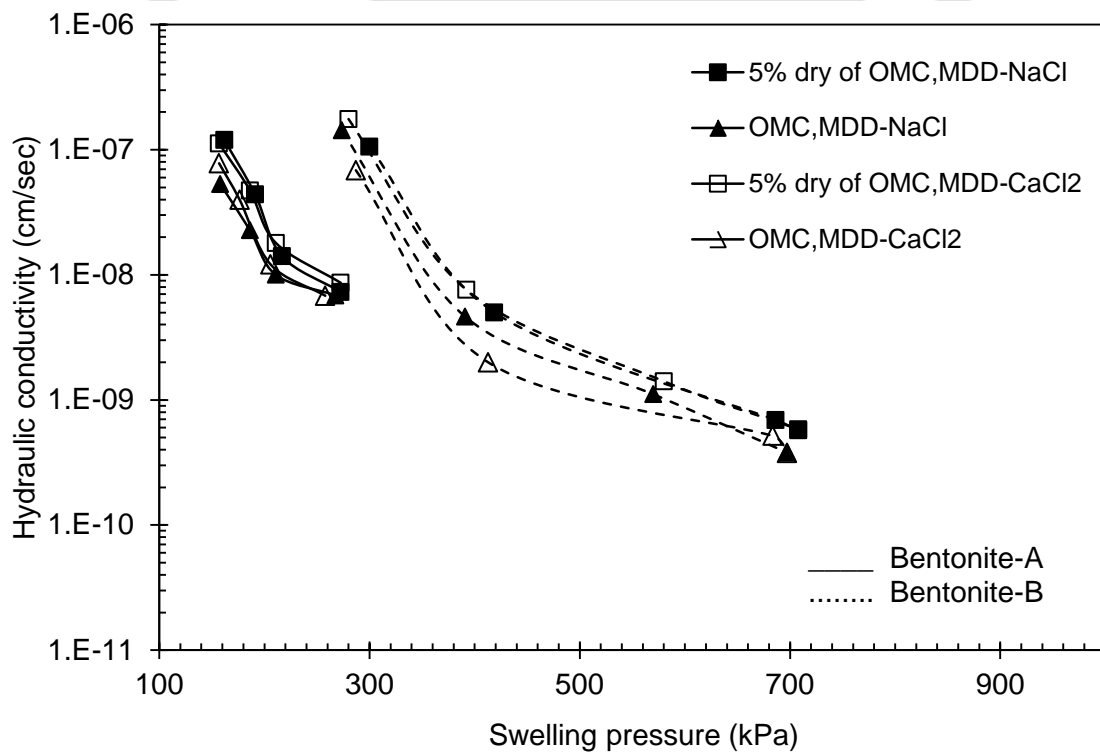


Figure 4.20 Hydraulic conductivity versus swelling pressure plot for Bentonite-A and -B

For Bentonite-A, in presence of NaCl solution and compacted at OMC-MDD, with an increase in the swelling pressure from 157.9 kPa to 210.8 kPa the hydraulic conductivity decreased from 5.3×10^{-8} cm/sec to 1×10^{-8} cm/sec (5.3 times), however, with a further increase in the swelling pressure from 210.8 kPa to 267.7 kPa, the hydraulic conductivity decreased only from 1×10^{-8} cm/sec to 6.8×10^{-9} cm/sec (1.4 times). Similarly, for Bentonite-B, in presence of NaCl solution with an increase in the swelling pressure from 300.0 kPa to 412.7 kPa, hydraulic conductivity decreased from 6.8×10^{-8} cm/sec to 2×10^{-9} cm/sec (34.2 times), however, a further increase in the swelling pressure from 412.7 kPa to 708.0 kPa the hydraulic conductivity decreased only from 2×10^{-9} cm/sec to 3.7×10^{-10} cm/sec (5.3 times). Similar observation was also made for both the bentonites for CaCl_2 solution.

4.2.7. Consolidation characteristics

4.2.7.1. Void ratio-pressure relationship

The void ratio versus pressure (e - $\log P$) relationships for both the bentonites in the presence of various concentrations of NaCl and CaCl_2 solution at two different compaction conditions as shown in Figs. 4.21 to 4.24 indicates that with an increase in the consolidation pressure the void ratio of the bentonites decreases. This decrease in the void ratio due to the consolidation pressure was higher for the bentonite with lower salt concentration and the overall compression decreased with increasing the salt concentration. The higher compressibility of the bentonites permeated with low salt concentration is due to the consequence of the higher porosity they reached after saturation. As the salt concentration in the pore fluid increases, a large number of cations diffused into the interlayer of montmorillonite. This results decrease in the inter-particle repulsive forces between montmorillonite particles resulting in the bentonite getting compressed to a lower void ratio (Bolt, 1956; Olson and Mesri, 1970; Sridharan et al, 1986b).

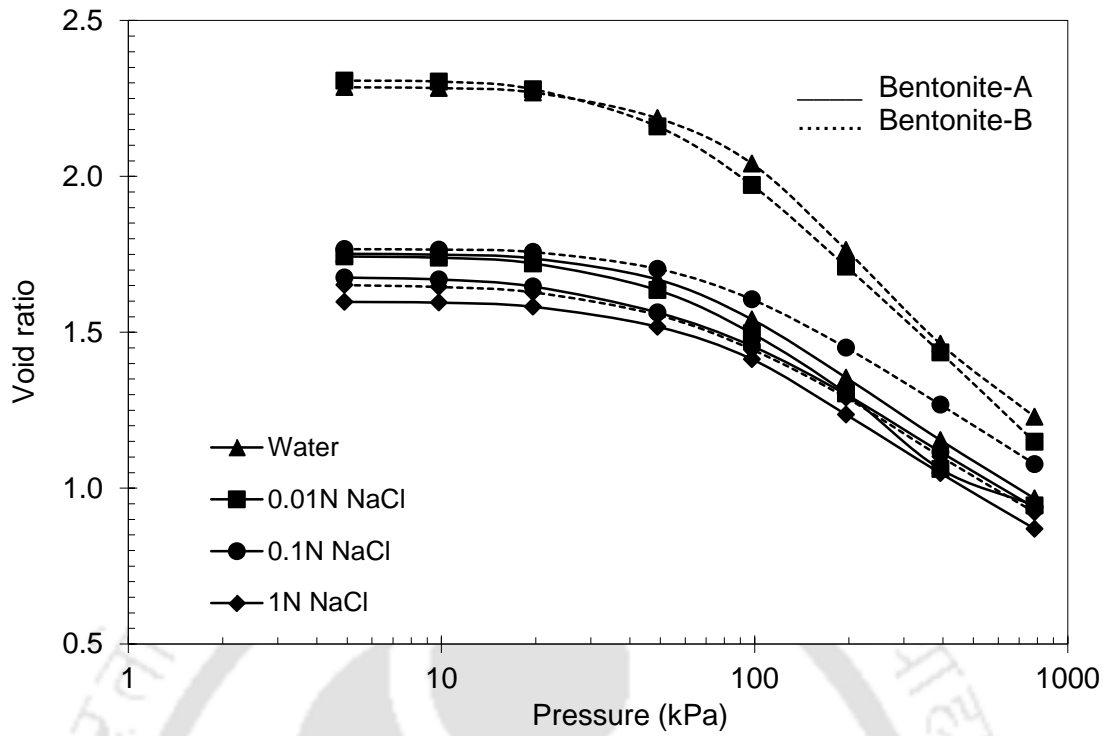


Figure 4.21 Void ratio-pressure plots for Bentonite-A and -B for MDD and OMC at various concentrations of NaCl solution

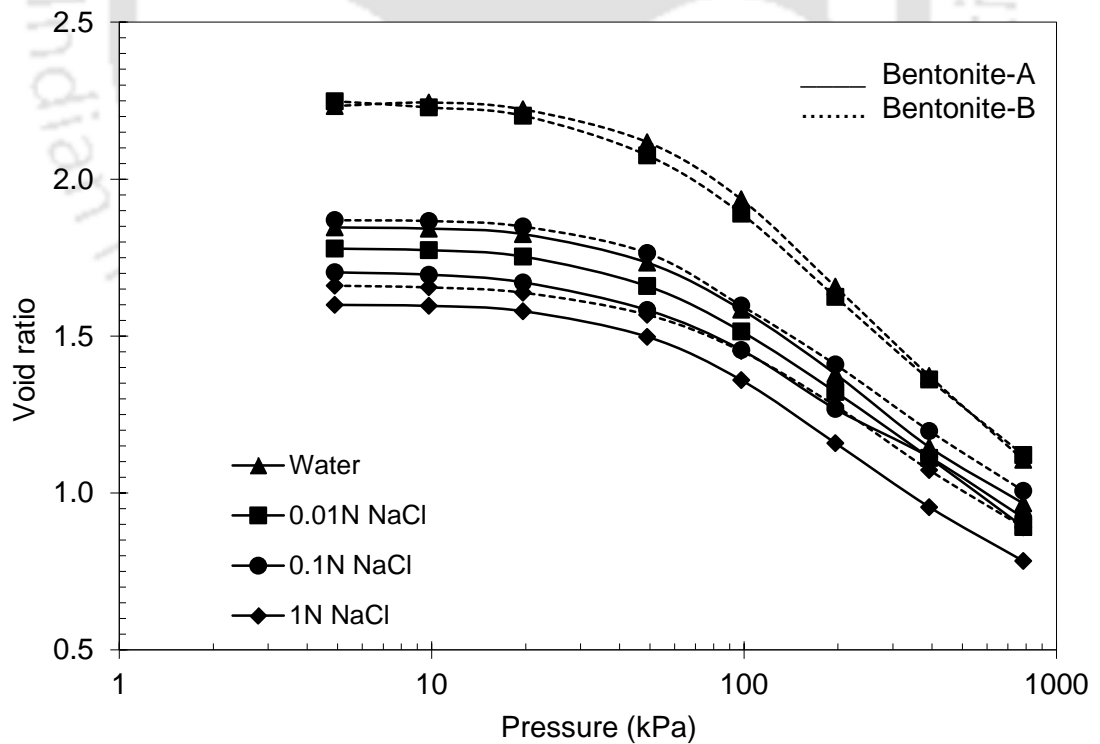


Figure 4.22 Void ratio-pressure plots for Bentonite-A and -B for MDD and 5% dry of OMC at various concentrations of NaCl solution

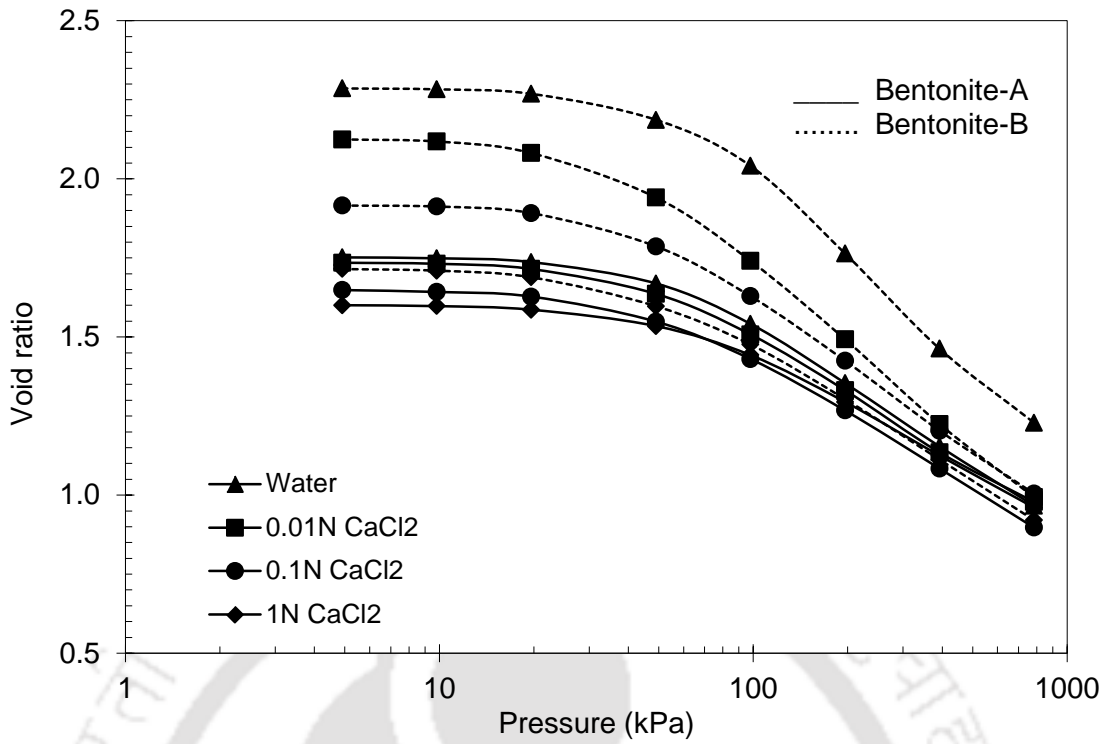


Figure 4.23 Void ratio-pressure plots for Bentonite-A and -B for MDD and OMC at various concentrations of CaCl_2 solution

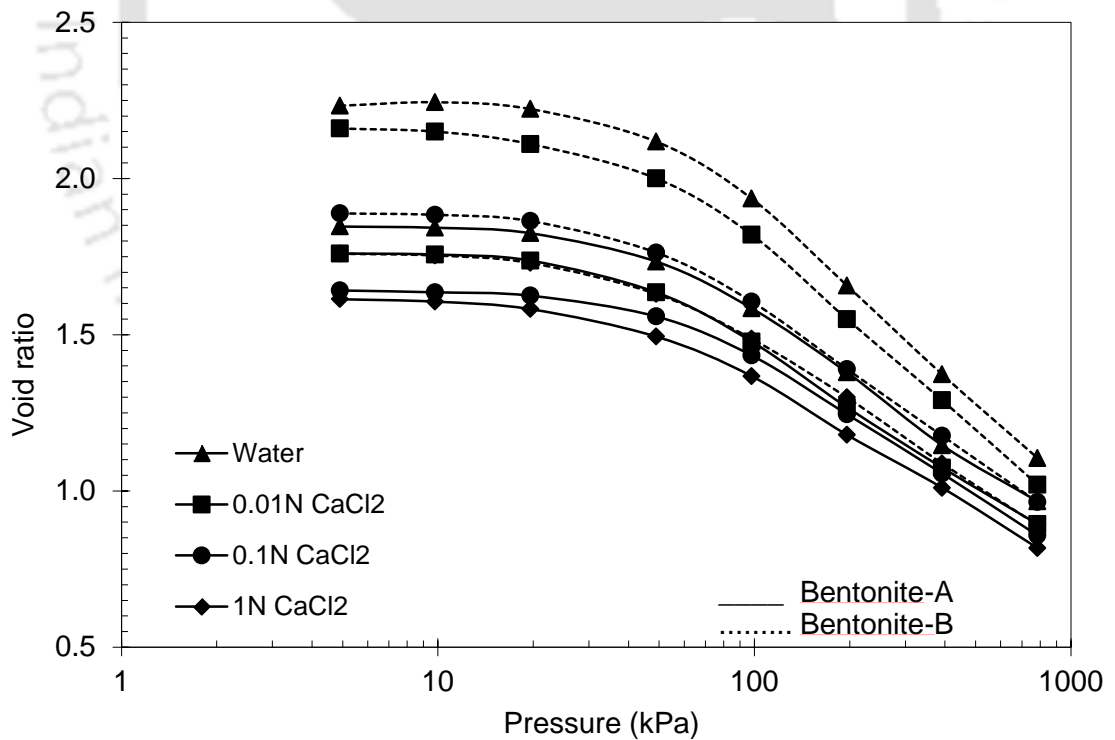


Figure 4.24 Void ratio-pressure plots for Bentonite-A and -B for MDD and 5% dry of OMC at various concentrations of CaCl_2 solution

A comparison between the two bentonites showed that the reduction in void ratio was higher for Bentonite-B in comparison to Bentonite-A. The effect of the increase in the concentration of NaCl from 0.01 to 0.1 N on the e -log P curve for Bentonite-B was significant; however, a further increase in the concentration from 0.1 to 1 N had a nominal effect on the e -log P curve. Whereas, the increase in the concentration of CaCl₂ from 0 to 0.01 N and further from 0.01 to 0.1 N had a significant impact on the e -log P curve for Bentonite-B. However, a further increase in the concentration from 0.1 to 1 N had a nominal effect on the e -log P curve.

4.2.7.2. Compressibility behaviour from the diffuse double layer thickness

Since the compressibility behaviour of bentonite is controlled by the physico-chemical forces present in a clay-electrolyte system (Bolt, 1956; Sridharan and Jayadeva, 1982), the behaviour can be derived using the diffuse double layer theory. The theory was first proposed by Gouy (1910) and later modified by Chapman (1913) and known as Gouy-Chapman's diffuse double layer theory. This theory was further derived and used by many researchers (Bolt, 1956; van Olphen, 1977; Sridharan and Jayadeva, 1982; Ouhadi et al, 2006) to determine the compressibility behaviour of bentonite in the presence of various pore fluids. The following sets of equations given by Sridharan and Jayadeva (1982) are used in this study to derive the void ratio-pressure relationship for the two bentonites in the presence of the salt solution.

$$\text{Void ratio, } e = G\gamma_w Sd \quad (\text{Eq 4.1})$$

$$\text{Swelling pressure, } P = 2nkT (\cosh u - 1) \quad (\text{Eq 4.2})$$

$$\int_z^u \frac{1}{\sqrt{(2 \cosh z - 2 \cosh u)}} dy = \int_0^d d\xi = -Kd \quad (\text{Eq 4.3})$$

$$= \frac{B}{S} \sqrt{\frac{2\pi}{\epsilon nkT}} \quad (\text{Eq 4.4})$$

$$\text{at } x = 0, y = z$$

$$\text{Double layer parameter, } K = \sqrt{\frac{8\pi e'^2 v^2 n}{\epsilon kT}} \quad (\text{Eq 4.5})$$

where,

G is the specific gravity of soil solid particles,

γ_w is the unit weight of pore water,

S is the specific surface area of soil,

d is the half distance between the parallel clay plates,

n is the molar concentration of ions in pore fluid,

k is the Boltzmann's constant ($= 1.38 \times 10^{-23}$ J/K),

T is the temperature in Kelvin,

u is the non-dimensional midplane potential function,

z is the non-dimensional plane potential at clay surface,

ξ is the distance function,

B is the base exchange capacity of the clay,

ϵ is the dielectric constant of the pore fluid,

e' is the elementary electric charge ($= 4.8 \times 10^{-10}$ esu), and

v is valency of exchangeable cation.

The plots in Figs. 4.25 and 4.26 compare the experimental and theoretical void ratio-pressure (e - $\log P$) relationship for Bentonites-A and -B at different concentrations of NaCl and CaCl₂ solutions. A higher value of theoretical void ratio was obtained for both the bentonites at lower consolidation pressure and water as pore fluid. However, with increase

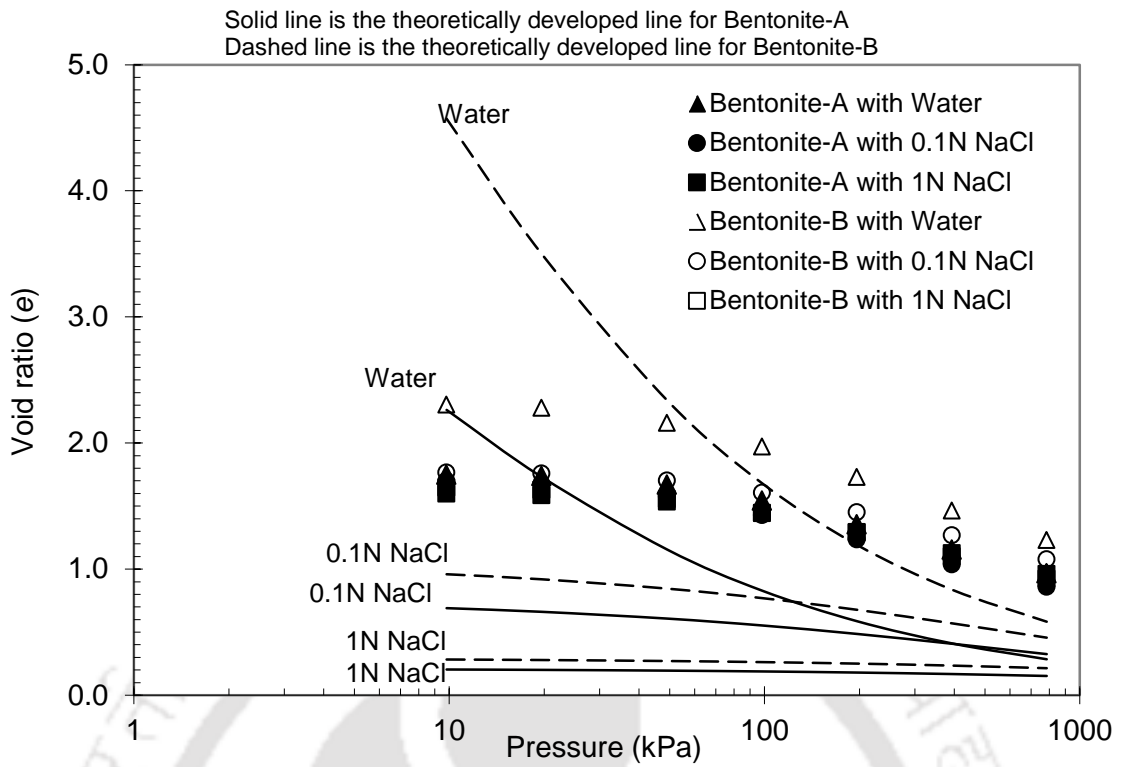


Figure 4.25 Experimental and theoretical void ratio - pressure plots for Bentonite-A and -B at various concentrations of NaCl solution

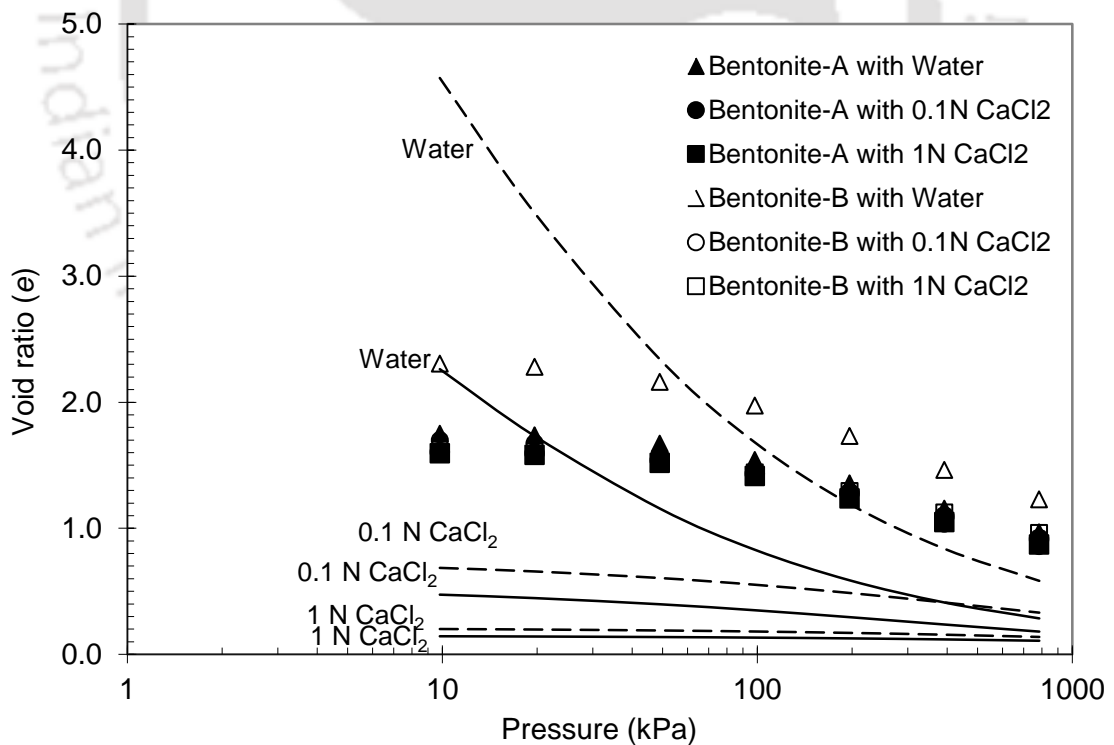


Figure 4.26 Experimental and theoretical void ratio - pressure plots for Bentonite-A and -B at various concentrations of CaCl₂ solution

in the consolidation pressure the theoretically obtained e - $\log P$ curve converged towards the experimentally obtained curve and crossed it at certain pressure and diverged again. The consolidation pressure at which both the theoretical and experimental curve crossed each other was not unique and it dependent on the type of bentonite. However with the increase in concentration of the pore fluid, a lower value of the theoretically calculated void ratio was obtained for both the bentonites. This difference in the experimentally and theoretically obtained values of void ratio can be attributed to the assumption made during the derivation of the DDL theory (Ludwig, 1979). During the development of the DDL theory it was assumed that the clay plates are parallel surfaces. However, with the increase in the salt concentration of the pore fluid the orientation of the clay plates changed and they formed a flocculated structure resulting in a higher value of experimental void ratio in comparison to the theoretical void ratio (Ouhadi et al., 2006).

Similar difference was also observed by Bolt (1956) and Ouhadi et al. (2006) for the bentonite permeated with various salt solutions. Ouhadi et al. (2006) suggested that the difference between these two values could be due to the presence of fraction of non-montmorillonite clay minerals, as shown in the XRD result, in the bentonite. In addition to this, one of the major assumptions in the development of double layer theory was that clay platelets are parallel surfaces. However, due to the presence of salt solution in soil pore fluid the parallel plate structure changes in to flocculated structure.

Further to investigate the effect of pressure and salt concentration on the diffuse double layer (DDL), the DDL thickness ($2d$) for both the bentonites was calculated at the consolidation pressures of 19.6, 196.1 and 784.5 kPa using Eqs. 4.1 to 4.5 for different concentrations of NaCl and CaCl₂ solution and tabulated in Table 4.2. The data in Table 4.2 shows that the DDL thickness decreases significantly with the increase in the consolidation pressure as well as concentration of the salt solution. The decrease in the

DDL thickness was found to be significant for Bentonite-B in comparison to Bentonite-A. An increase in the consolidation pressure from 19.6 to 784.5 kPa decreased the DDL thickness of Bentonite-B from 5.446×10^{-9} m to 0.907×10^{-9} m; whereas, for similar increase in the pressure the DDL thickness of Bentonite-A decreased from 3.649×10^{-9} m to 0.601×10^{-9} m. However, at 1 N concentration of both NaCl and CaCl₂ solution an identical value of DDL thickness was determined for both the bentonites and found to decrease marginally due to increase in the consolidation pressure.

Table 4.2 Diffuse double layer thickness for the bentonites at different salt concentrations

Salt concentration	Diffuse double layer (DDL) thickness, $2d \times 10^9$ in m					
	Bentonite-A			Bentonite-B		
	19.6 kPa	196.1 kPa	784.5 kPa	19.6 kPa	196.1 kPa	784.5 kPa
0 N (DI water)	3.649	1.238	0.601	5.446	1.855	0.907
0.01 N NaCl	3.472	1.669	0.869	3.484	1.682	0.881
0.1 N NaCl	1.394	1.025	0.687	1.440	1.061	0.715
1 N NaCl	0.423	0.379	0.322	0.437	0.393	0.336
0.01 N CaCl ₂	2.091	0.877	0.441	2.099	0.885	0.447
0.1 N CaCl ₂	0.940	0.622	0.380	1.030	0.763	0.518
1 N CaCl ₂	0.298	0.267	0.227	0.308	0.267	0.216

4.2.7.3. Coefficient of volume change (m_v)

When a load is applied to a clayey soil, its volume gets reduced, this principally being due to a reduction in the void ratio (Burland, 1990). Volume changes in soils are important because of their consequences in terms of settlement due to compression which leads to changes in strength and deformation properties, which in turn influence its stability (Mitchell and Soga, 2005).

The coefficient of volume change (m_v) is defined as the volume change per unit volume per unit increase in load and it depends on the range of stress over which it is determined.

From Figs. 4.27 to 4.30 it was observed that irrespective of the permeating fluid and type of bentonite, the m_v initially increased and then decreased with an increase in the consolidation pressure. At lower consolidation pressures, when the void ratio was high, with an increase in consolidation pressure a larger reduction in the void spaces took place resulting in a higher m_v . After reaching a peak value, with a further increase in the consolidation pressure the rate of volume change decreased. Similarly, the plots show that the m_v for both bentonites decreased with the increase in the salt concentration indicating the compressibility of the bentonite decreases due to the addition of salt in pore water.

Since the DDL thickness is large for the bentonites in the presence of DI water, a significant compression took place for the sample saturated with DI water due to the application of pressure resulting in a higher m_v . As the thickness of the DDL decreased with an increase in salt concentration (Table 4.2), the compressibility and consequently the m_v of the sample decreased with an increase in the salt concentration of the saturating fluid. The plots also show that the Bentonite-B, which had a higher DDL thickness with DI water (Table 4.2), exhibit higher m_v values in comparison to Bentonite-A. Similarly, a comparison between the samples compacted at MDD-OMC and MDD-5% dry of OMC shows that samples compacted at dry of OMC has higher m_v values.

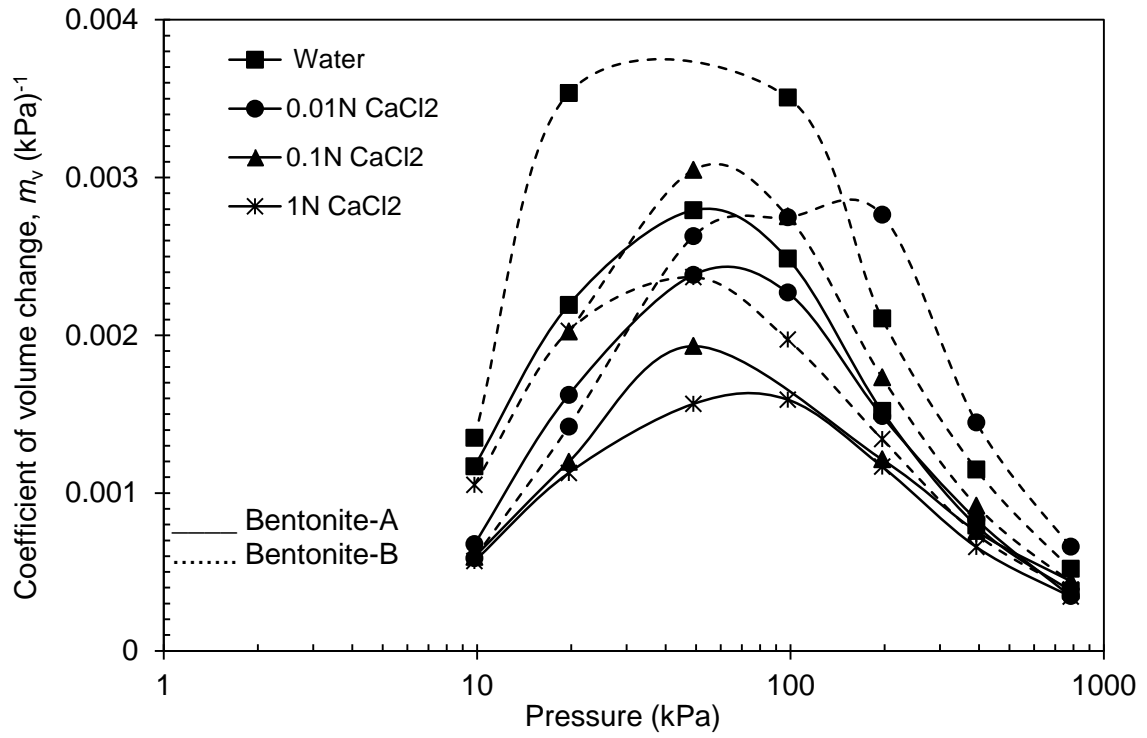


Figure 4.27 Plot between the coefficient of volume change and consolidation pressures of Bentonite-A and -B with CaCl₂ solution at OMC-MDD

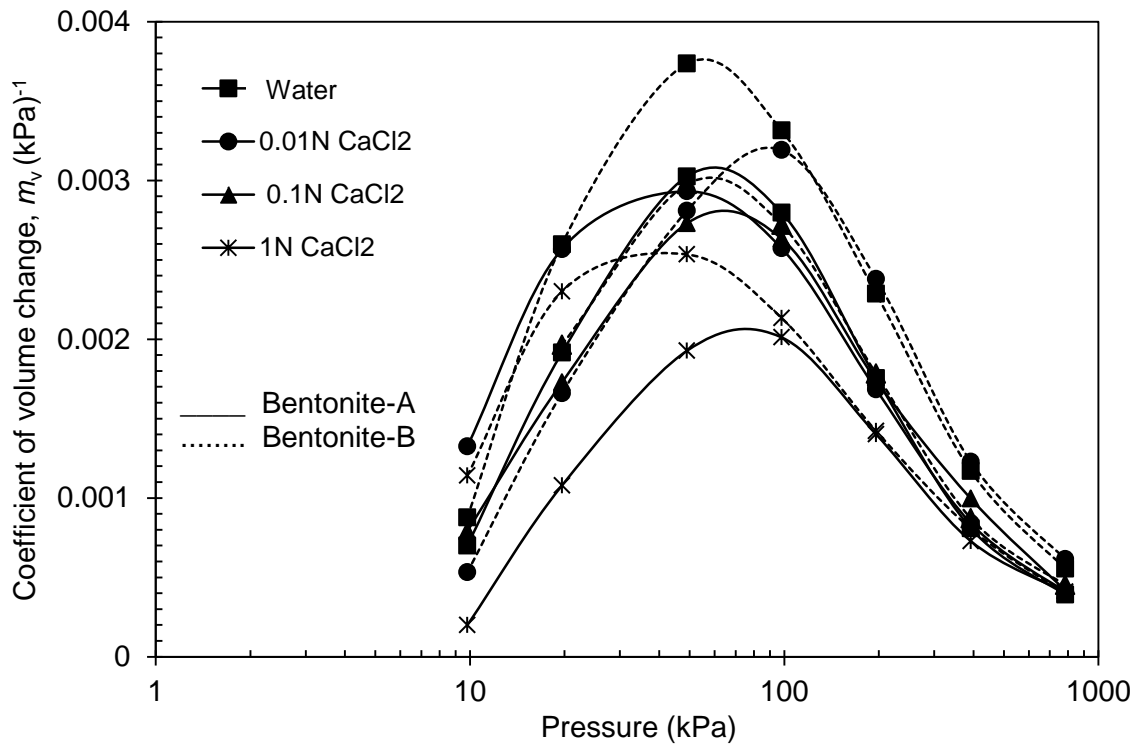


Figure 4.28 Plot between the coefficient of volume change and consolidation pressures of Bentonite-A and -B with CaCl₂ solution at 5% dry of OMC-MDD

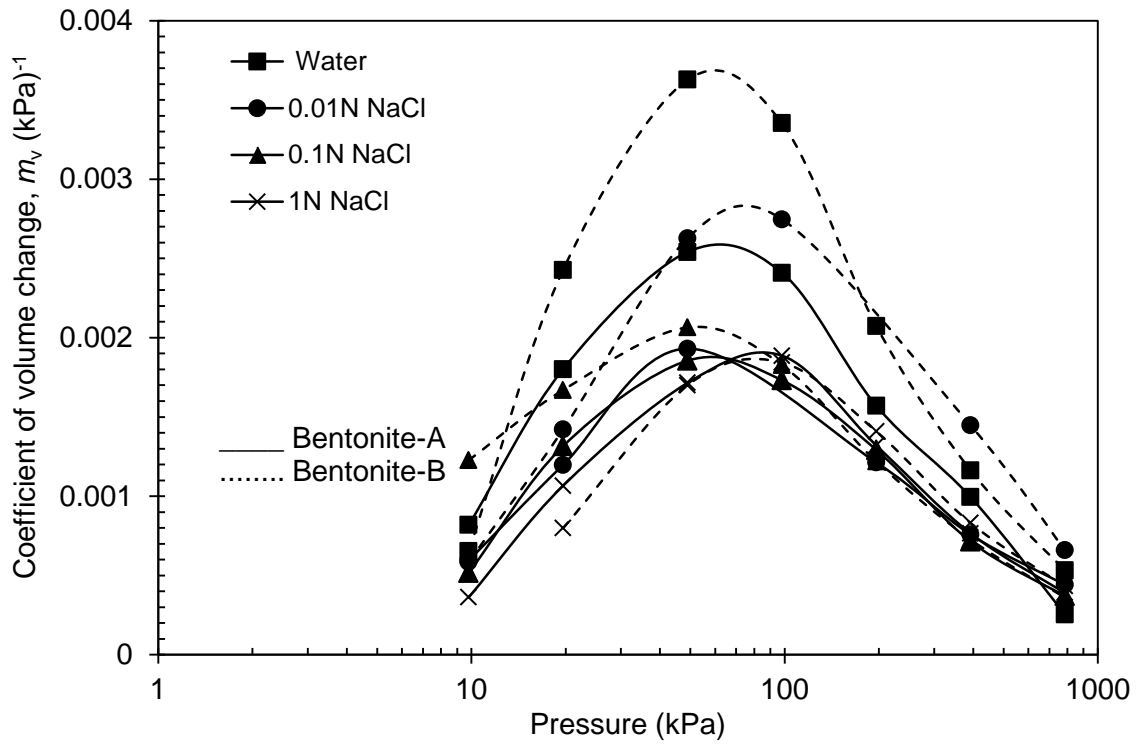


Figure 4.29 Plot between the coefficient of volume change and consolidation pressures of Bentonite-A and -B with NaCl solution at OMC-MDD

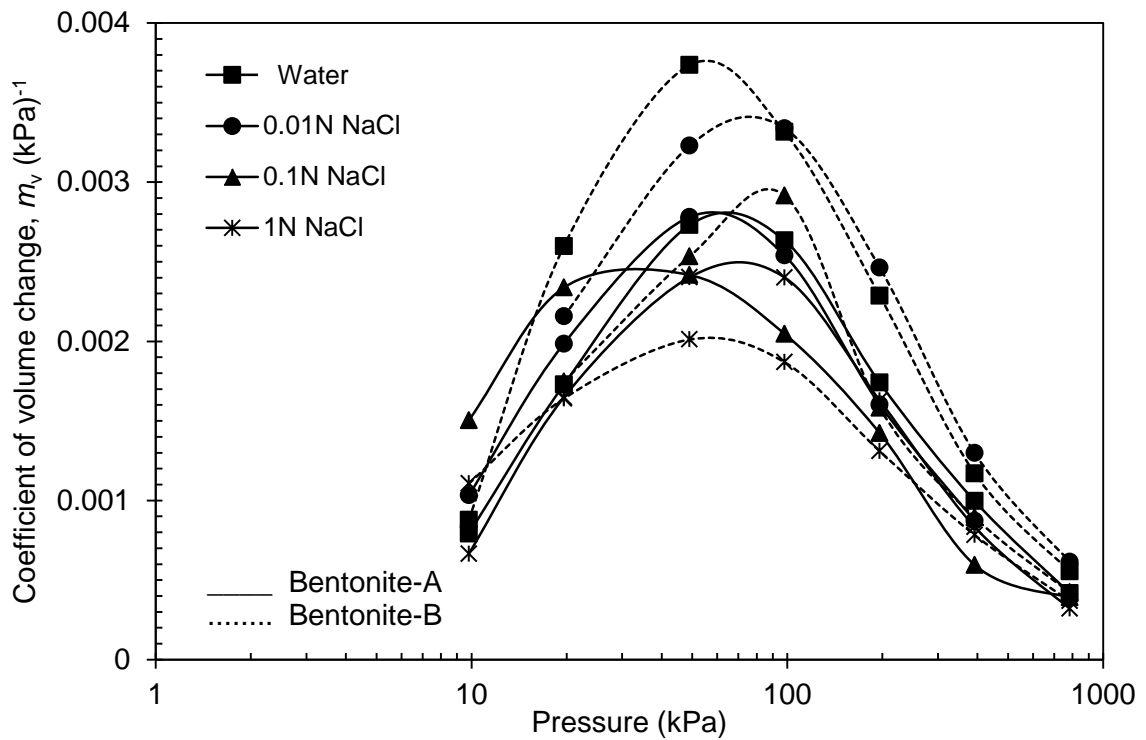


Figure 4.30 Plot between the coefficient of volume change and consolidation pressures of Bentonite-A and -B with NaCl solution at 5% dry of OMC-MDD

4.2.7.4. Coefficient of consolidation (c_v)

The coefficient of consolidation (c_v) signifies the rate at which a saturated soil sample undergoes one-dimensional consolidation when subjected to an increase in the consolidation pressure, which in turn directly depends on the hydraulic conductivity of the soil medium undergoing compression (Terzaghi, 1943). To determine the rate of settlement of soils as well as hydraulic conductivity, it is essential to know the c_v value. A higher value of c_v indicates a faster rate of consolidation and vice versa.

Figures 4.31 to 4.34 show that the c_v decreased with increasing consolidating pressure indicating a slower rate of consolidation at higher consolidation pressure. Similar trend was also observed by Robinson and Allam (1998) for montmorillonitic clay. However, this trend was quite opposite to the trend observed for the sand-bentonite mixtures by various researchers (Mishra et al., 2010; Bohnhoff and Shackelford, 2014). This opposite trend of relationship between c_v and consolidation pressure can be attributed to the mechanism which controls the compressibility behaviour of the samples. The compressibility of sand-bentonite mixture is mostly controlled by the mechanical factors (Robinson and Allam, 1998) which increases with an increase in the consolidation pressure, whereas, the compressibility behaviour of bentonite is controlled by the long range attractive and repulsive forces which are generated due to physico-chemical factors (Olson and Mesri 1970; Sridharan and Rao, 1973) which decreases with an increase in pressure. As the consolidation pressure increases the plates come to a closer distance resulting in a decrease in the DDL thickness (Table 4.2). As the clay plates comes to a closer distance the repulsion between the plates will increase which prevents the further consolidation of the sample resulting in a decrease in the c_v .

However, a comparison of the c_v values for the two bentonites at different salt concentration for any given consolidation pressure in Figs. 4.31 to 4.34 show that the c_v

increased with increase in the salt concentration indicating a faster rate of consolidation in the presence of salt solution. With the increase in the salt concentration, the DDL thickness reduces (Table 4.2) resulting in a decrease in the long range repulsive forces and the samples consolidated at a faster rate. The plot also shows that the decrease in the c_v with increase in the pressure was significantly affected by the presence of salt solution. For the samples compacted at OMC-MDD, with an increase in the pressure from 19.6 kPa to 784.5 kPa the $2d$ thickness for Bentonite-A permeated with DI water reduced from 3.649×10^{-9} m to 0.601×10^{-9} m and consequently the c_v decreased from 3.5×10^{-4} cm²/sec to 2.28×10^{-5} cm²/sec (15.3 times). However, for the similar increase in the pressure the $2d$ thickness reduced only from 0.298×10^{-9} m to 0.227×10^{-9} m; whereas, the c_v decreased from 1.09×10^{-2} cm²/sec to 1.07×10^{-4} cm²/sec (101.3 times) when Bentonite-A was permeated with 1 N of CaCl₂ solution (Fig. 4.31). Similarly for Bentonite-B when permeated with DI water, the $2d$ thickness reduced from 5.446×10^{-9} m to 0.907×10^{-9} m and the c_v decreased from 1.55×10^{-4} cm²/sec to 1.03×10^{-5} cm²/sec (15.1 times). However, when permeated with 1 N of CaCl₂ solution the $2d$ thickness reduced only from 0.308×10^{-9} m to 0.216×10^{-9} m whereas, the c_v decreased from 3.38×10^{-2} cm²/sec to 5.25×10^{-5} cm²/sec (644.2 times). A comparison between the values of c_v for the two bentonites at the same concentration and consolidation pressure indicates that Bentonite-B, which has a higher swelling and liquid limit, exhibited a lower c_v in comparison to Bentonite-A. However, the difference between the c_v values for the two bentonites decreased with the increase in the salt concentration.

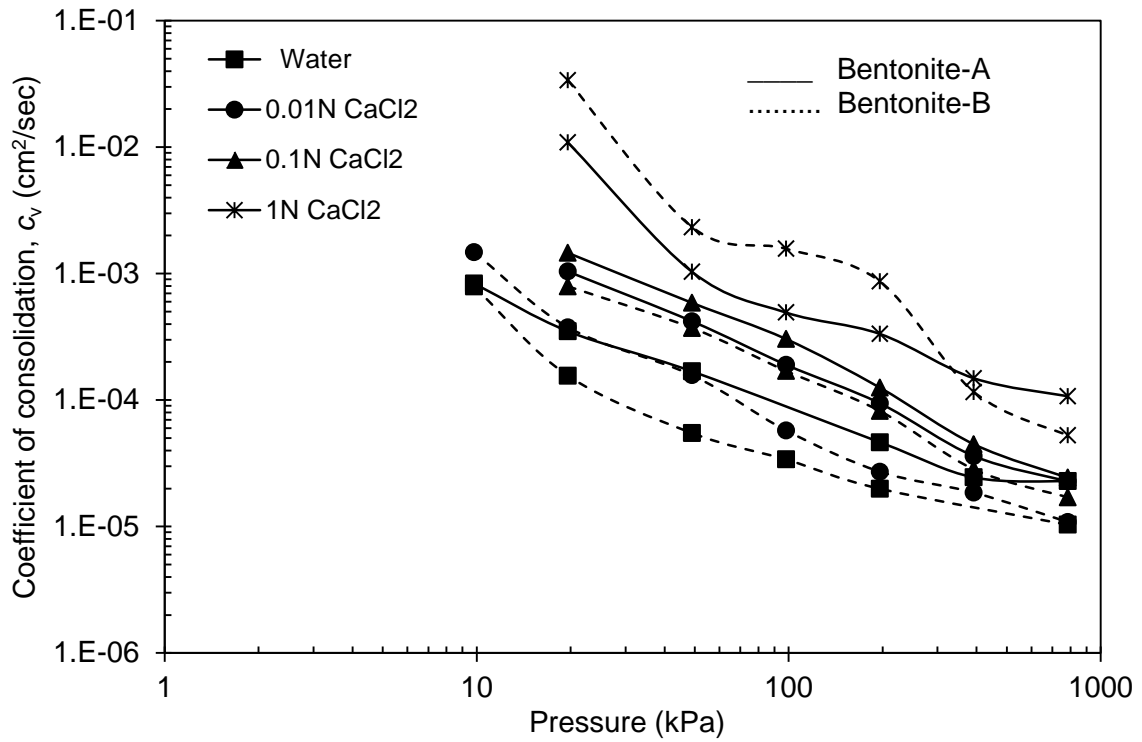


Figure 4.31 Plot between the coefficient of consolidation and consolidation pressures of Bentonite-A and -B for CaCl₂ solution at OMC-MDD

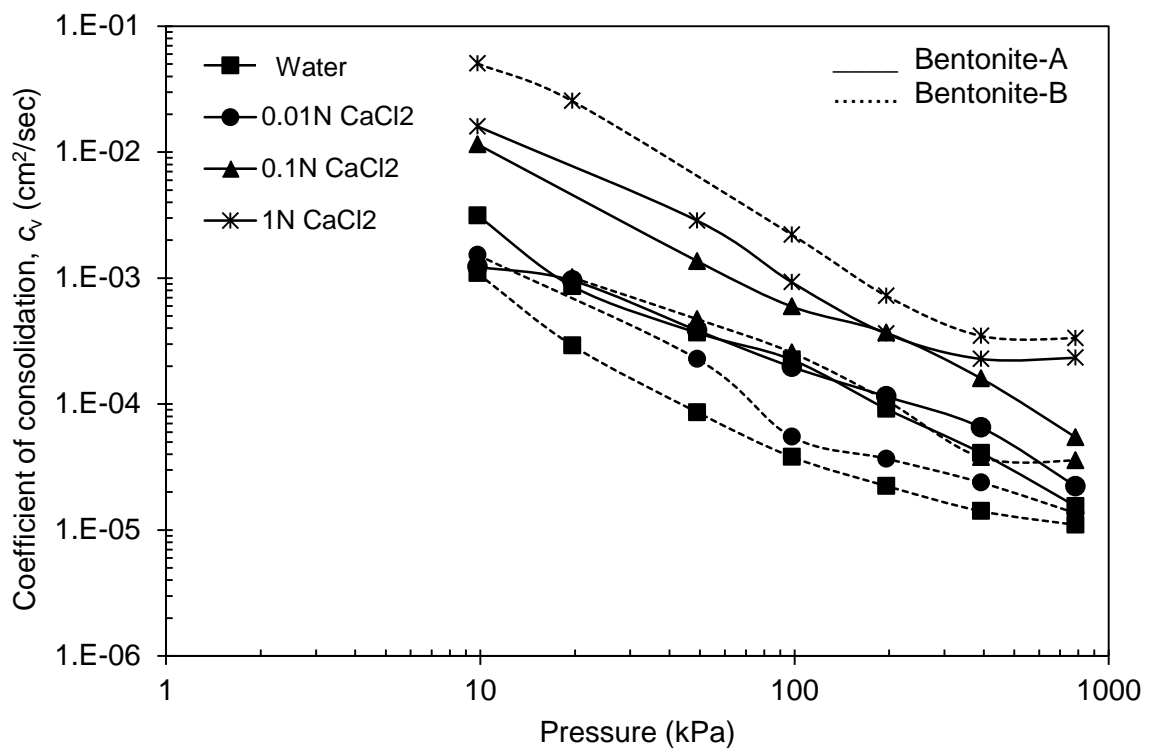


Figure 4.32 Plot between the coefficient of consolidation and consolidation pressures of Bentonite-A and -B for CaCl₂ solution at 5% dry of OMC-MDD

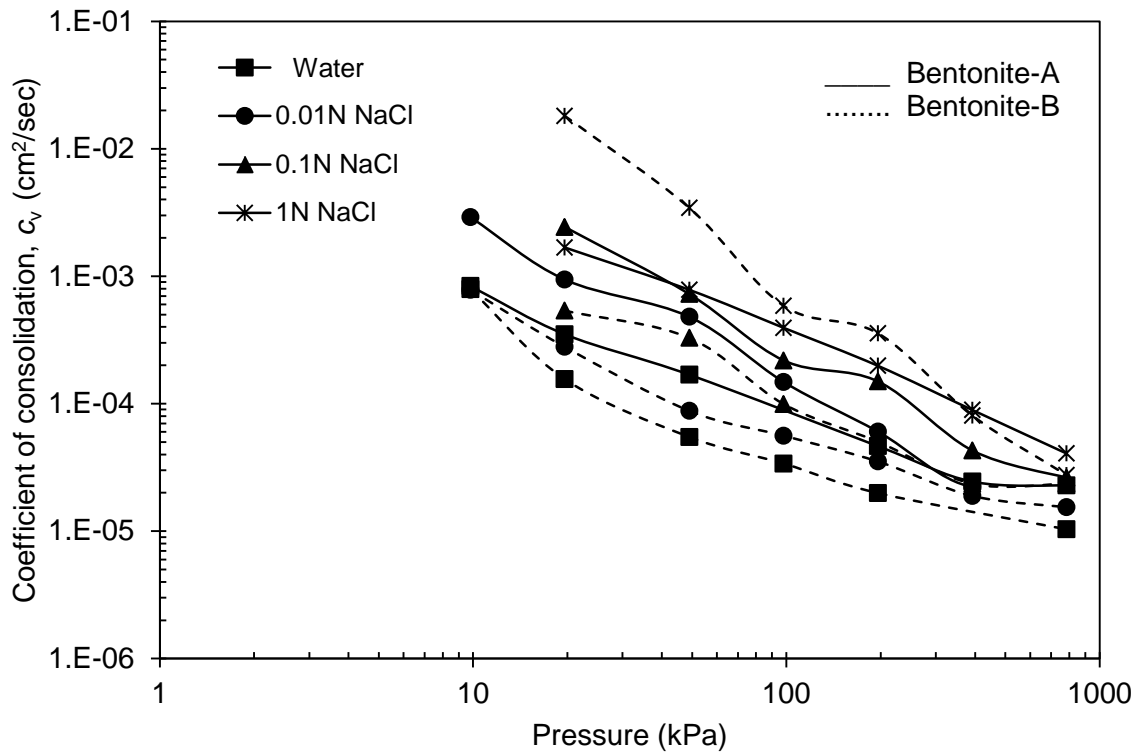


Figure 4.33 Plot between the coefficient of consolidation and consolidation pressures of Bentonite-A and -B for NaCl solution at OMC-MDD

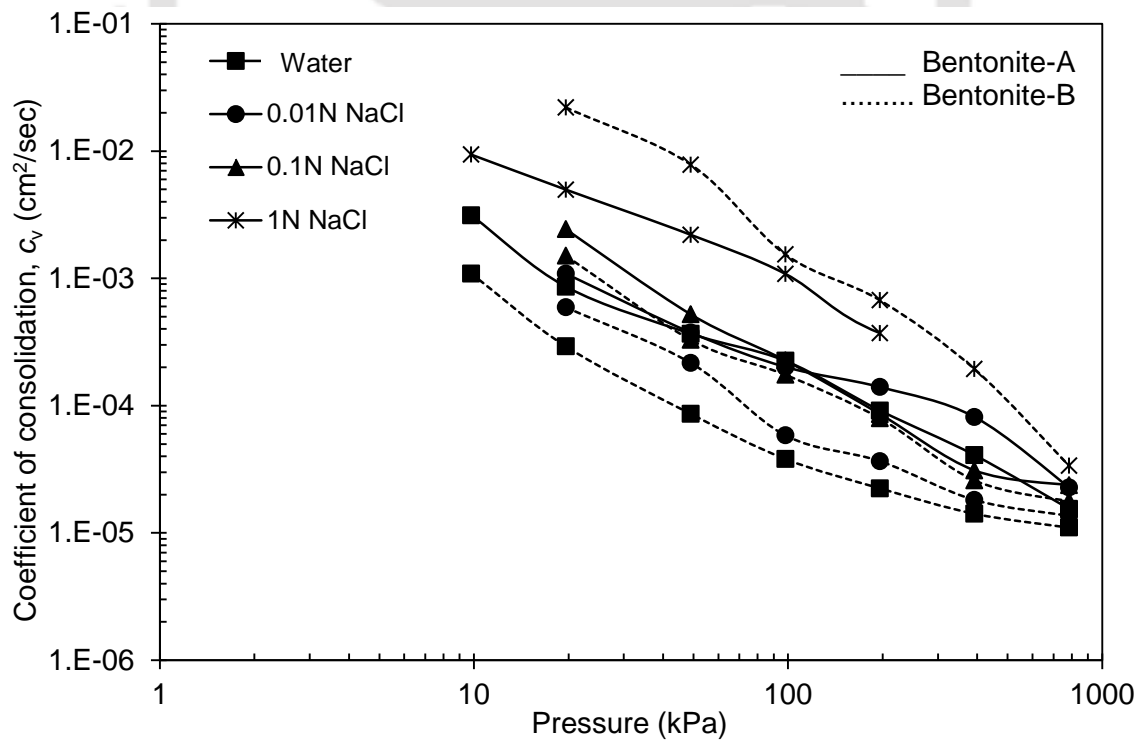
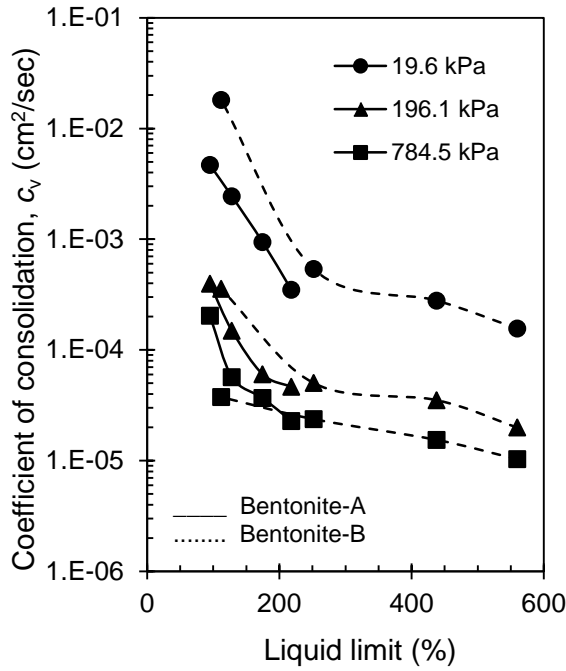
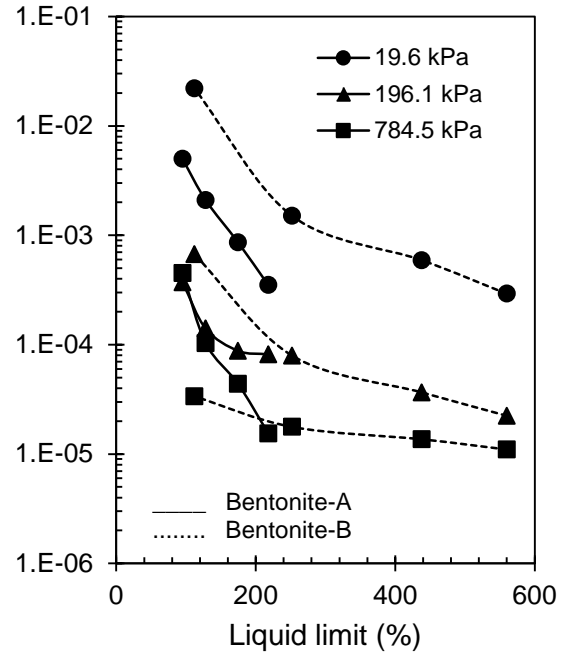


Figure 4.34 Plot between the coefficient of consolidation and consolidation pressures of Bentonite-A and -B for NaCl solution at 5% dry of OMC-MDD

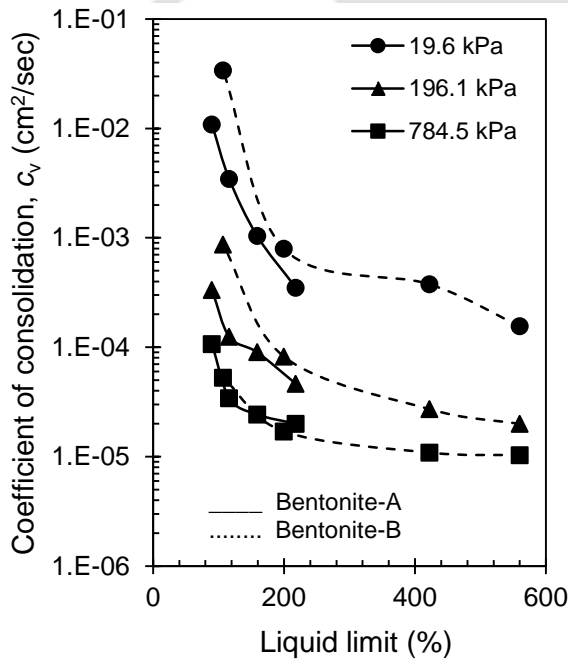
Since the interparticle repulsive forces and diffuse double layer thickness controls the liquid limit and free swelling of bentonite (Norrish, 1954; Sridharan and Rao, 1975; Sridharan et al., 1986b), the c_v value was further compared with liquid limit and free swelling of the two bentonites. Accordingly, c_v values corresponding to three different pressure, i.e. 19.6, 196.1 and 784.5 kPa representing minimum, average and maximum pressure during the consolidation test, were chosen and plotted against the liquid limit and free swelling of the two bentonites. Figure 4.35 shows that irrespective of the overburden pressure, the c_v decreased with the increase in the liquid limit of the bentonite. The decrease in c_v with increase in the liquid limit was significant for Bentonite-B compared to that of Bentonite-A. For Bentonite-A, in presence of NaCl solution, compacted at OMC-MDD and under a consolidation pressure of 19.6 kPa, the c_v decreased from 4.68×10^{-3} cm²/sec to 3.5×10^{-4} cm²/sec (13.0 times) when the liquid limit was increased from 94.9 % to 218.0 %; whereas, it decreased from 1.81×10^{-2} cm²/sec to 1.56×10^{-4} cm²/sec (116.0 times) for Bentonite-B due to an increase in the liquid limit from 112.0 % to 560.0 %. The decrease in the c_v with increase in the liquid limit was quite steep at the beginning and followed by a gradual decrease thereafter. For Bentonite-B, in presence of NaCl solution, compacted at OMC-MDD and under a consolidation pressure of 19.6 kPa, the c_v decreased from 1.81×10^{-2} cm²/sec to 5.37×10^{-4} cm²/sec (33.7 times) when the liquid limit was increased from 112.0 % to 252.0 %; however, with a further increase in the liquid limit from 252.0 % to 560.0 % the c_v decreased only from 5.37×10^{-4} cm²/sec to 1.56×10^{-4} cm²/sec (3.4 times). Similarly for Bentonite-B, in presence of CaCl₂ solution, compacted at OMC-MDD and under a consolidation pressure of 19.6 kPa, c_v decreased from 3.38×10^{-2} cm²/sec to 7.94×10^{-4} cm²/sec (42.6 times) when the liquid limit was increased from 107.0 % to 200.0 %; but with a further increase in the liquid limit from 200.0 % to 560.0 % the c_v was decreased only from 7.94×10^{-4} cm²/sec to 1.56×10^{-4} cm²/sec (5.1 times).



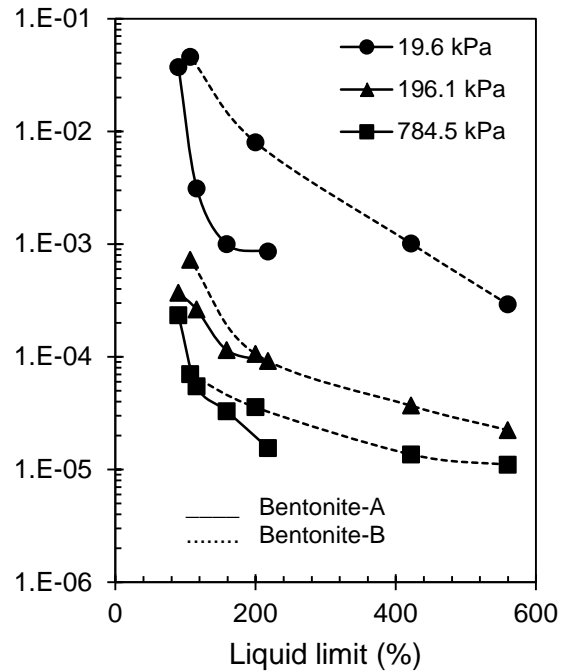
A. For NaCl solution and compacted at OMC-MDD



B. For NaCl solution and compacted at 5% dry of OMC-MDD

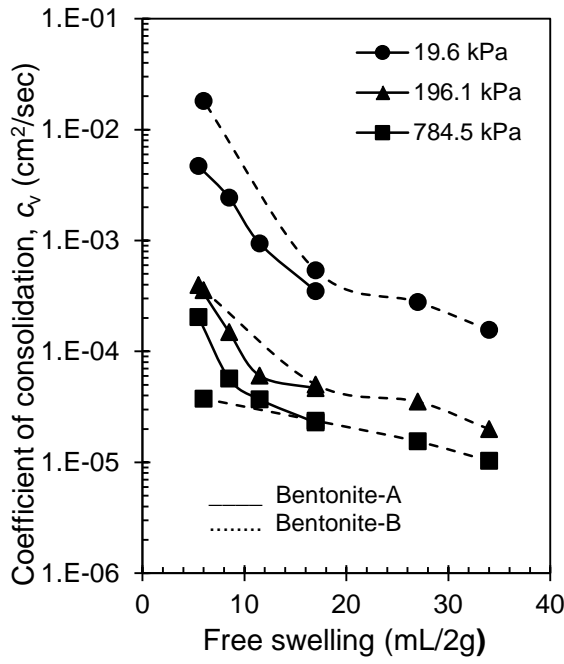


C. For CaCl₂ solution and compacted at OMC-MDD

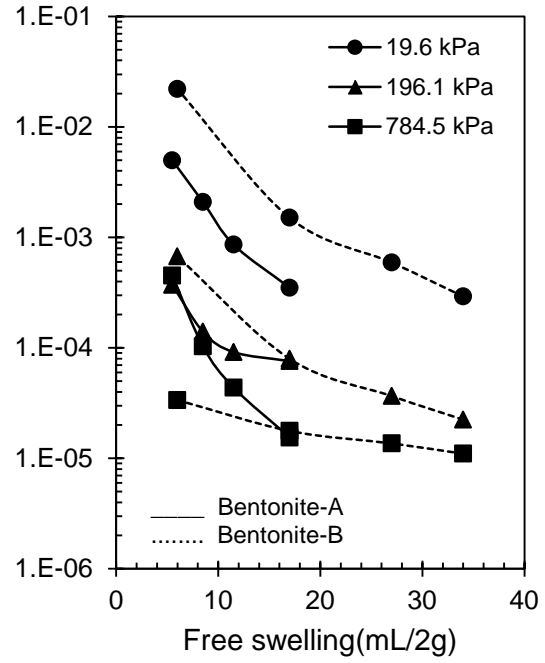


D. For CaCl₂ solution and compacted at 5% dry of OMC-MDD

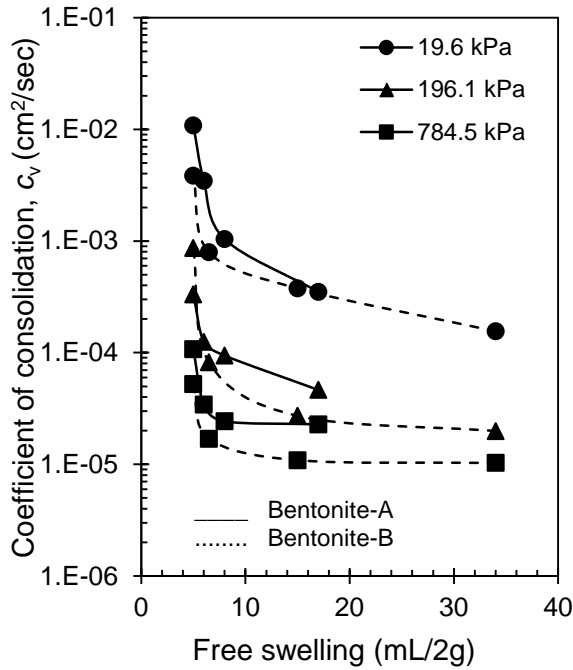
Figure 4.35 Plot between coefficient of consolidation and the liquid limit for Bentonite-A and -B for different salt solution at different initial compaction condition



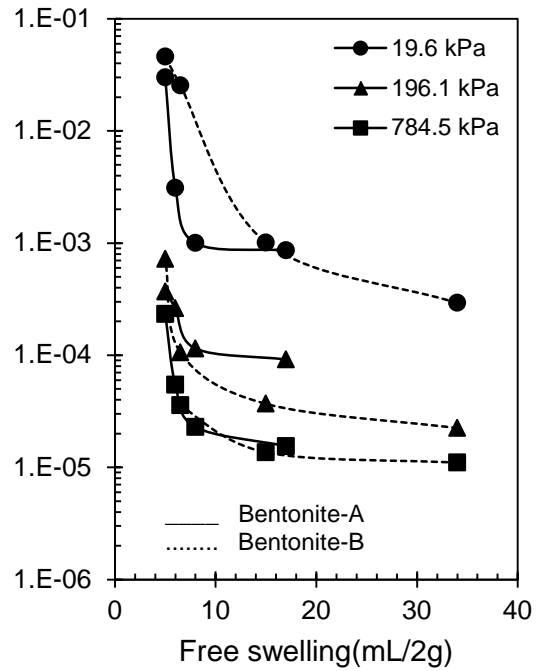
A. For NaCl solution and compacted at OMC-MDD



B. For NaCl solution and compacted at 5% dry of OMC-MDD



C. For CaCl₂ solution and compacted at OMC-MDD



D. For CaCl₂ solution and compacted at 5% dry of OMC-MDD

Figure 4.36 Plot between coefficient of consolidation and free swelling for Bentonite-A and -B for different salt solution at different initial compaction condition

Similarly, Fig. 4.36 shows that irrespective of the consolidation pressure, the c_v of both the bentonites decreased with the increase in the free swelling and was significant at low overburden pressure. Similar to the liquid limit-coefficient of consolidation (c_v) plot, the decrease in the c_v with the increase in the free swelling was quite steep in the beginning. For Bentonite-B, in presence of NaCl solution, compacted at OMC-MDD and under a consolidation pressure of 19.6 kPa, c_v decreased from 1.81×10^{-2} cm²/sec to 5.37×10^{-4} cm²/sec due to the increase in the free swelling from 6 mL/2g to 17 mL/2g. However, a further increase in the swelling from 17 mL/2g to 34 mL/2g resulting in a decrease in the c_v only from 5.37×10^{-4} cm²/sec to 1.56×10^{-4} cm²/sec. For Bentonite-B, in presence of CaCl₂ solution and under a consolidation pressure of 19.6 kPa, c_v decreased from 3.38×10^{-2} cm²/sec to 7.94×10^{-4} cm²/sec due to the increase in the free swelling from 5 mL/2g to 7 mL/2g. However, a further increase in the swelling from 7 mL/2g to 34 mL/2g resulting in a decrease in the c_v only from 7.94×10^{-4} cm²/sec to 1.56×10^{-4} cm²/sec. A comparison between the samples compacted at the two different condition shows that samples compacted at dry of OMC exhibited higher c_v values.

4.2.7.5. Time for 90% of consolidation (t_{90})

Time for 90% of consolidation (t_{90}) of a sample indicates the time required to complete 90 % of the consolidation under a given consolidation pressure. Figures 4.37 and 4.38 show the relationship between consolidation pressure and time to complete 90% of consolidation (t_{90}). The plots indicate that with an increase in the overburden pressure the t_{90} for the sample increases. The plots also show that the t_{90} for the samples depends not only on the type of bentonite but also on the saturating fluid as well. For any given concentration and pressure, a higher value of t_{90} was observed for the Bentonite-B, which had higher CEC, ESP, and liquid limit and exhibited higher $2d$ thickness, in comparison to Bentonite-A.

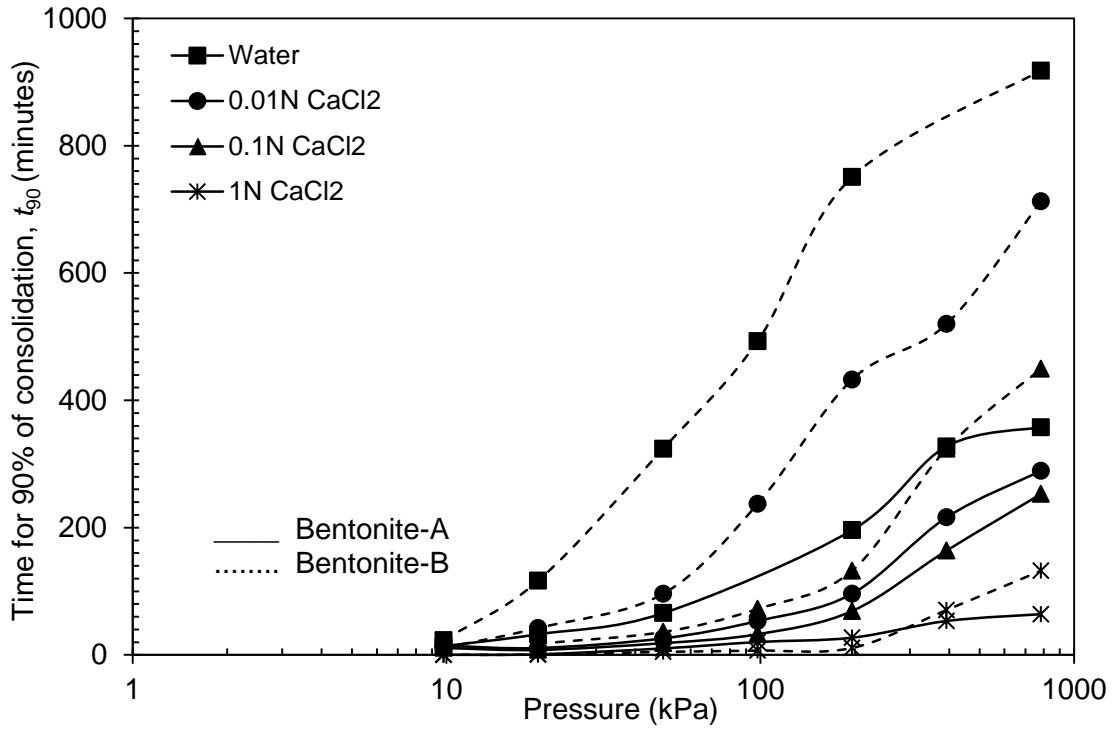


Figure 4.37 Plot between the time for 90% of consolidation and consolidation pressures of Bentonite-A and -B for CaCl₂ solution

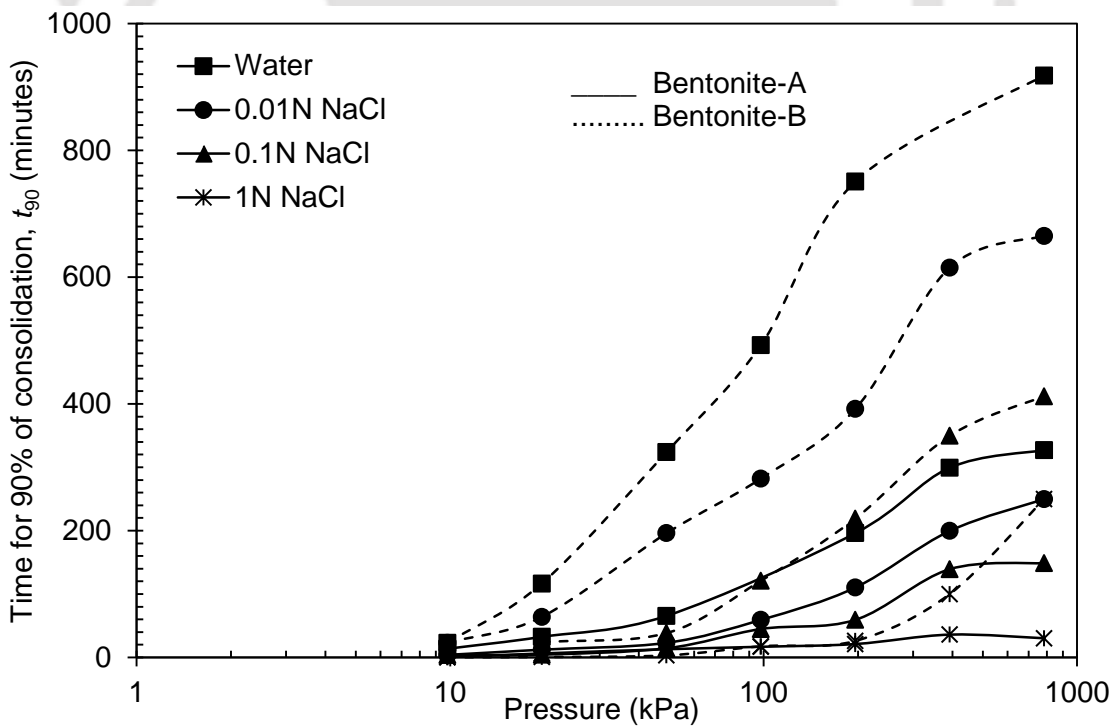
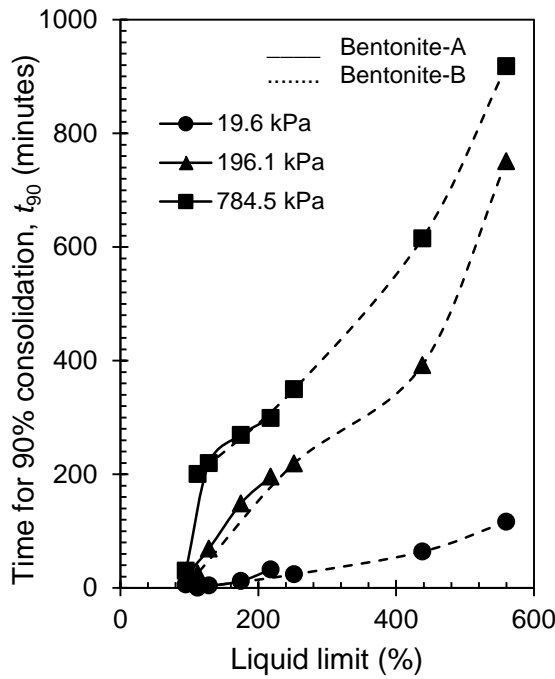


Figure 4.38 Plot between the time for 90% of consolidation and consolidation pressures of Bentonite-A and -B for NaCl solution

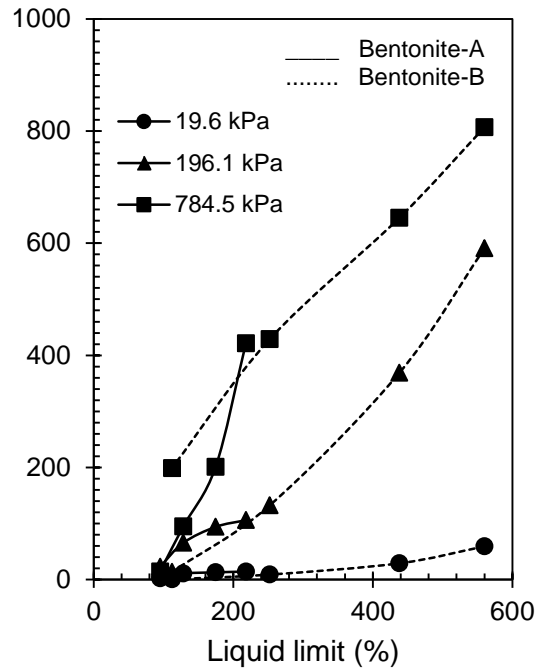
Figures 4.37 and 4.38 show that the rate of increase in the t_{90} with the consolidation pressure decrease significantly with the increase in the salt concentration of the saturating fluid. For the samples compacted at OMC-MDD, with an increase in the pressure from 9.8 kPa to 784.5 kPa the t_{90} for the Bentonite-B permeated with DI water increased from 23.1 minutes to 918.1 minutes; whereas, it increased only from 0.49 minutes to 132.2 minutes for 1 N of CaCl_2 solution. Similarly, for Bentonite-A the t_{90} was increased from 13.7 minutes to 357.6 minutes when permeated with DI water. However, on permeation with 1 N of CaCl_2 t_{90} increased only from 0.2 minutes to 64.0 minutes.

Further to study the relationship between t_{90} with liquid limit and free swelling of bentonite, t_{90} value corresponding to three different pressures, i.e. 19.6, 196.1 and 784.8 kPa were plotted in Figs. 4.39 and 4.40. The plots between t_{90} and liquid limit in Fig. 4.39 show that the t_{90} of the bentonites gets significantly affected by the clay-pore fluid interaction. It can be seen that the increase in the value of t_{90} with increase in the consolidation pressure was quite significant for the bentonite with higher liquid limit. For the samples of Bentonite-A compacted at OMC-MDD and with a liquid limit of 218.0 %, the t_{90} increased from 32.4 minutes to 299.1 minutes when the consolidation pressure increased from 19.6 kPa to 784.8 kPa; whereas, samples of Bentonite-B with a liquid limit of 560.0 %, the t_{90} increased from 116.2 minutes to 918.1 minutes for a similar increase in the pressure.

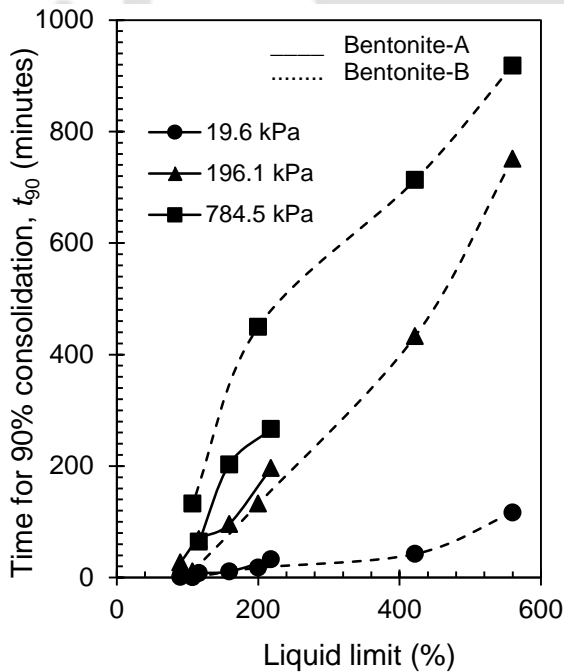
The plot also shows that irrespective of the consolidation pressure, the t_{90} increased with the increase in the liquid limit of the bentonite. However, the increase in the t_{90} with the liquid limit was prominent at high consolidation pressure compared to that at low consolidation pressure. For Bentonite-A, in presence of NaCl solution and compacted at OMC-MDD and at a consolidation pressure of 784.5 kPa, t_{90} increased from 30.2 minutes



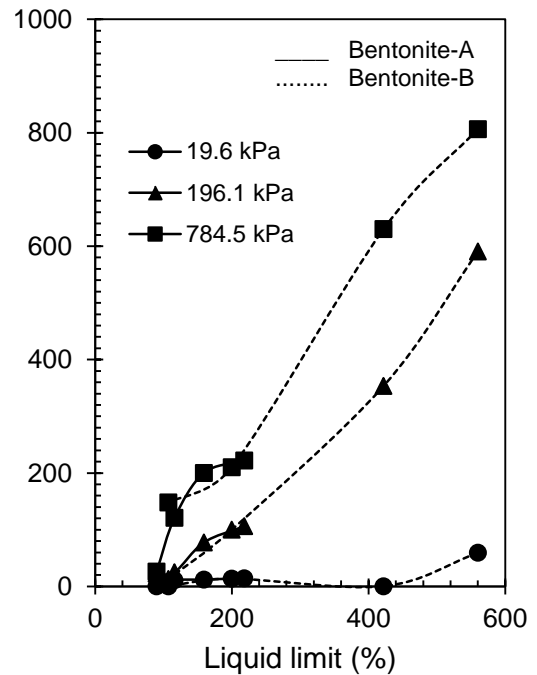
A. For NaCl solution and compacted at OMC-MDD



B. For NaCl solution and compacted at 5% dry of OMC-MDD

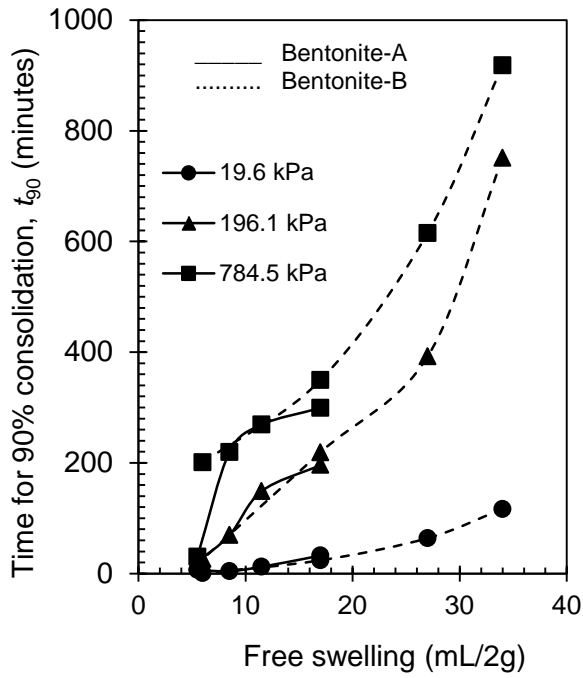


C. For CaCl₂ solution and compacted at OMC-MDD

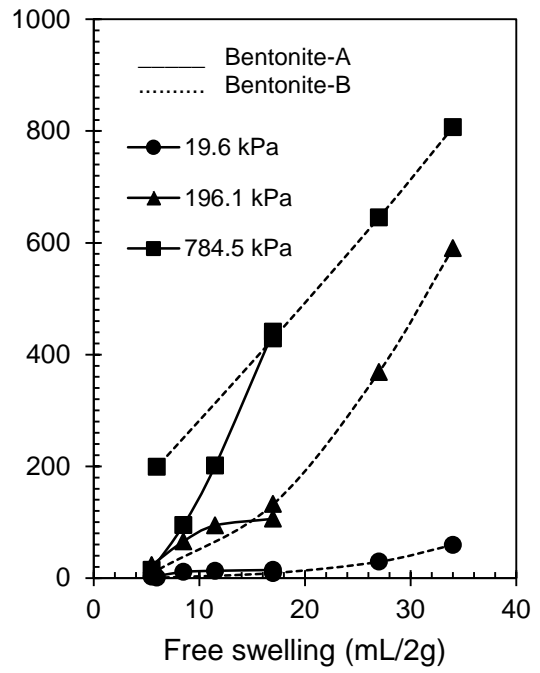


D. For CaCl₂ solution and compacted at 5% dry of OMC-MDD

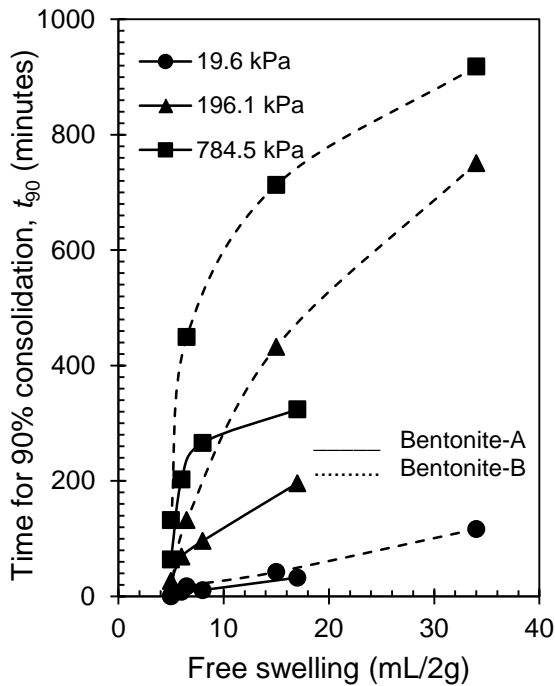
Figure 4.39 Plot between time for 90% consolidation and the liquid limit for Bentonite-A and -B for different salt solution at different initial compaction condition



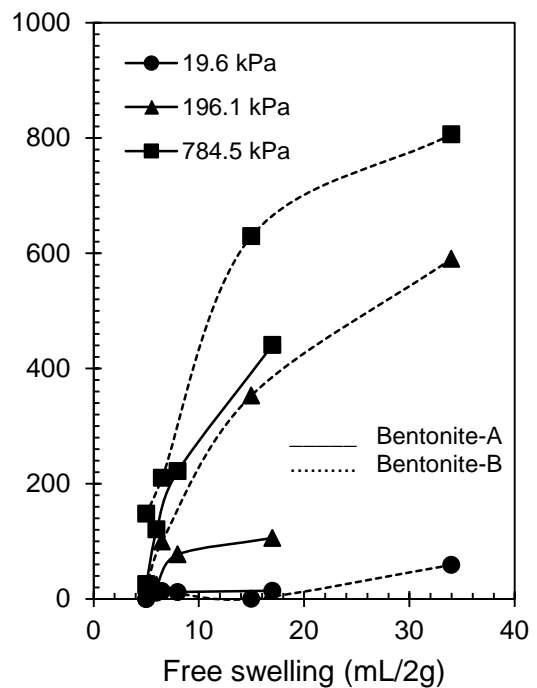
A. For NaCl solution and compacted at OMC-MDD



B. For NaCl solution and compacted at 5% dry of OMC-MDD



C. For CaCl₂ solution and compacted at OMC-MDD



D. For CaCl₂ solution and compacted at 5% dry of OMC-MDD

Figure 4.40 Plot between time for 90% consolidation and free swelling for Bentonite-A and -B for different salt solution at different initial compaction condition

to 299.3 minutes when liquid limit increased from 94.9 % to 218.0 %; whereas, at a pressure of 19.6 kPa, t_{90} increased from 6.3 minutes to 32.5 minutes. Similarly for Bentonite-B in presence of NaCl solution and at a consolidation pressure of 784.5 kPa, t_{90} increased from 200.2 minutes to 918.0 minutes when liquid limit increased from 112.0 % to 560.0 %, whereas, at pressure of 19.6 kPa, t_{90} increased from 0.7 minutes to 116.6 minutes.

Figure 4.40 shows the relationship between the t_{90} and the free swelling of the bentonites at the consolidation pressure of 19.6, 196.1 and 784.5 kPa in the presence of different concentration of NaCl and CaCl₂ solution. The plot shows that the t_{90} for the bentonites increased with the increase in the swelling capacity of the bentonites. The increase in the value of t_{90} with increase in the swelling capacity was quite significant for Bentonite-B in comparison to Bentonite-A. The plot also shows that the effect of the swelling on the t_{90} was significant at high consolidation pressure. The effect of swelling on the t_{90} value decreased with the decrease in the pressure. A comparison between the samples compacted at two different compaction condition shows that the samples compacted at dry of OMC exhibited lower t_{90} values.

4.2.7.6. Compression index (C_c)

Compression index (C_c) is defined as the slope of the straight line portion of virgin void ratio-pressure (e -log P) curve. The C_c of a sample gives an indication about its compressibility and is used to determine the settlement of the sample due to application of a consolidation pressure. The plot between the C_c and salt concentration in Fig. 4.41 shows that the C_c decreased with an increase in the salt concentration. Samples compacted at dry of OMC has higher C_c values in comparison to the samples compacted at OMC. With the increase in the salt concentration the orientation of the clay particles becomes more flocculated which resists the settlement resulting in a lower value of C_c . For samples

compacted at OMC-MDD, the C_c for Bentonite-A decreased from 0.699 to 0.564 (i.e. 19.3 %) due to an increase the concentration of pore fluid from 0 (DI water) to 1 N of NaCl solution; whereas, for the same increase in the concentration of the pore fluid the C_c for Bentonite-B decreased from 0.934 to 0.602 (i.e. 35.7 %). The C_c for Bentonite-B was decreased significantly with an increase in the concentration of both NaCl and CaCl₂ from 0 to 0.1 N; however, it decreased marginally with a further increase in the concentration from 0.1 to 1 N. Whereas, the C_c for Bentonite-A decreased uniformly with an increase in concentration of 0 to 1 N of both NaCl and CaCl₂ solution. The plot between C_c and liquid limit in Fig. 4.42 shows that with the increase in liquid limit, the C_c of both Bentonite-A and -B increased. With increase in the liquid limit from 90.0 % to 560.0 % the C_c increased from 0.53 to 1.01. The increase in the C_c with the increase in liquid limit followed a linear trend, however, it deviate significantly from the compression index and liquid limit relationship proposed by Skempton (1944).

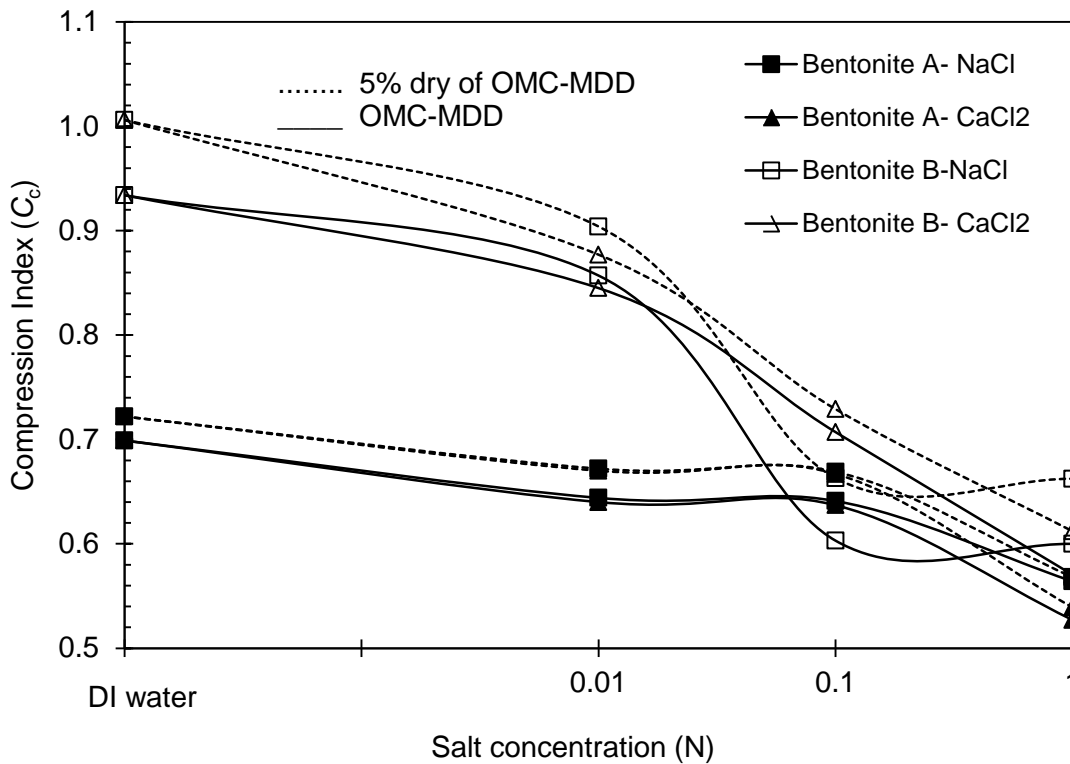


Figure 4.41 Effect of salt concentrations on compression index of Bentonite-A and -B

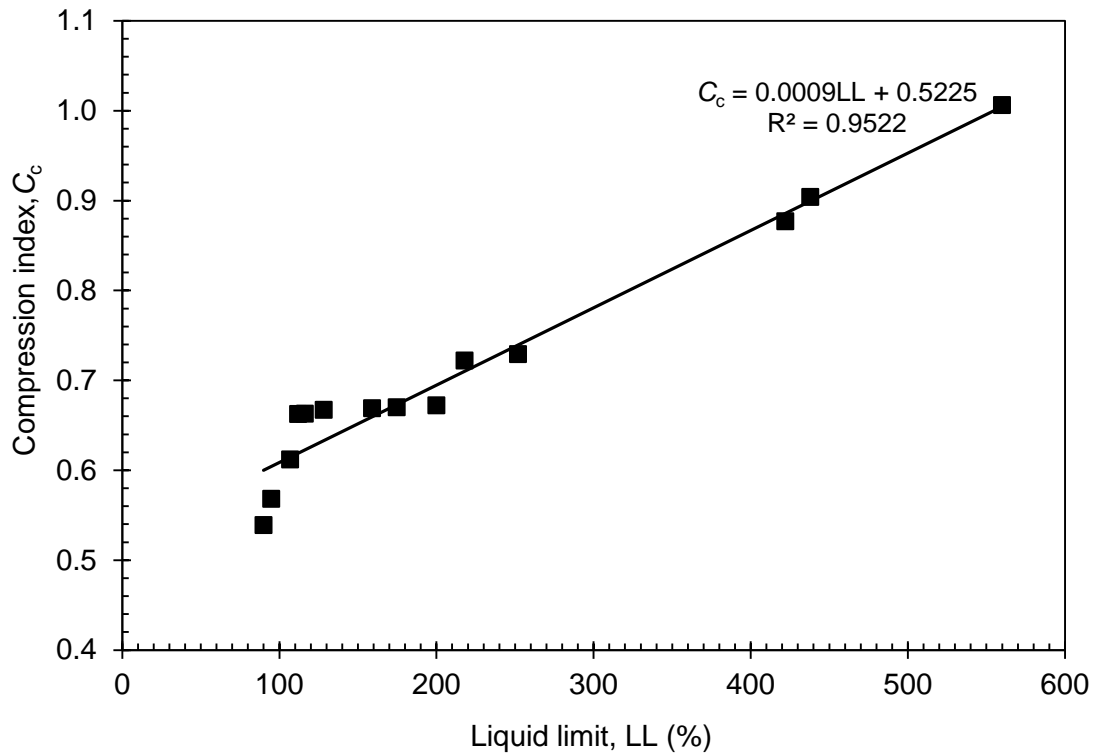


Figure 4.42 Plot between the compression index and the liquid limit of the bentonites

4.3. SUMMARY

This chapter includes study on the effect of various concentration of NaCl and CaCl₂ solution on the behaviour of two bentonites with different mineralogical composition. The result concluded that the liquid limit and free swelling of the bentonites decreases significantly, whereas, the plastic limit increases marginally due to the inclusion of salt in the pore liquid. The liquid limit and free swelling of the Bentonite-B, which has a higher cation exchange capacity (CEC), exchangeable sodium percentage (ESP) and specific surface area and marked as high quality bentonite, decreased considerably due to the increase in the salt concentration. The data also shows that the bentonite with NaCl solution exhibited a higher value of liquid limit and free swelling in comparison to CaCl₂ solution due to the formation of a relatively large diffuse double layer thickness in the presence of NaCl solution in comparison with the same concentration of CaCl₂ solution. However, the difference in the liquid limit and free swelling of the bentonites for the two

salts decreased with the increase in the salt concentration and reached to an almost identical value at 1 N.

A comparison of the time-swelling plot for the two bentonites showed that at the same time elapsed, the percentage of swelling was higher for Bentonite-B in comparison to Bentonite-A. Irrespective of the bentonite quality, swelling was least in presence of high concentration solution. The results also showed that the bentonites compacted at dry of optimum moisture content (OMC) exhibited higher percentage of swelling in comparison to the samples compacted at OMC indicating the influence of the initial compaction on the swelling behaviour.

A comparison of the values of swelling potential for the two bentonites showed that the swelling potential of Bentonite-B was affected significantly due to an increase in the salt concentration. The decrease in the swelling potential with increase in salt concentration was found to follow different trends for NaCl and CaCl₂ solution. An increase in the concentration from 0 to 0.01 N of NaCl solution decreased the swelling potential of both the bentonites marginally, whereas, same increase in the concentration of CaCl₂ solution decreased the swelling potential significantly. Irrespective of the salt concentration, sample compacted on the dry side of the OMC possessed a higher value of swelling potential in comparison to the samples compacted at OMC. The results also showed that the swelling potential of the bentonites increased with an increase in the liquid limit and free swelling.

The results showed that the swelling pressure of the bentonite decreased with the increase in the salt concentration. Similar to the liquid limit, free swelling and swelling potential, the decrease in the swelling pressure with increase in the concentration was different for different range of concentration. In comparison to the CaCl₂ solution a higher value of swelling pressure was observed for NaCl solution for any given concentration, however, the difference in swelling pressure value for the two bentonites decreased with the increase

in the concentration. A comparison of the swelling pressure for the two bentonites showed that the swelling pressure of Bentonite-B decreased significantly due to increase in the salt concentration in comparison to Bentonite-A. A comparison of the initial compaction condition on the swelling pressure shows initial water content has a marginal effect on the swelling pressure irrespective of the permeating liquid.

The results showed that irrespective of the initial compaction condition, the hydraulic conductivity of the bentonite increased with an increase in the salt concentration. The increase in the hydraulic conductivity with salt concentration was more prominent for higher salt concentration. The effect of salt concentration was found to be more prominent for the concentration of 0.1 N and above of both NaCl and CaCl₂ solution. It was observed that the $k_{\text{salt}}/k_{\text{water}}$ ratio decreased with the increase in the $FS_{\text{salt}}/FS_{\text{water}}$ ratio. The decrease was higher for Bentonite-B compared to Bentonite-A.

A comparison between the two bentonites for a given concentration and compaction condition shows that salt had a significant impact on Bentonite-B in comparison to Bentonite-A and the effect was more prominent at higher concentration.

The results for the coefficient of volume change (m_v) showed that irrespective of the permeating fluid and type of bentonite, the m_v initially increased and then decreased with an increase in the pressure. The plots also show that the Bentonite-B exhibited higher m_v values in comparison with that of Bentonite-A.

The data for the coefficient of consolidation (c_v) showed that it decreases with increasing consolidating pressure indicating a slower rate of consolidation at higher consolidation pressure and this trend was significantly affected by the presence of salt solution. A comparison between the values of c_v for the two bentonites at the same concentration and consolidation pressure indicates that Bentonite-B exhibited a lower c_v in comparison to Bentonite-A. However, the difference between the c_v values for the two bentonites

decreased with the increase in the salt concentration. Samples compacted at dry of OMC exhibited higher c_v and m_v values.

The plots indicate that with an increase in the consolidation pressure the t_{90} for the sample increases. The plots also show that the t_{90} for the samples depends not only on the type of bentonite but also on the saturating fluid as well. For any given concentration and pressure, a higher value of t_{90} was observed for the Bentonite-B in comparison to Bentonite-A. The result showed that the increase in t_{90} with pressure decreased significantly with increase in the salt concentration of the saturating fluid.

A higher value of theoretical void ratio obtained for both the bentonites from the diffuse double layer theory at lower consolidation pressure; however, with an increase in the consolidation pressure the value of theoretically obtained void ratio exceeds the experimentally obtained value. However, with the salt as a pore fluid a lower value of theoretical void ratio was obtained for both the bentonites. The results for the compression index (C_c) showed that the C_c decreased with an increase in the salt concentration.

EFFECT OF HEAVY METALS ON BEHAVIOUR OF BENTONITES

5.1. INTRODUCTION

Clay soils used in landfill liners get exposed to intensive physico-chemical attacks by leachates generated from the wastes. Existence of heavy metals in the leachates affects the pore fluid chemistry and influences the diffuse double layer of the clay particles. As such the durability and service life of a liner in waste containment facilities depends to a great extent on the leachates coming in contact with the liner. Though landfill leachates usually contain only modest concentrations of heavy metals, it is important for a geotechnical engineer to evaluate the engineering properties of clay soils in presence of the contaminants.

Because of high specific surface area (SSA), high cation exchange capacity (CEC), contaminant adsorption capacity and low hydraulic conductivity, bentonites are frequently used as liner material at waste disposal sites (Ryan, 1987; Murray, 2000). Montmorillonite, a mineral present in bentonite, can adsorb heavy metals in two different mechanisms: (i) cation exchange in the interlayers resulting from the interactions between ions and permanent negative charge and (ii) formation of inner-sphere complexes through Si-O- and Al-O-groups at the clay particle edges (Sparks, 1995). When the montmorillonite reacts with water, diffuse double layer develops (Mitchell and Soga, 2005) and due to the formation of the diffuse double layer, bentonite swells and then fills the pore spaces of the solid particles in a soil matrix and provides a lower value of hydraulic conductivity. However, the heavy metals present in the leachate suppress the thickness of the diffuse double layer which in turn shrinks the bentonite. As the bentonite shrinks, the flow path becomes open and the hydraulic conductivity increases.

Hydraulic conductivity and compressibility are the two important factors which controls the usefulness of bentonite as a landfill liner material. Compressibility performance of bentonites is governed by physico-chemical effects and double layer repulsive forces (Bolt, 1956; Sridharan and Rao, 1973). Studies have been carried out in the past to investigate the effect of heavy metals on the behaviour of bentonite (Abollino et al., 2001; Li, 2003; Lo et al., 2004; Nakano et al., 2008; Du et al., 2015) and are already discussed in Chapter 2.

Most of the studies in past on heavy metals contaminant-soil interaction have been carried out on retention, sorption and conduction phenomena; however, it is very important to understand the effect of the interaction of the heavy metals on the swelling, hydraulic and consolidation behaviour of bentonite. Although the swelling and the hydraulic conductivity is an important factor for a bentonite for its usefulness as a landfill liner material, no studies have been carried out in the past to investigate the effect of heavy metals on the swelling, hydraulic conductivity and consolidation behaviour of the bentonite. Hence, the objective of this chapter was to examine the impact of the presence of heavy metals in leachate on the swelling, hydraulic and consolidation behaviour of bentonite. Two bentonites with different mineralogical composition, which was reflected in their different liquid limit and free swelling value, were evaluated for their change in free swelling, Atterberg limits, hydraulic conductivity, swelling potential, swelling pressure and various consolidation parameters such as compression index (C_c), coefficient of volume change (m_v), coefficient of consolidation (c_v) and time to complete 90% of the consolidation (t_{90}) due to the presence of various concentrations of Zn^{2+} , Pb^{2+} and Cu^{2+} ions. Further, to study the effect of initial compaction conditions on the behaviour of compacted bentonite in the presence of these solutions, experiments were also carried out on samples with different initial compaction condition.

5.2. RESULTS AND DISCUSSIONS

5.2.1 Atterberg limits

The effect of various concentrations of Zn^{2+} , Pb^{2+} and Cu^{2+} ions on the Atterberg limits of the bentonites is shown in Fig. 5.1. Similar to the results obtained for the inorganic salt solution, the plot also shows that the liquid limit of the bentonites decreased with increase in the heavy metal ion concentration and the decrease was more prominent for Bentonite-B in comparison to Bentonite-A. The liquid limit of Bentonite-A decreased from 218.0 % with DI water to 165.1 %, 170.2 % and 163.0 % for Zn^{2+} , Pb^{2+} , and Cu^{2+} solution with 1000 ppm concentration, respectively; whereas, for a similar increase in the concentration the liquid limit of Bentonite-B decreased from 560.0 % with DI water to 279.1 %, 286.0 % and 264.2 % for Zn^{2+} , Pb^{2+} , and Cu^{2+} solution, respectively. This can be attributed to the formation of a relatively large diffuse double layer (DDL) thickness in case of Bentonite-B in comparison to Bentonite-A. An increase in the metal ion concentration decreases the inter-particle repulsion, which in turn makes the particles to become free to move at lower water contents or lower inter-particle distances resulting in the decrease in the liquid limit (Warkentin, 1961; Sridharan and Rao, 1975). A comparison between the values of liquid limits for the two bentonites at the same concentration indicate that Bentonite-B, with a higher CEC, ESP and SSA value, exhibited a higher value of liquid limit in comparison to Bentonite-A. Bentonite with Pb^{2+} as pore fluid exhibited the highest liquid limit value in comparison to other heavy metal ions.

The plot in Fig. 5.2 shows that the plastic limit of the bentonites decreased marginally with the increasing heavy metal ion concentrations. Similar behaviour was also observed for the bentonites in the presence of inorganic salt solutions.

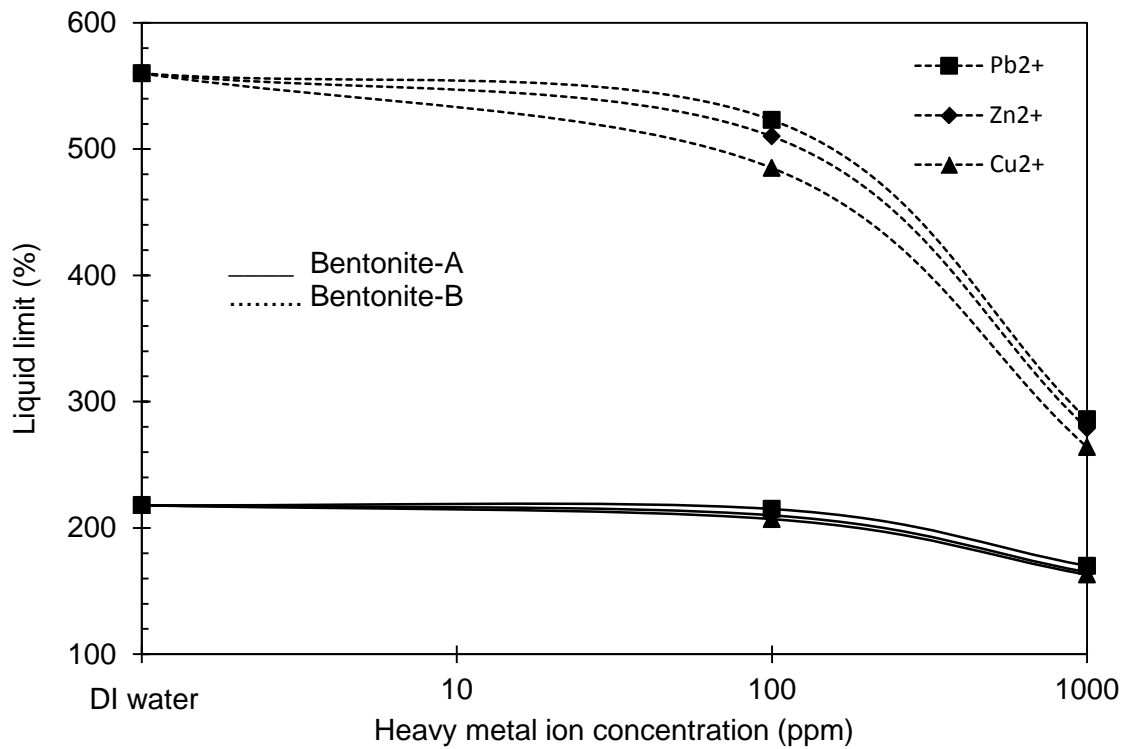


Figure 5.1 Liquid limits of Bentonite-A and -B in the presence of different concentrations of heavy metals

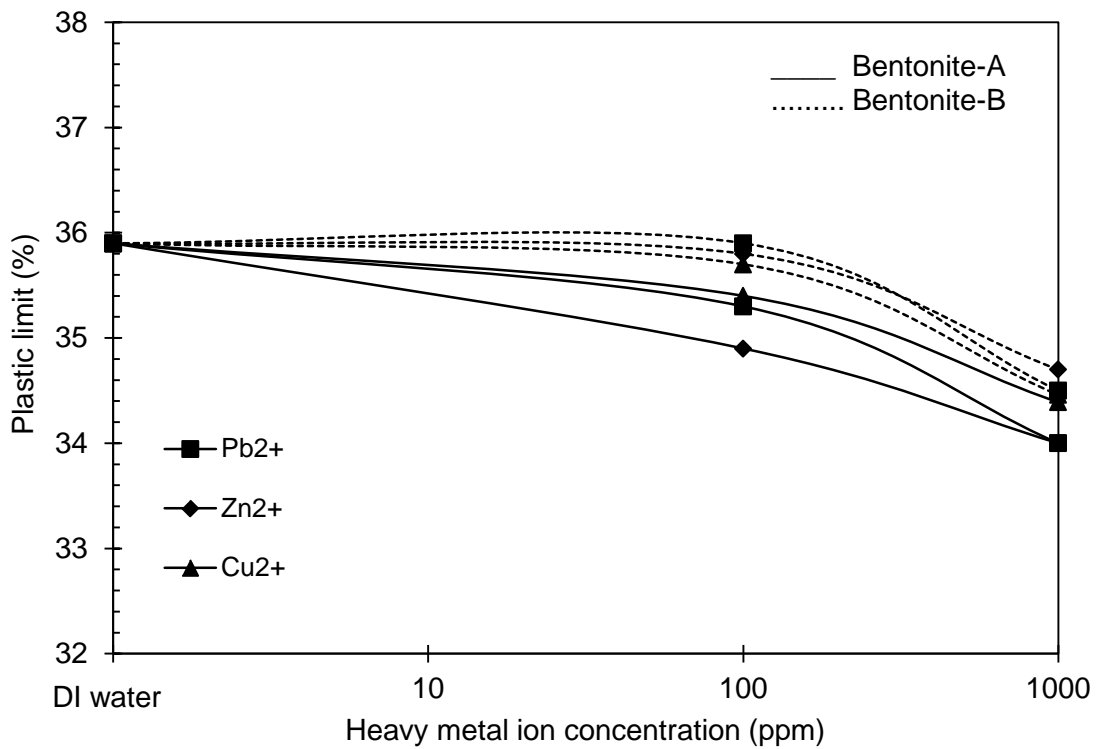


Figure 5.2 Plastic limits of Bentonite-A and -B in the presence of different concentrations of heavy metals

5.2.2. Free swelling

The effect of various concentrations of lead, zinc and copper ions on the free swelling of bentonites is shown in Fig 5.3. The plot in the figure shows that free swelling of bentonites decreased with increasing the concentration of heavy metal ions. The free swelling of Bentonite-B was found to be decreased significantly due to the increase in the metal ion concentration in comparison to Bentonite-A. For Bentonite-B, the decrease in the free swelling with metal ion concentration was minimal for an increase in concentration from 0 to 100 ppm; however, with a further increase in concentration from 100 ppm to 1000 ppm the swelling decreased significantly. With an increase in the concentration from 0 to 100 ppm of Pb^{2+} solution the free swelling decreased from 34 mL/2g to 29 mL/2g for Bentonite-B; whereas, with a further increase in the concentration from 100 ppm to 1000 ppm the free swelling decreased from 29 mL/2g to 16 mL/2g.

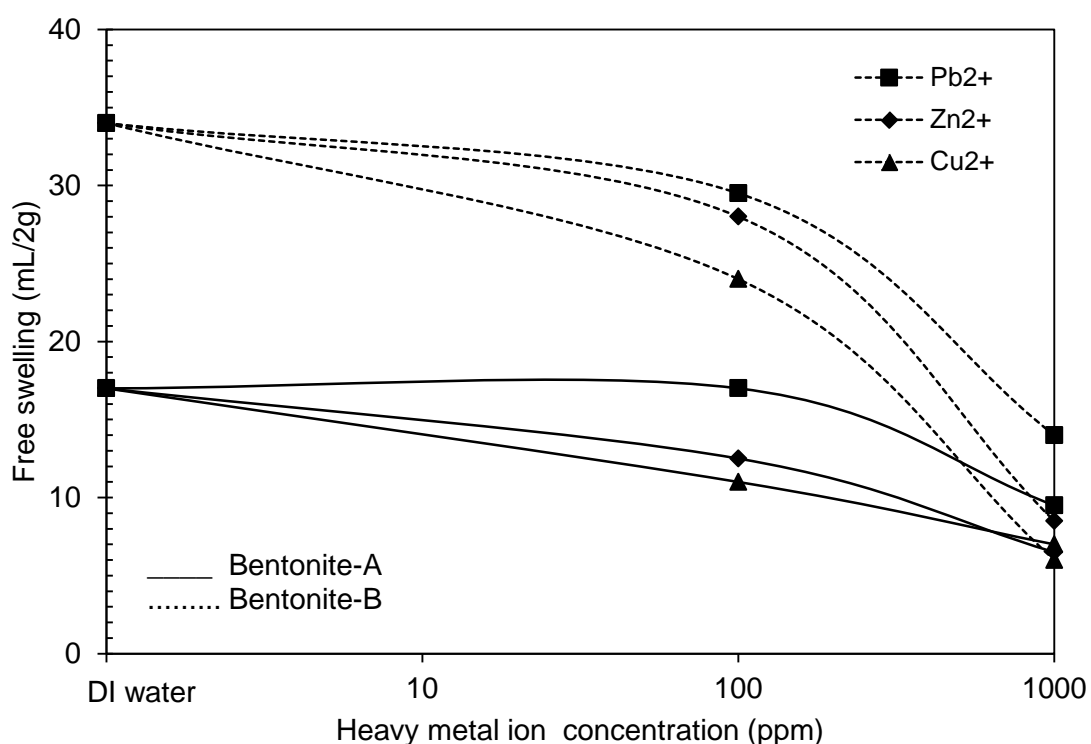


Figure 5.3 Plots for the free swelling of Bentonite-A and -B in the presence of heavy metals

Similarly, an increase in the concentration from 0 to 100 ppm of Pb^{2+} solution decreased the free swelling from 17 mL/2g to 16 mL/2g for Bentonite-A and with a further increase in the concentration from 100 ppm to 1000 ppm decreased the swelling from 16 mL/2g to 9 mL/2g. A higher reduction in the free swelling of Bentonite-B can be attributed to the significant reduction in the DDL thickness due to the addition of heavy metal solutions. The plot shows that the bentonite swelled to a higher value in the presence of solution of Pb^{2+} followed by solution of Zn^{2+} and Cu^{2+} .

5.2.3. Swelling pressure

Figure 5.4 shows the effect of the metal ion concentration on the swelling pressure of the bentonites compacted at OMC-MDD and 5% dry of OMC-MDD. The plot shows that the swelling pressure for both the bentonites decreased with the increase in the metal ion concentration in the pore fluid.

Similar to the free swelling and liquid limit behaviour, the swelling pressure of Bentonite-B also found to be affected significantly due to the presence of heavy metal ions in the pore fluid in comparison to Bentonite-A. For Bentonite-B, compacted at OMC-MDD, the swelling pressure decreased from a value of 708.0 kPa with DI water to 450.1 kPa (i.e. decrease by 36%) due to presence of 1000 ppm of Cu^{2+} solution. For a similar increase in the concentration the swelling pressure of Bentonite-A decreased from 267.7 kPa to 193.2 kPa (i.e. decrease by 27%). Since the reduction in the DDL due to the addition of metal solutions was also higher for Bentonite-B in comparison to Bentonite-A, a larger reduction in the swelling pressure was observed for Bentonite-B. The plot also shows that Cu^{+2} ions have more influence on the swelling pressure in comparison to Pb^{2+} ions followed by Zn^{+2} ions. In addition to this, it can also be observed that the difference in the effect was more prominent for 1000 ppm in comparison to 100 ppm. This observation was quite

contrary to the behaviour obtained for NaCl and CaCl₂ solution where the difference was more prominent at lower salt concentration.

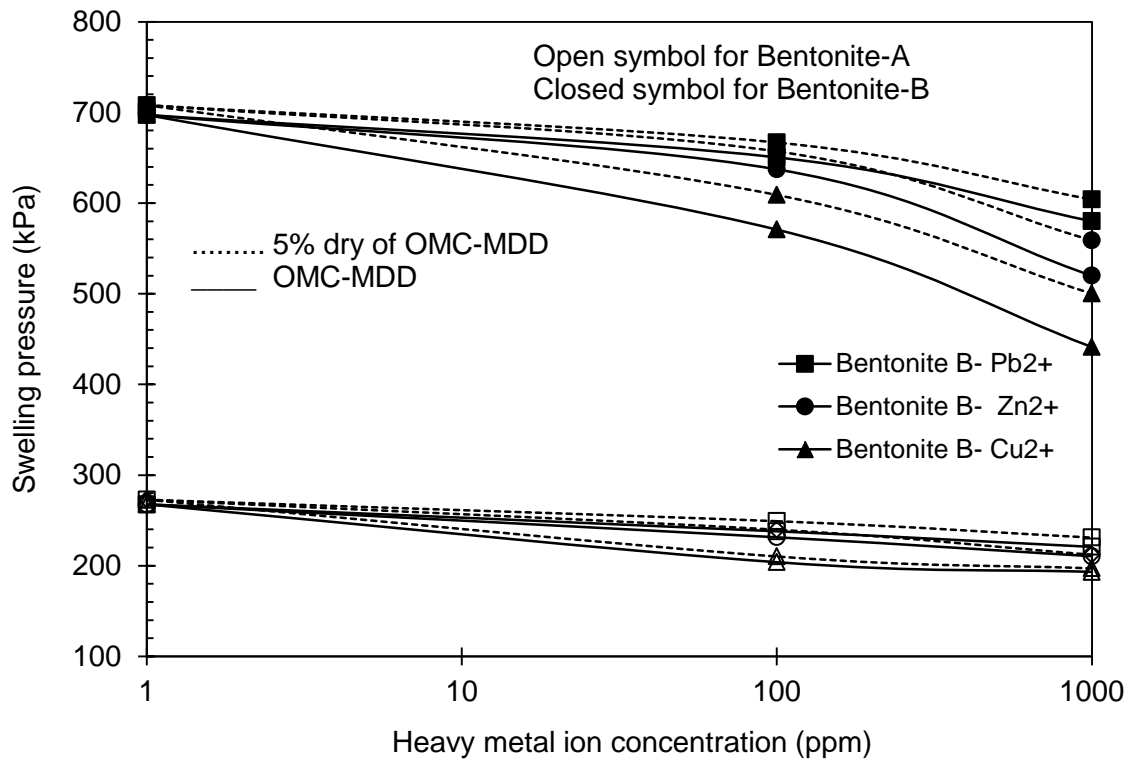


Figure 5.4 Effect of heavy metal concentrations on swelling pressure of Bentonite-A and -B at different compaction conditions

5.2.4. Swelling potential

Figure 5.5 shows the effect of heavy metals and initial water content on the swelling potential of both the bentonites. Plot shows that irrespective of initial water content the swelling potential of bentonites decreased with the increase in metal ion concentration. In comparison to Cu²⁺ and Zn²⁺ solutions, a higher value of swelling potential was observed for Pb²⁺ solution. The pH conditions affect the adsorption rate which increases as the solution becomes more acidic. The pH values of 100 ppm Pb²⁺, Zn²⁺, and Cu²⁺ solutions was measured to be 6.6, 6.5, 6.0, respectively; whereas, for 1000 ppm Pb²⁺, Zn²⁺, and Cu²⁺ solutions the pH was 5.9, 5.6, 5.1, respectively. The Pb²⁺ solution was the least acidic among the solutions tested, resulting in less adsorption rate. Thus Pb²⁺ precipitates and

there is lesser interaction of Pb^{2+} ion and bentonite due to which the swelling potential was highest when bentonite was permeated with lead solution (Ouhadi et al. 2006). For Bentonite-A, the samples compacted at OMC-MDD exhibited a swelling potential of 22.7% when permeated with DI water and decreased to 20.5%, 18.7%, and 18.0% due to permeation with 1000 ppm of Pb^{2+} , Zn^{2+} , and Cu^{2+} solution, respectively. Similarly, for the samples compacted at 5% dry of OMC-MDD the swelling potential decreased from 25.6% when it permeated with DI water to 20.9%, 20.4%, 19.9% due to permeation with 1000 ppm of Pb^{2+} , Zn^{2+} , and Cu^{2+} solution, respectively. Similarly, Bentonite-B compacted at OMC-MDD, exhibited a swelling potential of 48.4% with DI water and it decreased to 41.5%, 36.4%, and 38.9% after permeating with 1000 ppm of Pb^{2+} , Zn^{2+} , and Cu^{2+} solution, respectively.

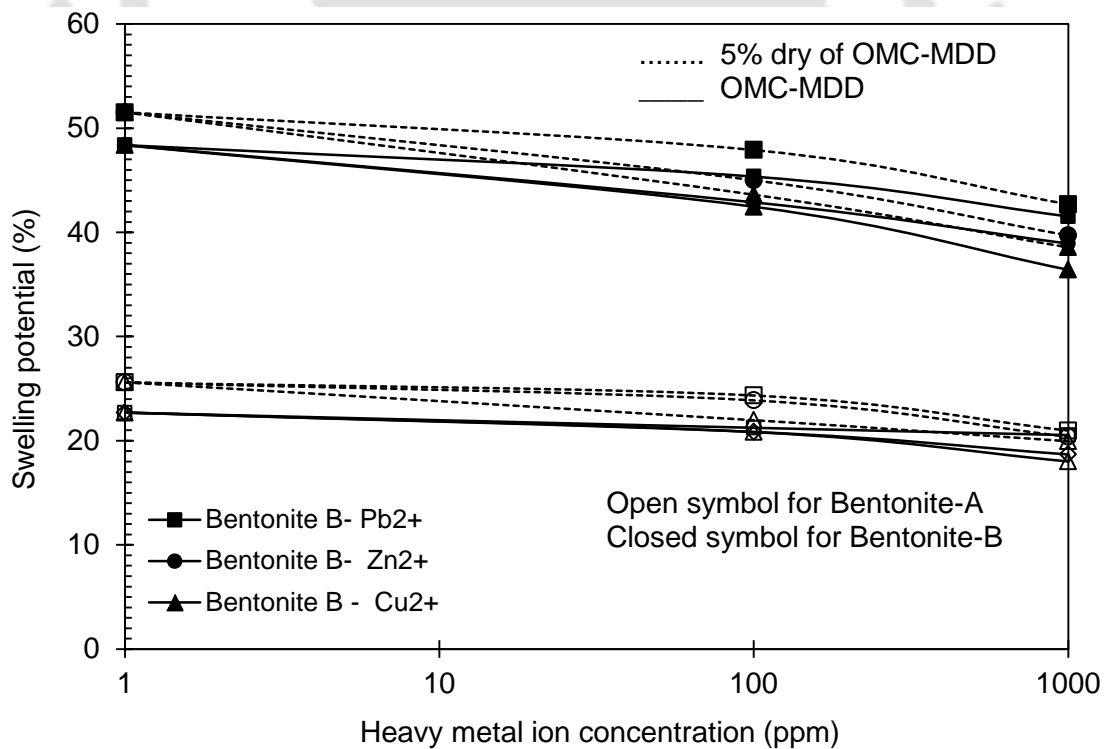


Figure 5.5 Swelling potential of Bentonite-A and -B at different compaction conditions for various concentrations of Pb^{2+} , Zn^{2+} and Cu^{2+} solution

For the samples compacted at 5% dry of OMC-MDD, the swelling potential decreased from 51.5% to 42.7%, 38.5%, and 39.7% due to increase in the concentration from 0 (i.e. DI water) to 1000 ppm of Pb^{2+} , Zn^{2+} , and Cu^{2+} solution, respectively. Figure 5.5 also shows that, irrespective of the metal ion concentration, samples compacted on the dry side of the OMC possessed a higher value of swelling potential in comparison to the samples compacted at OMC. This can be attributed to higher suction values for samples compacted at the dry side of OMC resulting in a higher tendency to swell and a higher swelling potential (Chen, 1975).

5.2.5. Time swelling relationship

Figures 5.6 to 5.9 show the relationship between swelling of the bentonites expressed in percentage and elapsed time for samples compacted at two different compaction conditions in the presence of various concentrations of Pb^{2+} , Zn^{2+} , and Cu^{2+} solutions. Irrespective of their initial compaction condition and type of saturating fluid, the time-swelling curve followed a “S” shape in which initially bentonite swelled slowly, then increased steeply and finally reached to an asymptotic value. Similar to the samples with NaCl and $CaCl_2$ solutions, the plots show the samples with heavy metals ions also swelled in three distinct stages of swelling, i.e. initial, primary and secondary swelling (Rao et al., 2006; Mishra et al., 2008). The swelling of the macrostructure contribute to the initial swelling while the swelling of the microstructure contribute to the primary and secondary swelling of the bentonites (Rao et al., 2006). Figures 5.6 to 5.9 show that with the increase in the heavy metal ion concentrations, the time taken for the completion of primary swelling reduces. A comparison between the two bentonites showed that at the same elapsed time, the percentage of swelling was higher for Bentonite-B in comparison to Bentonite-A. Irrespective of the bentonite type, swelling was marginally higher in presence of Pb^{2+} solution in comparison to Zn^{2+} and Cu^{2+} solution. Samples compacted at dry of OMC

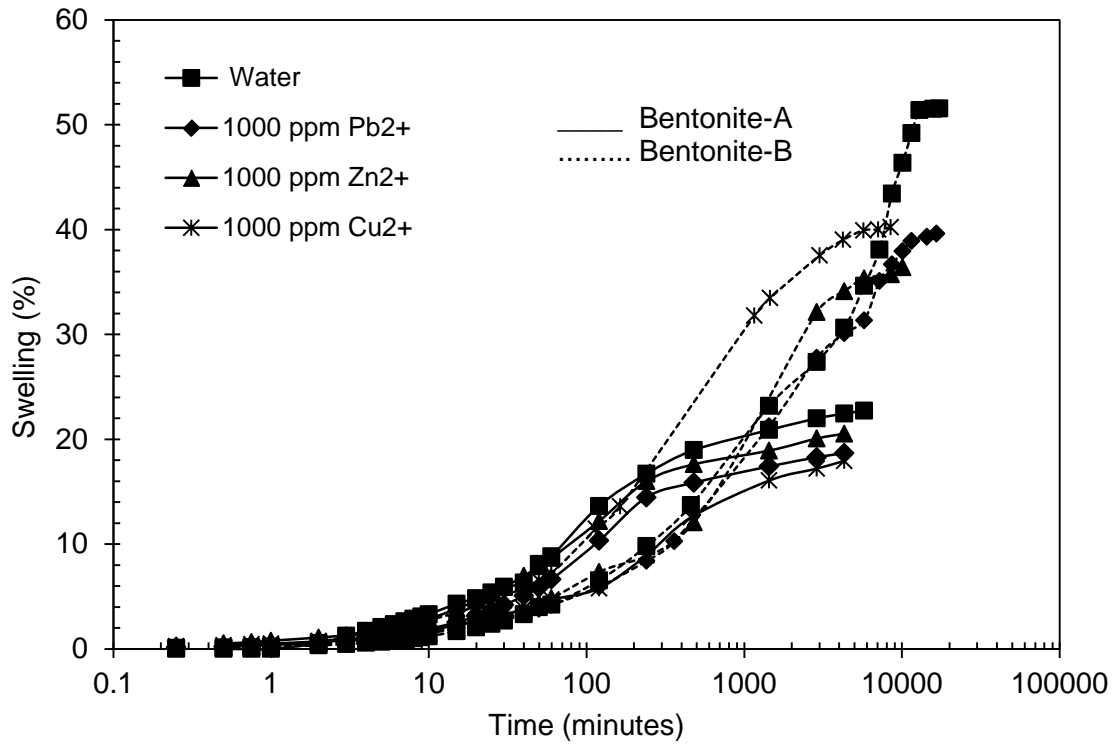


Figure 5.6 Time–swelling plot for Bentonite-A and -B compacted at MDD-OMC in the presence of 1000 ppm concentration of heavy metals

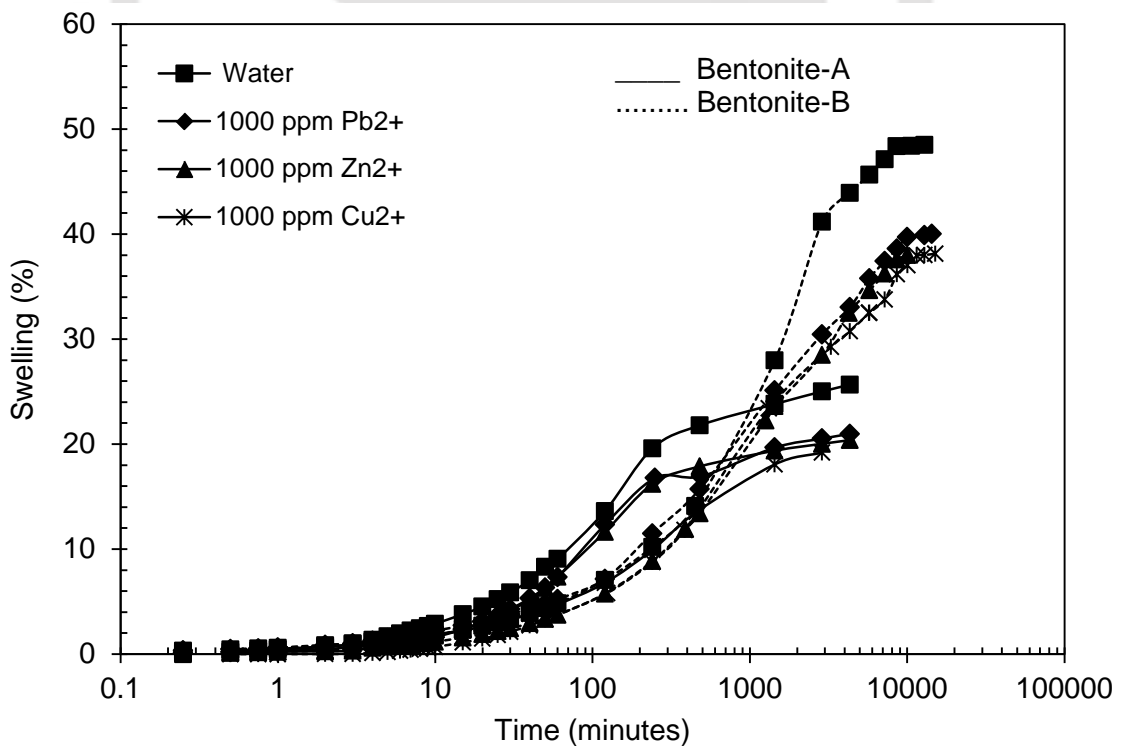


Figure 5.7 Time–swelling plot for Bentonite-A and -B compacted at MDD-5% dry of OMC in the presence of 1000 ppm concentration of heavy metals

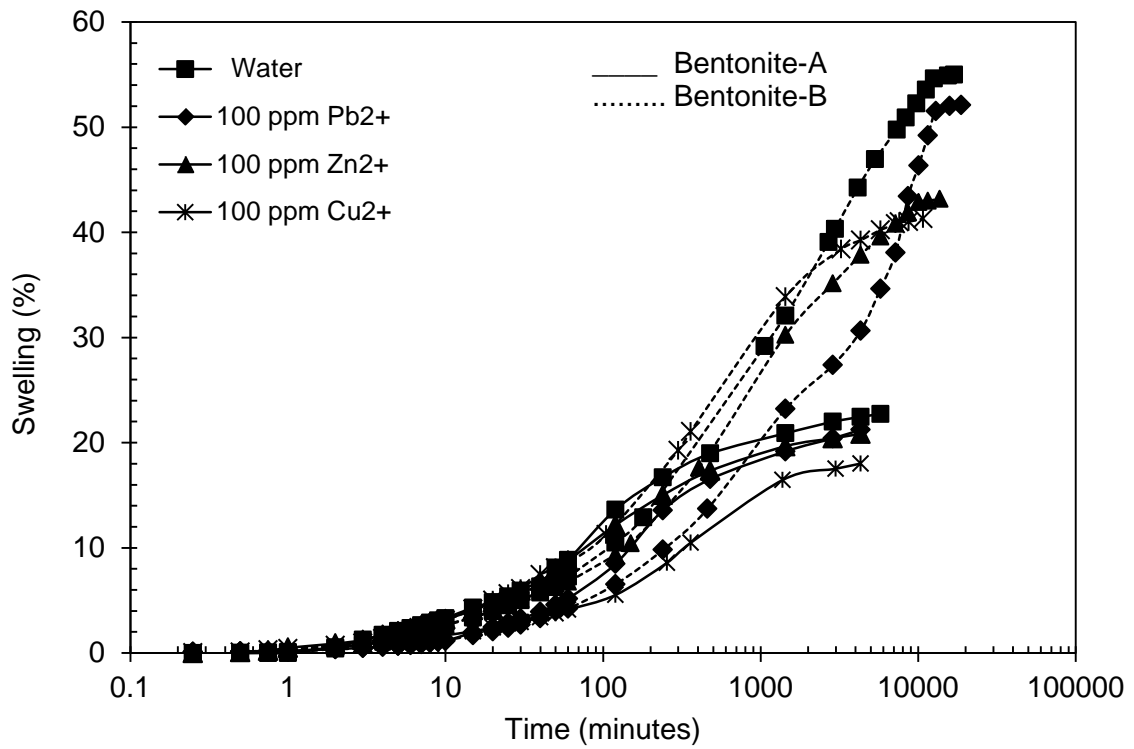


Figure 5.8 Time-swelling plot for Bentonite-A and -B compacted at MDD-OMC in the presence of 100 ppm concentration of heavy metals

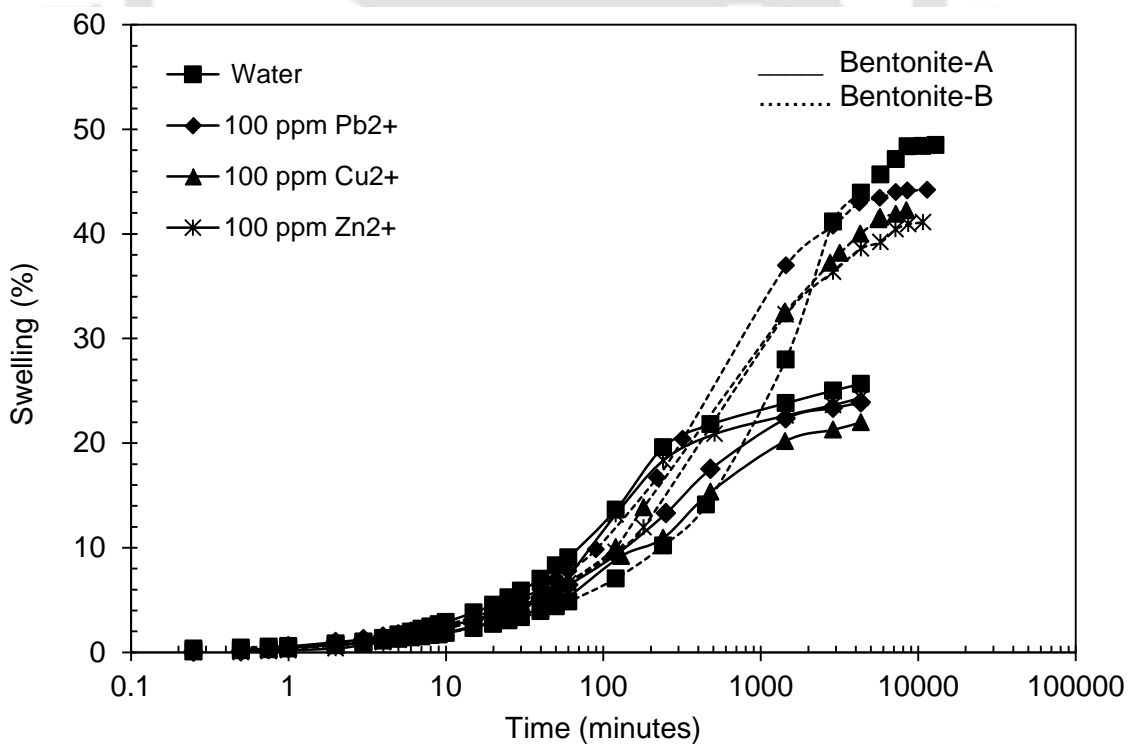


Figure 5.9 Time-swelling plot for Bentonite-A and -B compacted at MDD-5% dry of OMC in the presence of 100 ppm concentration of heavy metals

exhibited higher percentage of swelling in comparison to the samples compacted at OMC for the similar concentration of heavy metals ion.

5.2.6. Hydraulic conductivity

Plot in Figs. 5.10 to 5.13 shows the hydraulic conductivity versus void ratio relationships for the two bentonites compacted at two different compaction conditions and permeated with different concentrations of heavy metals. Each of these plot shows that the hydraulic conductivity (k) of the samples increased due to addition of heavy metal ions into the pore fluid. Hydraulic conductivity increased marginally when the metal concentration was increased from 0 (i.e. DI water) to 100 ppm; however, a further increase in concentration from 100 ppm to 1000 ppm, the k increased significantly. With an increase in the concentration of heavy metals in the pore fluid, the quantity of non-adsorbed concentration of ions on the surface of the clay particles increases causing a reduction on the repulsive forces among clay particles. Consequently the thickness of double layer decreases which allows the particles to get close to each other resulting in an increases the hydraulic conductivity (Ouhadi and Sedighi, 2003). The plots also shows that the sample compacted at dry side of OMC exhibited a higher value of hydraulic conductivity in comparison to the sample compacted at OMC. Since the sample compacted at dry side of OMC has a more random orientation, it has more large pores than the sample compacted at OMC and having a more nearly parallel arrangement (Lambe, 1958a) resulting in a higher value of hydraulic conductivity. Similar to the free swelling, liquid limit, and swelling potential data, a marginally lower value of hydraulic conductivity was observed for solution containing Pb^{2+} metal ion in comparison to Zn^{2+} and Cu^{2+} ions at any given void ratio.

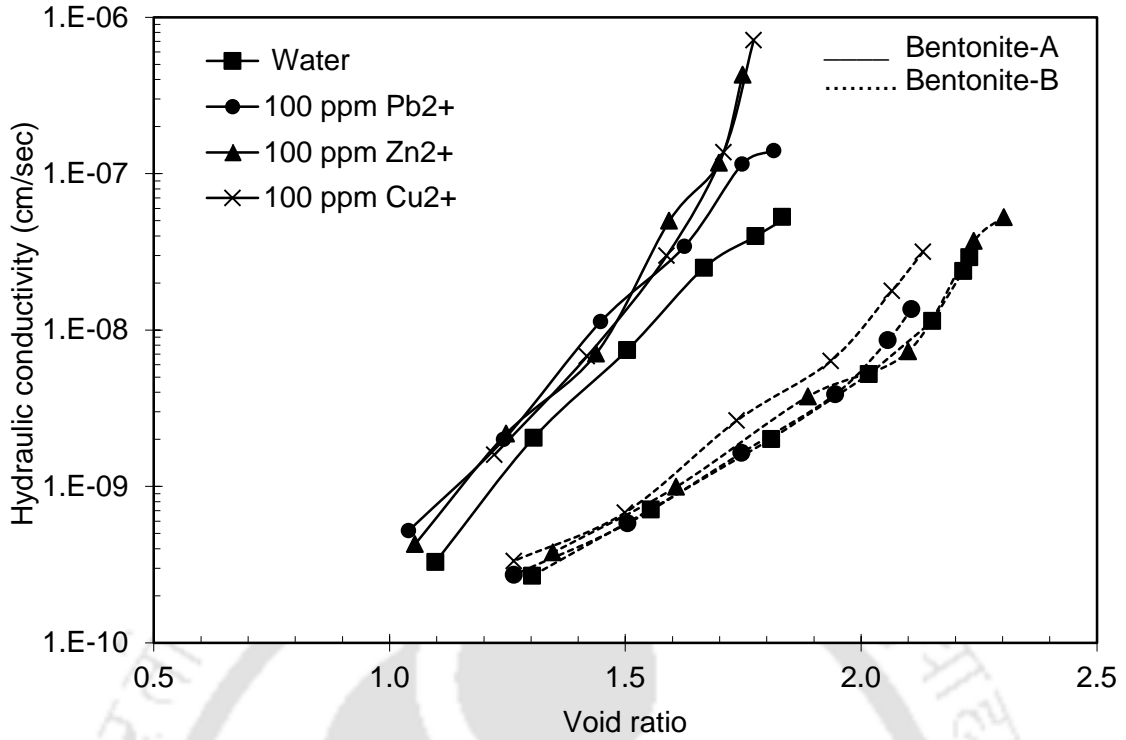


Figure 5.10 Void ratio-hydraulic conductivity plots for Bentonite-A and -B compacted at MDD-5% dry of OMC for 100 ppm concentration of different heavy metals

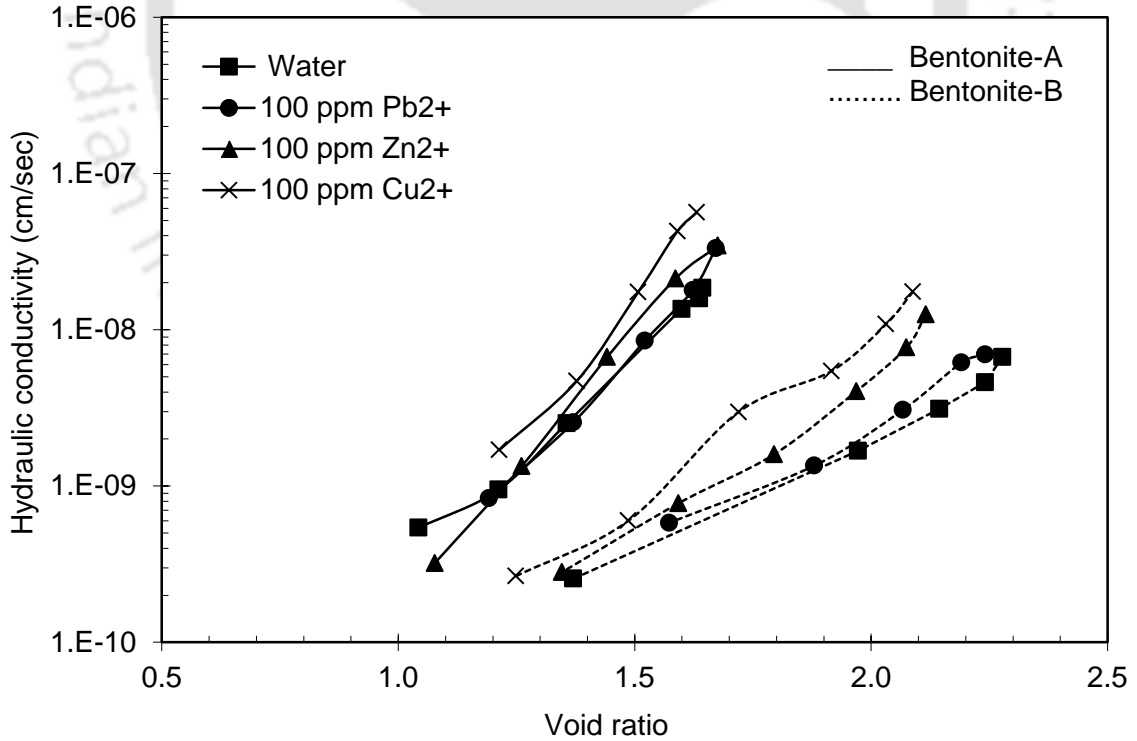


Figure 5.11 Void ratio-hydraulic conductivity plots for Bentonite-A and -B compacted at OMC-MDD for 100 ppm concentration of different heavy metals

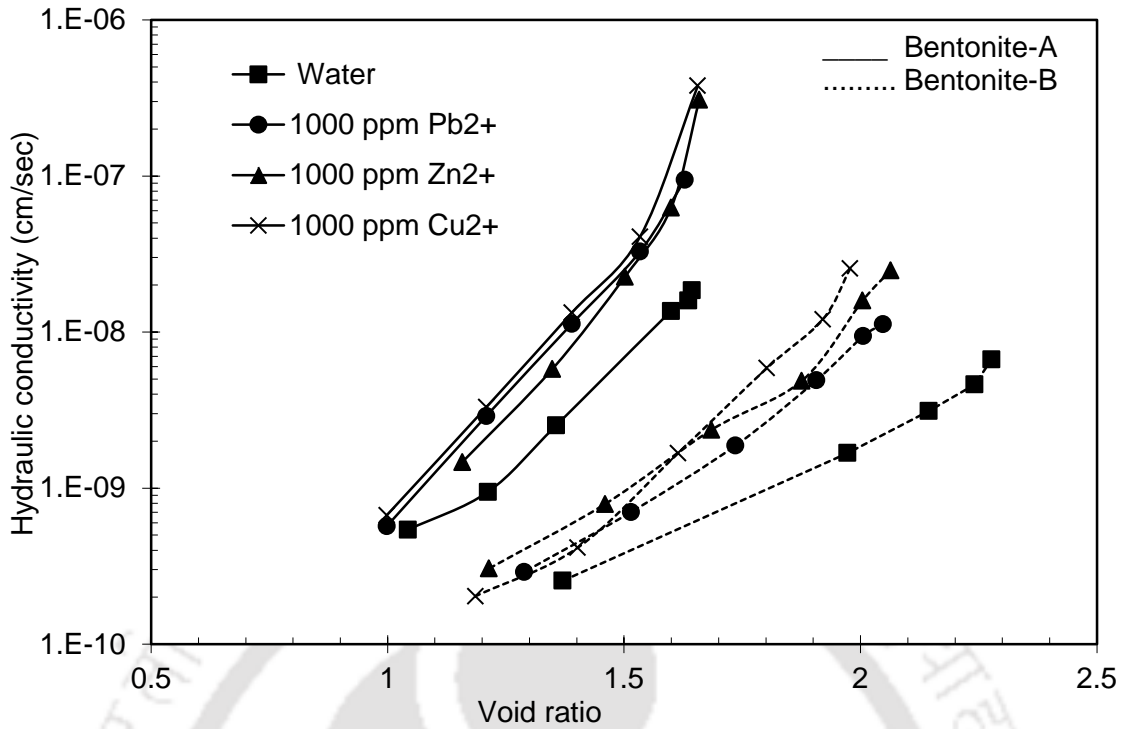


Figure 5.12 Void ratio-hydraulic conductivity plots for Bentonite-A and -B compacted at MDD-OMC for 1000 ppm concentration of different heavy metals

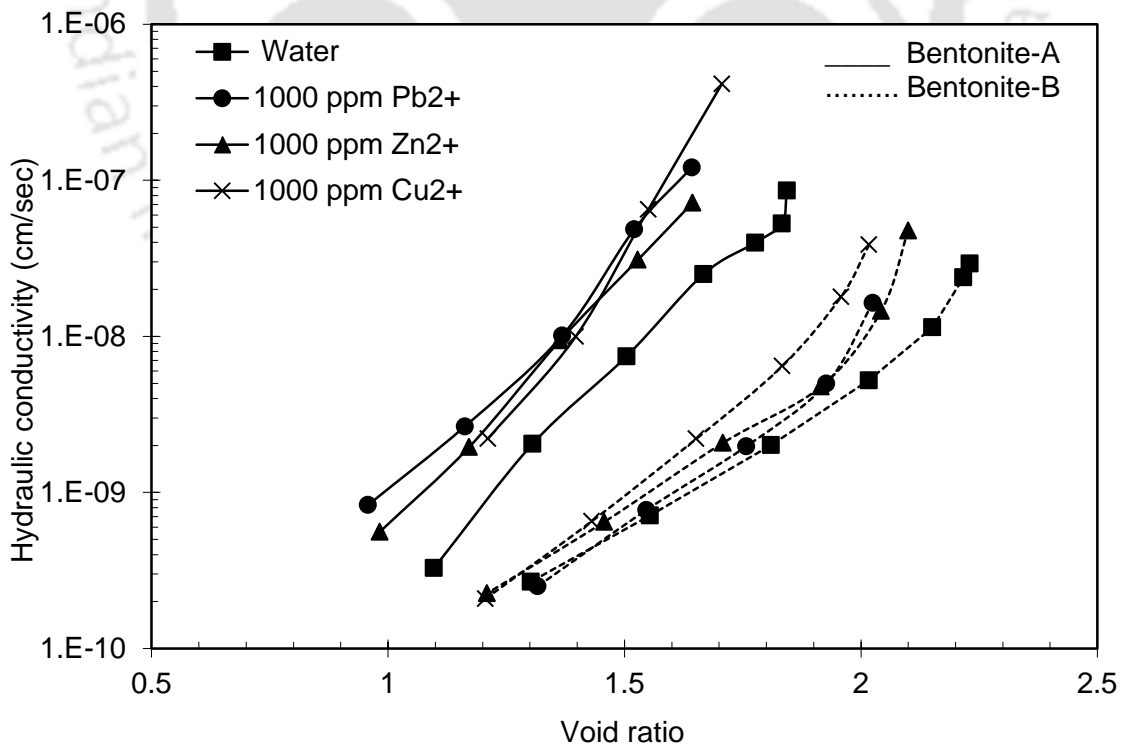


Figure 5.13 Void ratio-hydraulic conductivity plots for Bentonite-A and -B compacted at MDD-5% dry of OMC for 1000 ppm concentration of different heavy metals

In order to compare the hydraulic conductivity of all the samples with different concentration of heavy metals, hydraulic conductivity value corresponding to a void ratio of 1.5 was determined from the Figs. 5.10 to 5.13 and compared.

Table 5.1 $k_{\text{salt}} / k_{\text{water}}$ for Bentonites-A and-B at a void ratio of 1.5

Heavy metal Type and concentration	Bentonite-A		Bentonite-B	
	$k_{\text{salt}} / k_{\text{water}}$ at $e = 1.5$		$k_{\text{salt}} / k_{\text{water}}$ at $e = 1.5$	
	OMC-MDD	5% DRY OF OMC-MDD	OMC-MDD	5% DRY OF OMC-MDD
DI water	1	1	1	1
100 ppm Cu ²⁺	1.47	1.77	2.55	2.42
100 ppm Zn ²⁺	1.19	1.41	1.76	1.97
100 ppm Pb ²⁺	1.13	1.17	1.26	1.72
1000 ppm Cu ²⁺	1.59	2.62	4.97	5.73
1000 ppm Zn ²⁺	1.37	2.13	3.96	4.43
1000 ppm Pb ²⁺	1.64	1.11	3.05	3.32

The data in Table 5.1 shows the ratio between the hydraulic conductivity values for the samples at a void ratio of 1.5 in the presence of different concentration of heavy metal ions to the value with DI water for the same compaction condition. It can be observed that the increase in the hydraulic conductivity was prominent for higher concentrations. The hydraulic conductivity of Bentonite-A, compacted at 5% dry of OMC-MDD, was increased from 3.72×10^{-10} cm/sec to 6.59×10^{-10} cm/sec (i.e. 1.8 times) due to increase in the concentration from 0 to 100 ppm of Cu²⁺ solution in comparison to an increase from 3.72×10^{-10} cm/sec to 9.74×10^{-10} cm/sec (i.e. 2.6 times) for the increase in the concentration from 0 to 1000 ppm of Cu²⁺ solution. The samples with Zn²⁺ and Pb²⁺ solutions followed the similar trend, where due to an increase in the concentration from 0 to 100 ppm of Pb²⁺, Zn²⁺ the hydraulic conductivity increased by 1.2 and 1.4 times, respectively; whereas, for an increase in the concentration from 0 to 1000 ppm it increased by 1.1 and 2.1 times, respectively.

The hydraulic conductivity of Bentonite-B, compacted at 5% dry of OMC-MDD, was increased from 7.32×10^{-9} cm/sec to 1.77×10^{-8} cm/sec (i.e. 2.4 times) due to increase in the concentration from 0 to 100 ppm of Cu^{2+} solution in comparison to an increase from 7.32×10^{-9} cm/sec to 4.2×10^{-8} cm/sec (i.e. 5.7 times) for the increase in the concentration from 0 to 1000 ppm of Cu^{2+} solution. Similarly, due to increase in the concentration to 100 ppm of Pb^{2+} and Zn^{2+} ions, the hydraulic conductivity increased by 1.7 and 1.9 times, respectively; whereas, in presence of 1000 ppm Pb^{2+} and Zn^{2+} the hydraulic conductivity increased by 3.3 and 4.4 times, respectively. Similar trend was also observed for samples compacted at OMC-MDD.

A comparison between the two bentonites for a given concentration and compaction condition shows that heavy metal ions had a significant impact on Bentonite-B in comparison to Bentonite-A. Due to increase in the concentration from 0 to 100 ppm of Cu^{2+} , the hydraulic conductivity of Bentonite-B was increased by 2.5 times in comparison to 1.5 times for Bentonite-A for the corresponding increase in the concentration. Similarly, for an increase in the concentration from 0 to 1000 ppm of Cu^{2+} solution the hydraulic conductivity of Bentonite-B was increased by 4.9 times in comparison to 1.6 times for Bentonite-A. Data also shows that the hydraulic conductivity of samples compacted at 5% dry of OMC-MDD gets affected to a higher extent due to permeation of heavy metals ions in comparison to the samples compacted at OMC-MDD.

5.2.7. Consolidation characteristics

5.2.7.1. Void ratio-pressure relationship

Figures 5.14 to 5.17 show the void ratio-pressure relationship for the two bentonites at different concentration of heavy metal ions. Results showed that under any given consolidation pressure samples with heavy metals ions exhibited a lower value of void ratio in comparison to the sample with DI water. This trend can be attributed to the reduction in

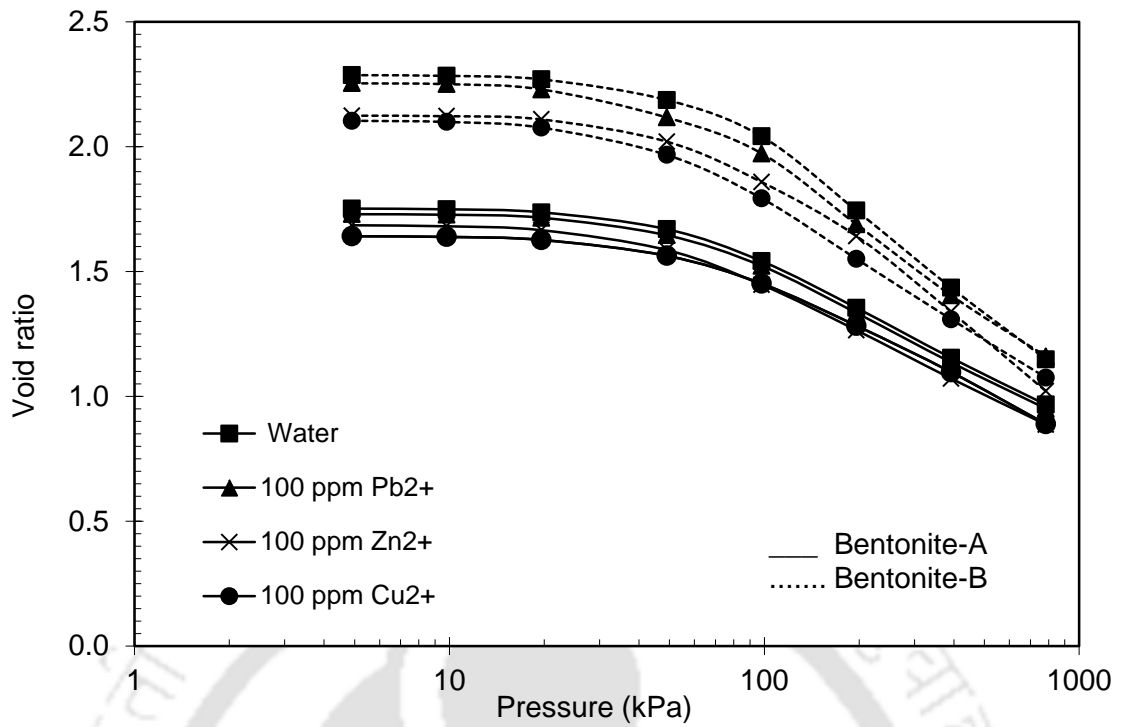


Figure 5.14 Void ratio-pressure plots for Bentonite-A and -B at 100 ppm concentration of heavy metals at OMC-MDD

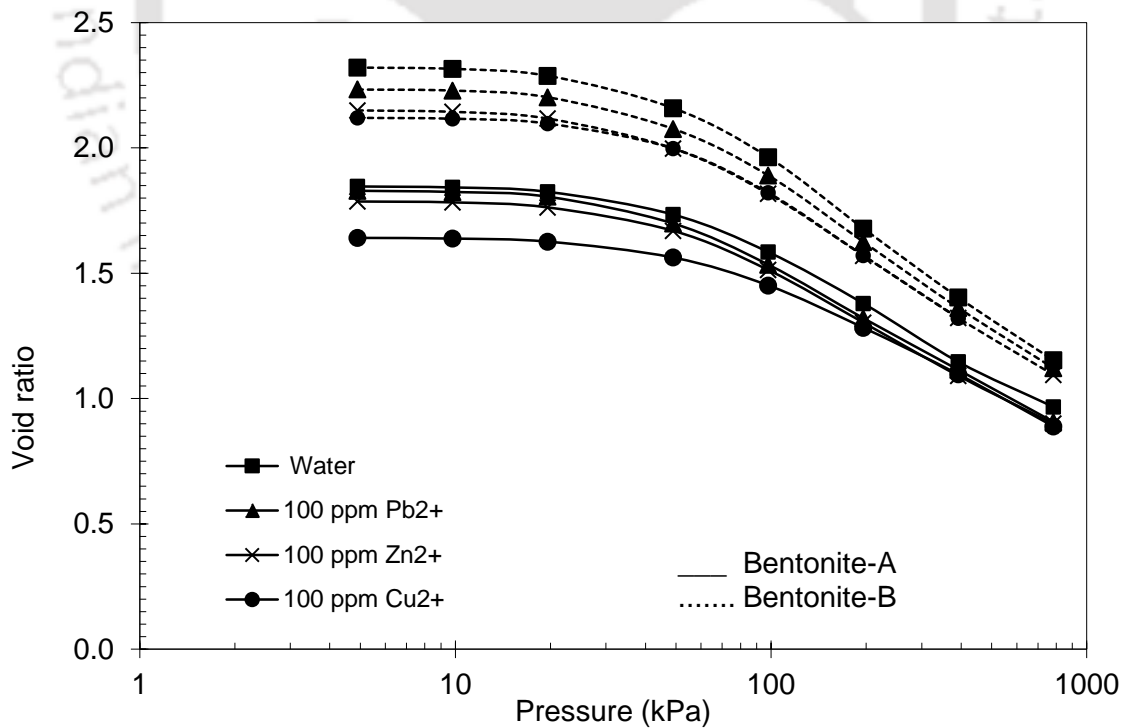


Figure 5.15 Void ratio-pressure plots for Bentonite-A and -B at 100 ppm concentration of heavy metals at 5% dry of OMC-MDD

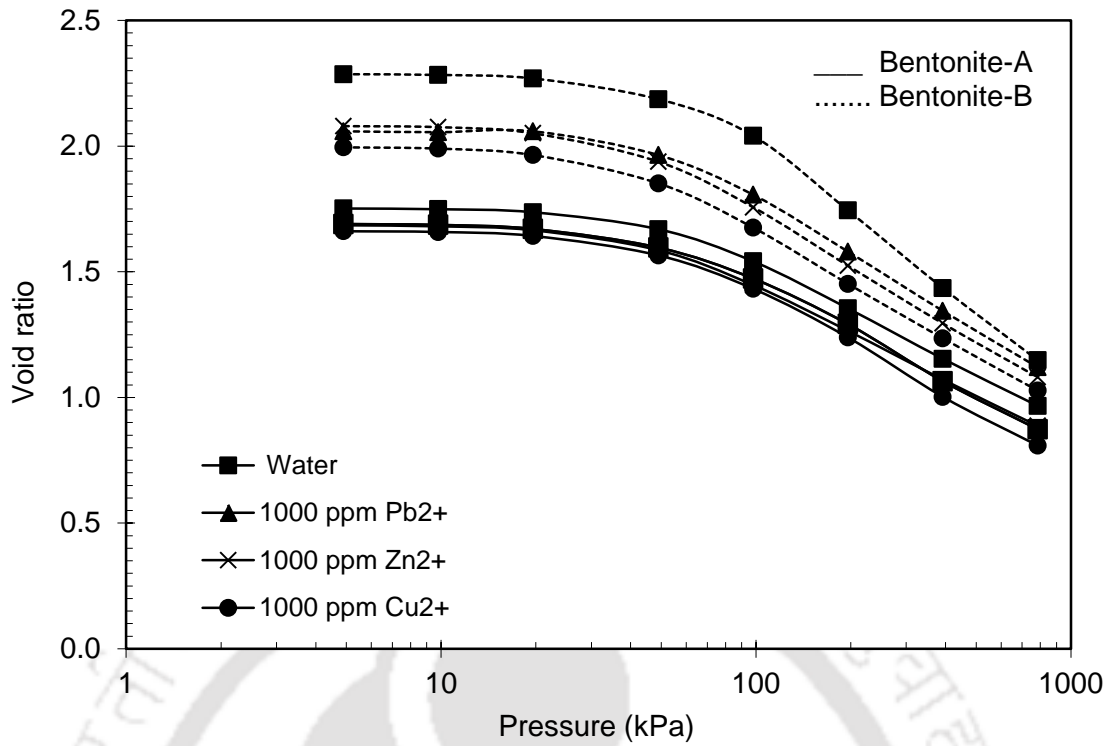


Figure 5.16 Void ratio-pressure plots for Bentonite-A and -B at 1000 ppm concentration of heavy metals at OMC-MDD

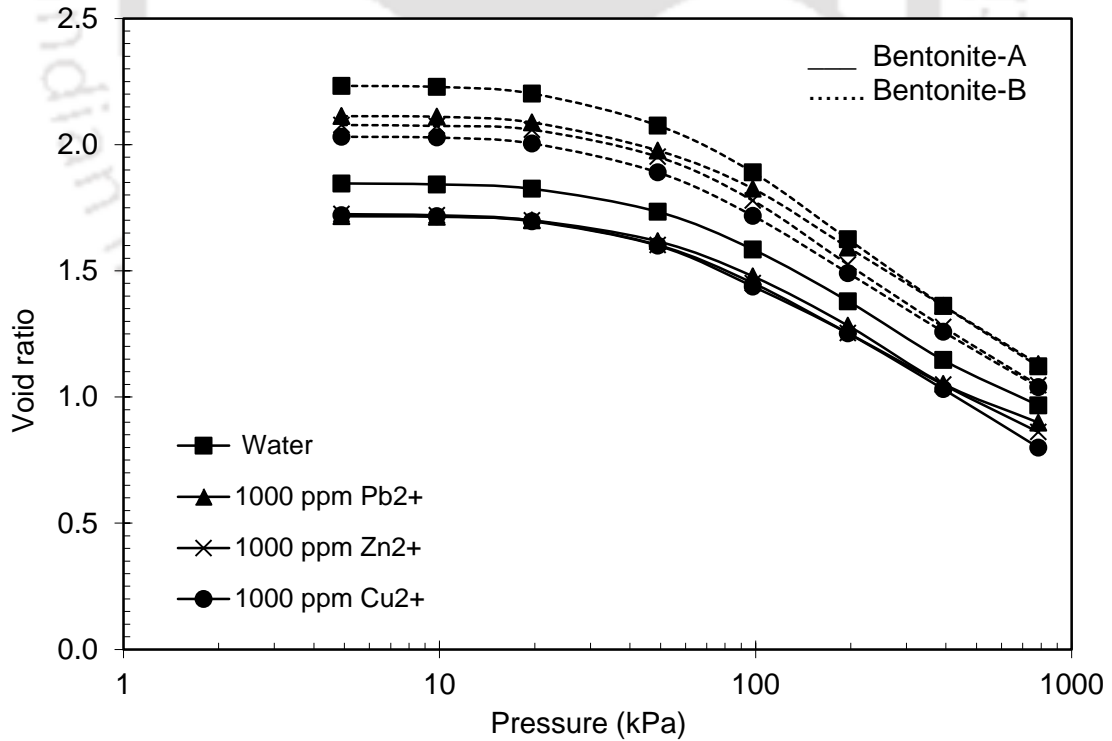


Figure 5.17 Void ratio-pressure plots for Bentonite-A and -B at 1000 ppm concentration of heavy metals at 5% dry of OMC-MDD

diffuse double layer thickness due to an increase in metal ion concentrations. With an increase in the concentration of heavy metal ions in the soil pore fluid, more ions get adsorbed onto the clay surface thus causing a decrease in repulsive forces. This will allow particles to get close to each other and consequently the thickness of double layer decreases. The decrease in the void ratio with the increase in the metal ion concentration was marginally higher for Zn^{2+} and Cu^{2+} solution in comparison to Pb^{2+} solution.

5.2.7.2. Compressibility behaviour from the diffuse double layer thickness

Further to compare the experimentally determined void ratio-pressure relationship with the theoretically obtained values for the bentonite in the presence of heavy metals, void ratio corresponds to various consolidation pressures. The plots in Figs. 5.18 to 5.20 compare the experimental and theoretical void ratio-pressure (e -log P) relationship for Bentonite-A and -B at different concentrations of heavy metals. Similar to the inorganic salt solution, a higher value of theoretical void ratio was determined for both the bentonites at lower consolidation pressure and water as pore fluid. However, with the increasing the consolidation pressure the theoretically obtained the e -log P curve converges towards the experimentally obtained curve and cross it at certain pressure and diverged again. The consolidation pressure at which both the theoretical and experimental curve crossed each other was not unique and it dependent on the type of bentonite. With the increase in concentration of the heavy metals in the pore fluid a lower value of the theoretically calculated void ratio was obtained for both the bentonites. With the increase in the concentration of the pore fluid the orientation of the clay plates changed and they formed a flocculated structure resulting in a higher value of experimental void ratio in comparison to the theoretical void ratio (Ouhadi et al., 2006).

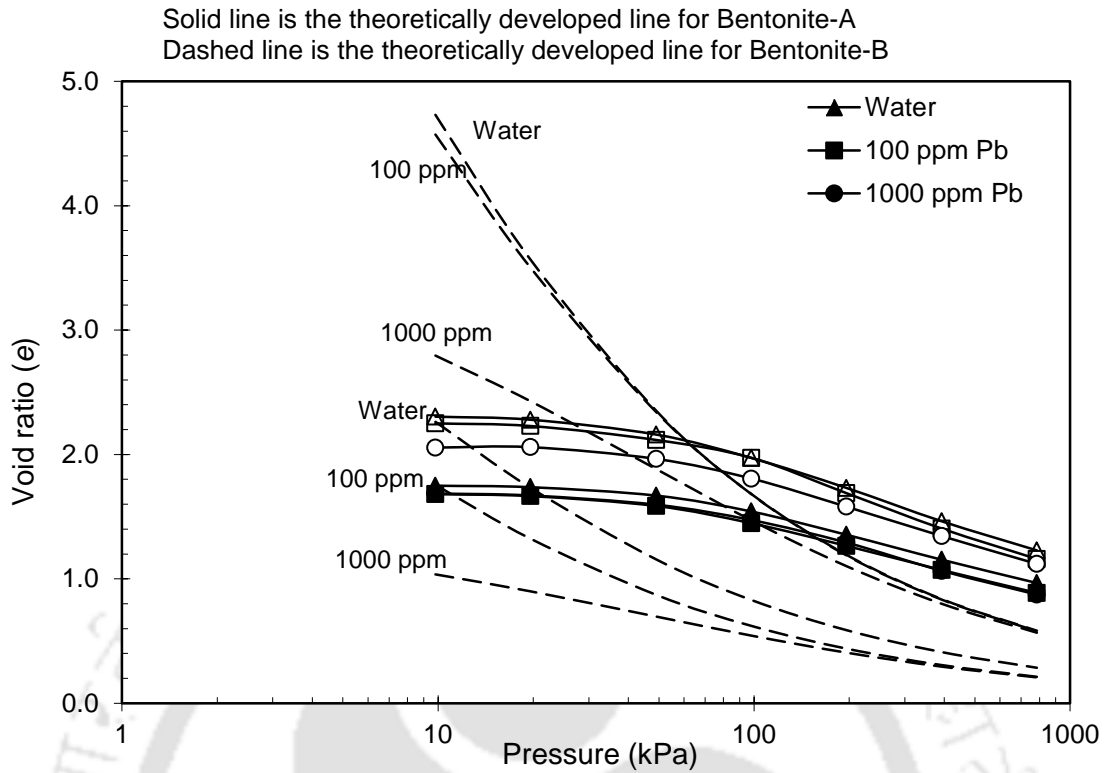


Figure 5.18 Experimental and theoretical void ratio - pressure plots for Bentonite-A and -B at various concentrations of Pb^{2+} solution

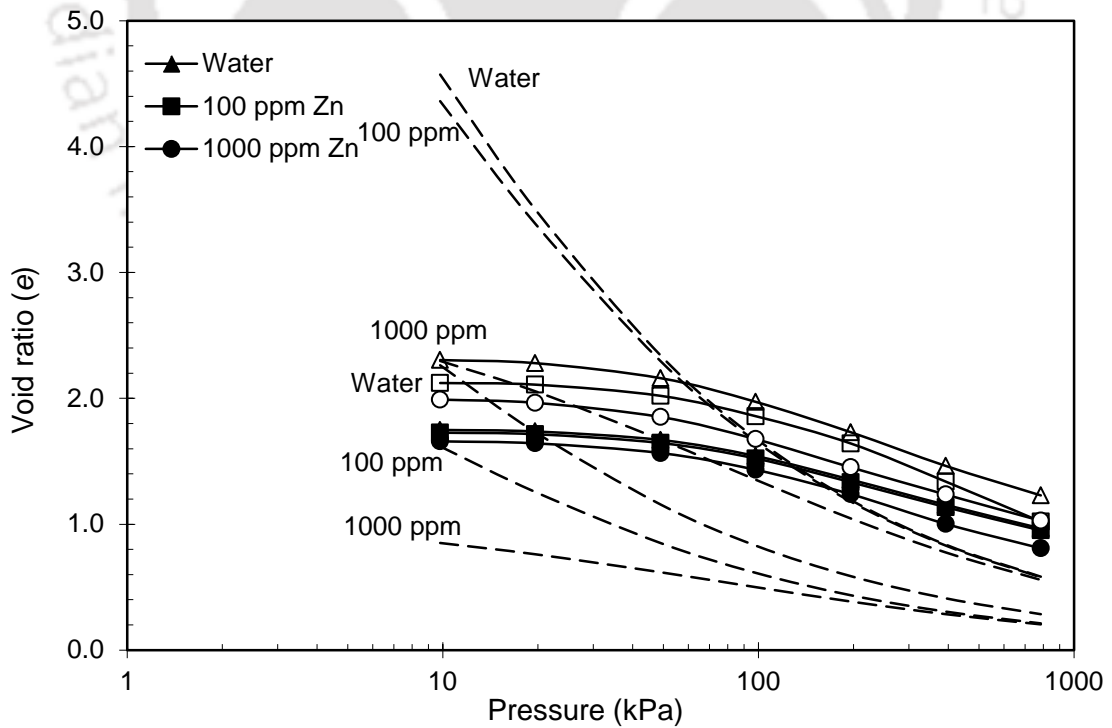


Figure 5.19 Experimental and theoretical void ratio - pressure plots for Bentonite-A and -B at various concentrations of Zn^{2+} solution

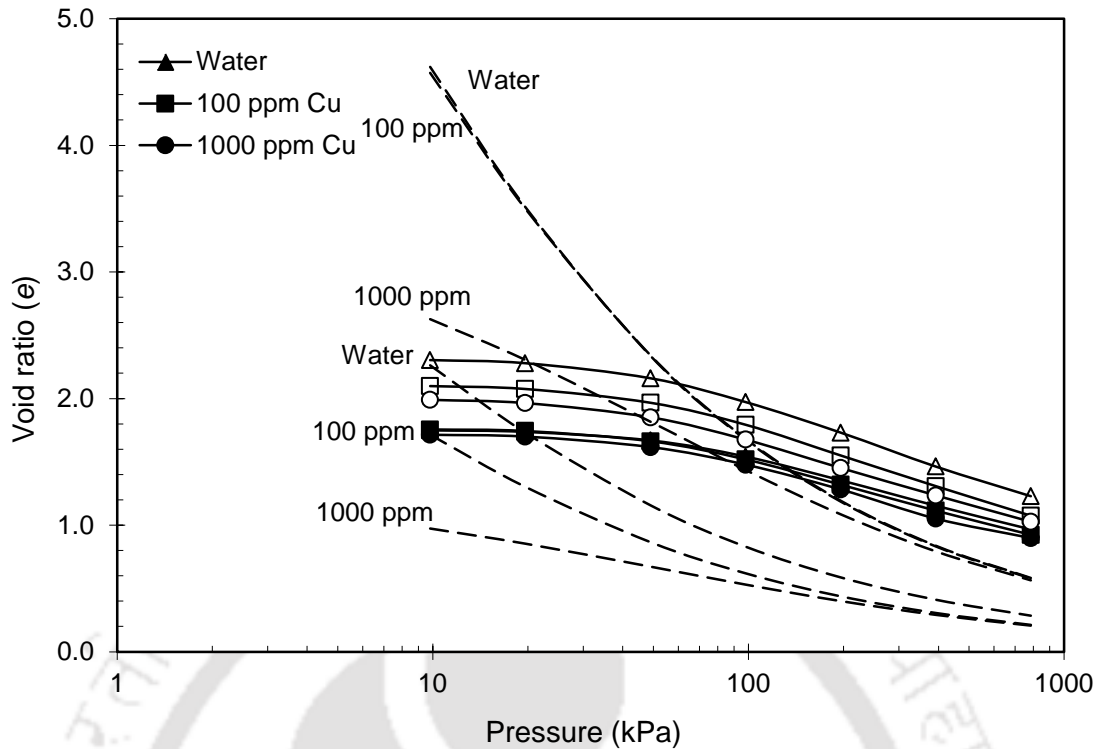


Figure 5.20 Experimental and theoretical void ratio - pressure plots for Bentonite-A and -B at various concentrations of Cu^{2+} solution

Further to investigate the effect of pressure and metal ion concentration on the diffuse double layer (DDL), the DDL thickness ($2d$) for both the bentonites was calculated at the consolidation pressures of 19.6, 196.1 and 784.5 kPa using Eqs. 4.1 to 4.5 for different concentrations of heavy metal and tabulated in Table 5.2. The data in Table 5.2 shows that the DDL thickness decreases significantly with the increase in the consolidation pressure and the decrease in the DDL thickness was found to be significant for Bentonite-B in comparison to Bentonite-A. For Bentonite-A, in presence of 100 ppm of Pb^{2+} solution, with an increase in pressure from 19.6 kPa to 784.5 kPa the DDL thickness reduced from 2.78×10^{-9} m to 0.447×10^{-9} m. Similarly for Bentonite-B, for the similar increase in the pressure, the DDL thickness reduced from 5.58×10^{-9} m to 0.91×10^{-9} m. The data also suggested that the DDL thickness gets reduced with an increase in concentration of heavy metal solutions. For Bentonite-A, at a consolidation pressure of 19.6 kPa with an increase

in concentration of pore fluid from 0 to 1000 ppm Pb^{2+} , the thickness of DDL reduced from 3.64×10^{-9} m to 1.89×10^{-9} m. Similarly for Bentonite-B, with an increase from 0 to 1000 ppm Pb^{2+} , the thickness of DDL reduced from 5.44×10^{-9} m to 3.80×10^{-9} m. Similar observations were also made for Zn^{2+} and Cu^{2+} ions.

Table 5.2 DDL thickness for the bentonites at different heavy metal concentrations

Heavy metal ion concentration	Diffuse double layer (DDL) thickness, $2d \times 10^{-9}$ in m					
	Bentonite-A			Bentonite-B		
	19.6 kPa	196.1 kPa	784.5 kPa	19.6 kPa	196.1 kPa	784.5 kPa
0 ppm (DI Water)	3.649	1.237	0.601	5.586	1.861	0.906
100 ppm Pb^{2+}	2.787	0.924	0.447	5.445	1.855	0.907
1000 ppm Pb^{2+}	1.896	0.856	0.438	3.803	1.726	0.888
100 ppm Zn^{2+}	2.647	0.918	0.446	5.307	1.848	0.906
1000 ppm Zn^{2+}	1.604	0.813	0.431	3.221	1.637	0.873
100 ppm Cu^{2+}	2.746	0.923	0.447	5.505	1.857	0.907
1000 ppm Cu^{2+}	1.799	0.844	0.436	3.612	1.701	0.884

5.2.7.3. Coefficient of volume change (m_v)

Figures 5.21 to 5.24 plots the relationship between coefficient of volume change (m_v) and the consolidation pressures for the two bentonites at different concentrations of heavy metal ions. From the plots it can be observed that irrespective of the permeating fluid and type of bentonite, the m_v of the bentonite initially increased and then decreased due an increase in the consolidation pressure. At lower consolidation pressures, when the void ratio was high, with an increase in pressure a larger reduction in the void spaces took place resulting in a higher m_v . After reaching a peak value, the rate of volume change decreased with a further increase in pressure. Similar observation was also made for the bentonites with inorganic salt solution. The plot also shows that the m_v for the bentonites decreased with the increase in the heavy metal ion concentration. Since the thickness of DDL is larger in case of DI water, sample undergoes a significant compression in presence of water due

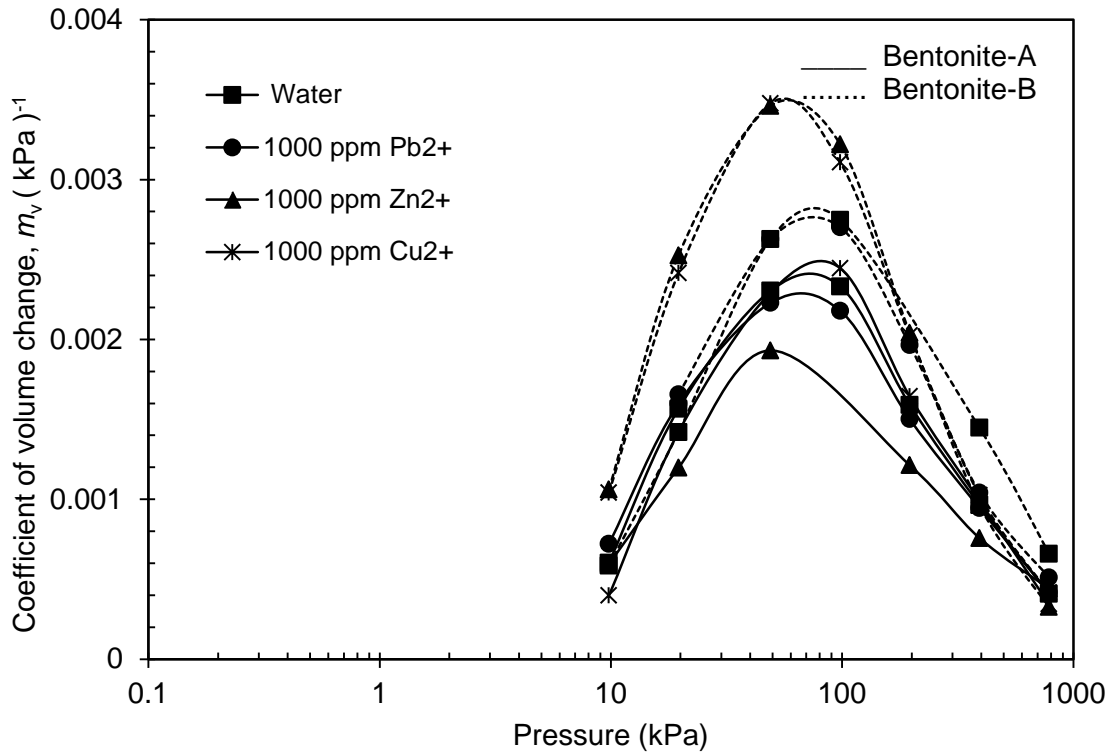


Figure 5.21 Plot between the coefficient of volume change and consolidation pressures of Bentonite-A and -B compacted at OMC-MDD at 1000 ppm concentration of heavy metals

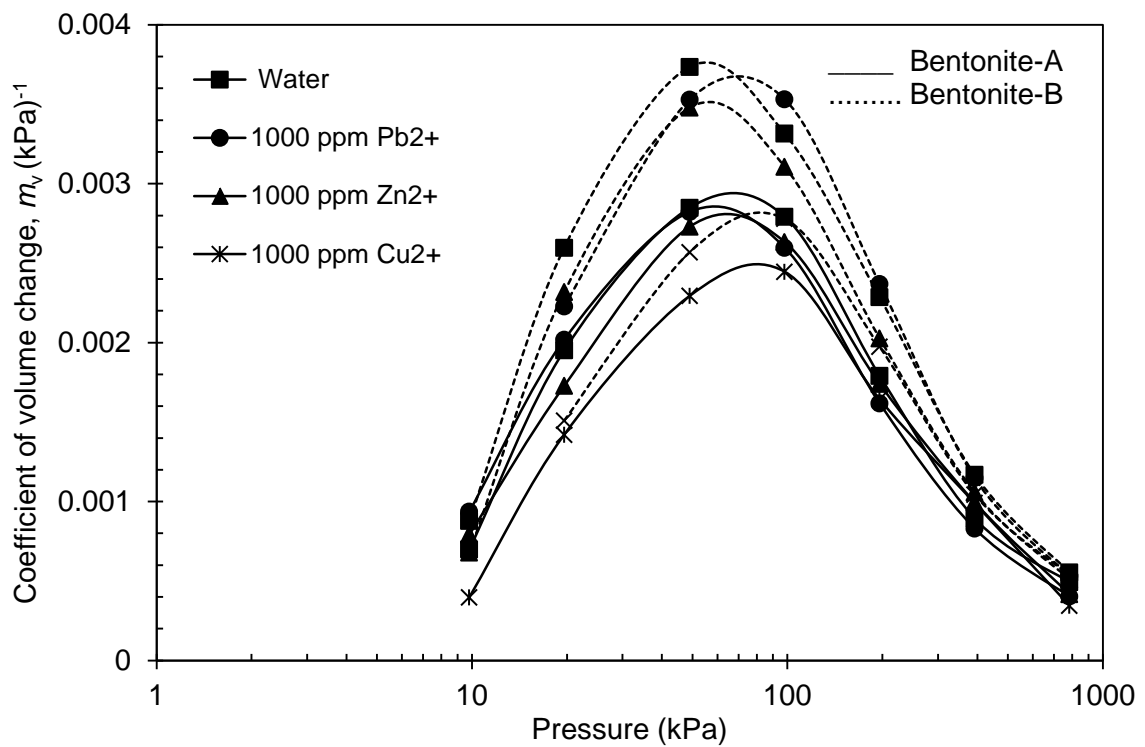


Figure 5.22 Plot between the coefficient of volume change and consolidation pressures of Bentonite-A and -B compacted at 5% dry of OMC-MDD at 1000 ppm concentration of heavy metals

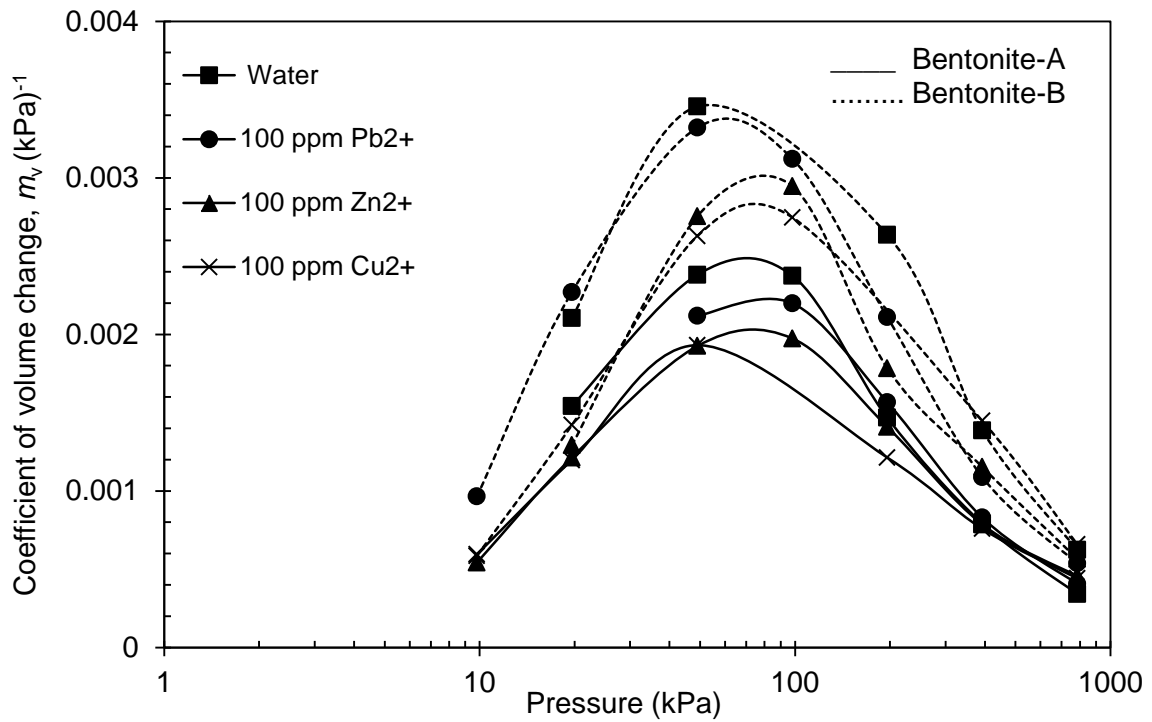


Figure 5.23 Plot between the coefficient of volume change and consolidation pressures of Bentonite-A and -B compacted at OMC-MDD at 100 ppm concentration of heavy metals

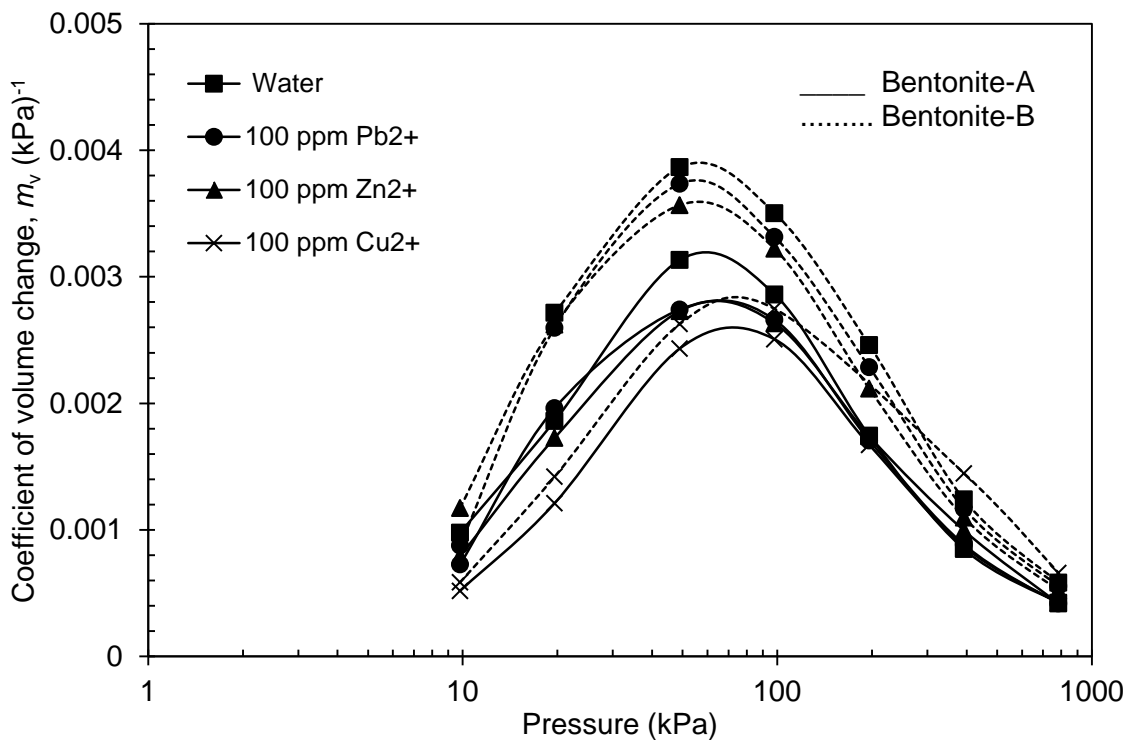


Figure 5.24 Plot between the coefficient of volume change and consolidation pressures of Bentonite-A and -B compacted at 5% dry of OMC-MDD at 100 ppm concentration of heavy metals

to application of pressure resulting in a higher m_v . As the thickness of the DDL decreases due to an increase in heavy metal concentration, the compressibility and consequently the m_v of sample also decreases. The plots also show that Bentonite-B, with a higher CEC, ESP and SSA, free swelling and liquid limit value, exhibited a higher m_v in comparison with that of Bentonite-A in the presence of heavy metals. A comparison for the effect of the initial compaction condition shows that the samples compacted at dry side of OMC exhibited higher m_v values.

5.2.7.4. Coefficient of consolidation (c_v)

Figures 5.25 to 5.28 plots the relationship between coefficient of consolidation and consolidation pressures for the two bentonites at different concentrations of heavy metals. From the plots it was observed that the c_v increases with increase in heavy metal ion concentrations due to a decrease in the diffuse double layer thickness. The increase in coefficient of consolidation decreases the required time for achieving the desired degree of consolidation. In other words, the presence of heavy metal ions in the pore fluid increases the rate of the consolidation during the application of specific load. This point might be responsible for relative quicker settlement of the liner material at waste disposal facility when it interacts with leachate (Ouhadi and Sedighi, 2003). Coefficient of consolidation (c_v) decreased with increasing vertical consolidating pressure indicating a slower rate of consolidation at higher consolidation pressure.

A comparison between the values of c_v for the two bentonites at the same concentration and consolidation pressure indicates that Bentonite-B, which has a higher swelling and liquid limit and lower hydraulic conductivity values, exhibited a lower c_v in comparison to Bentonite-A in the presence of heavy metal ions as well. Samples compacted at dry side of OMC exhibited higher c_v values in comparison to the sample compacted at OMC-MDD.

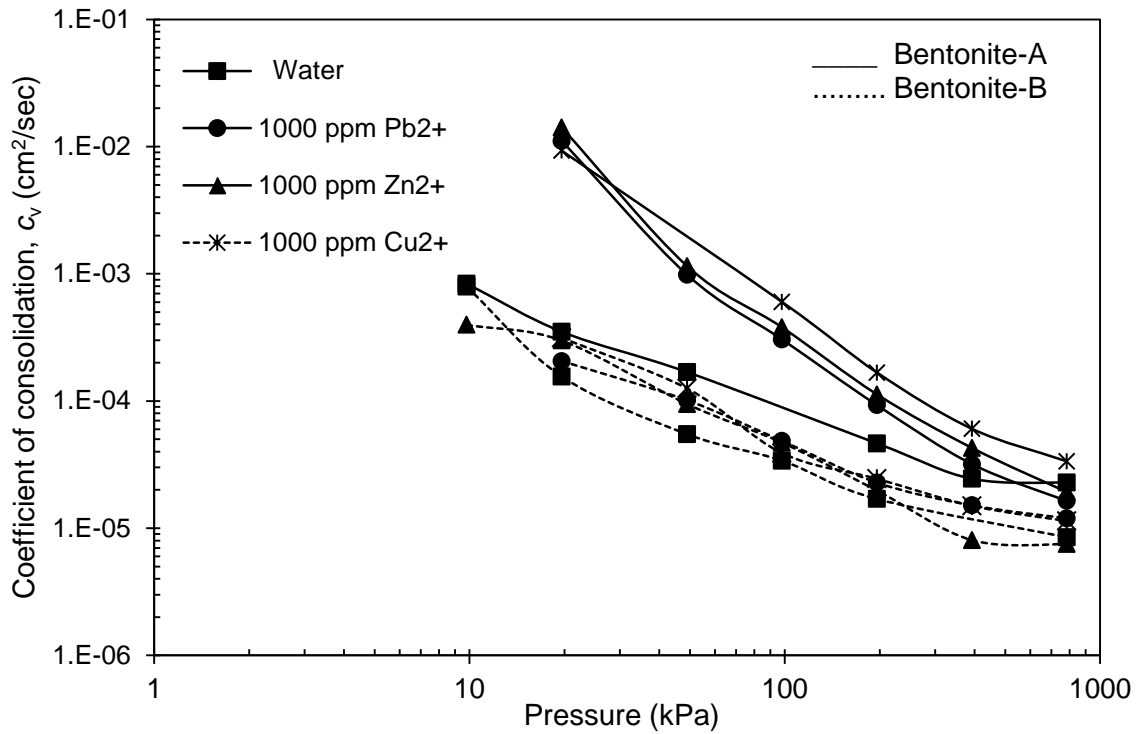


Figure 5.25 Plot between the coefficient of consolidation and consolidation pressures of Bentonite-A and -B compacted at OMC-MDD at 1000 ppm concentration of heavy metals

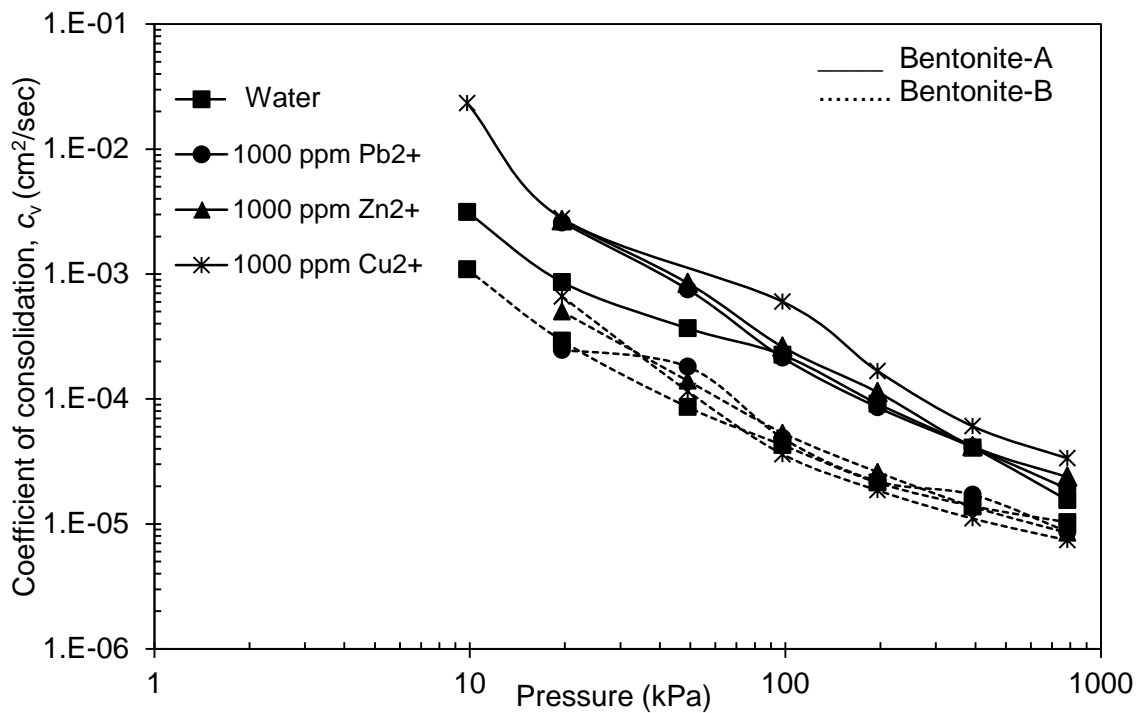


Figure 5.26 Plot between the coefficient of consolidation and consolidation pressures of Bentonite-A and -B compacted at 5% dry of OMC-MDD at 1000ppm concentration of heavy metals

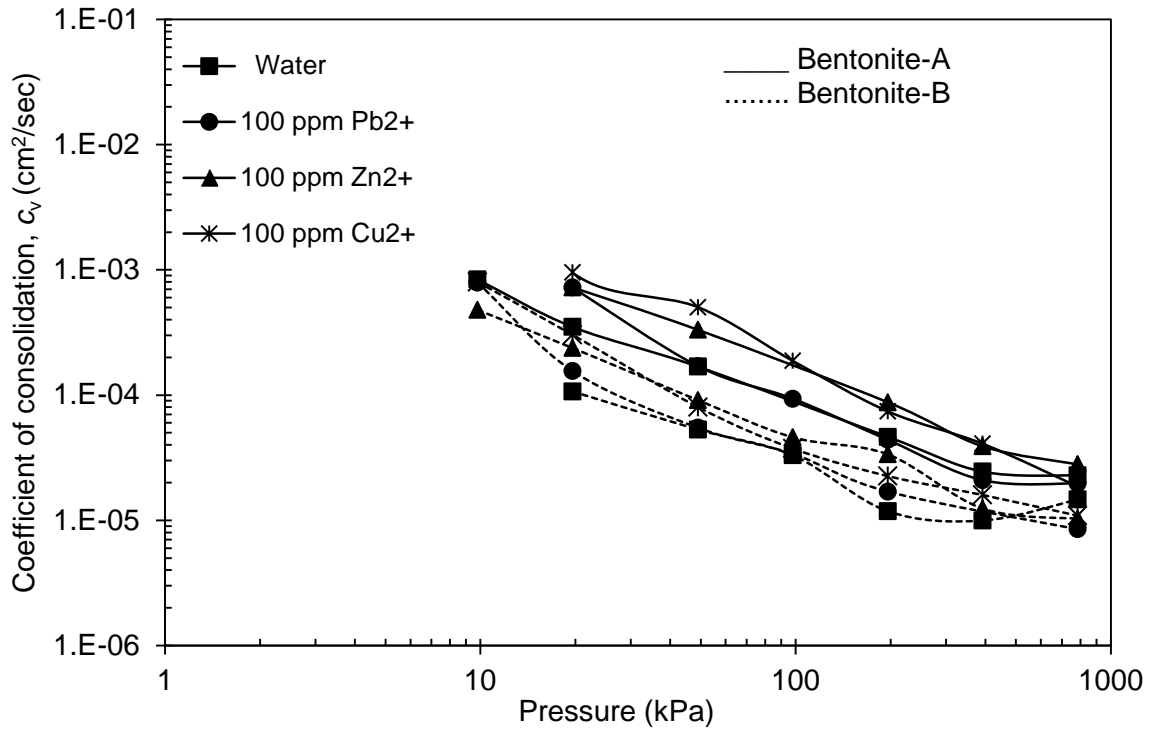


Figure 5.27 Plot between the coefficient of consolidation and consolidation pressures of Bentonite-A and -B compacted at OMC-MDD at 100 ppm concentration of heavy metals

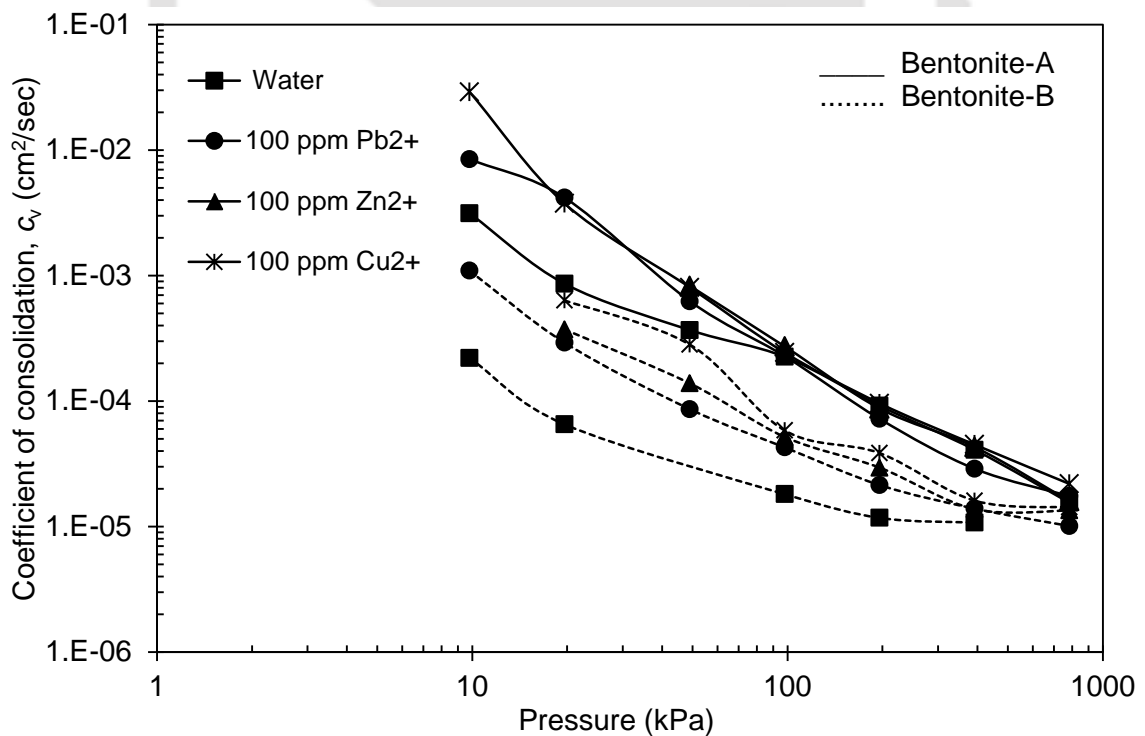


Figure 5.28 Plot between the coefficient of consolidation and consolidation pressures of Bentonite-A and -B compacted at 5% dry of OMC-MDD at 100 ppm concentration of heavy metals

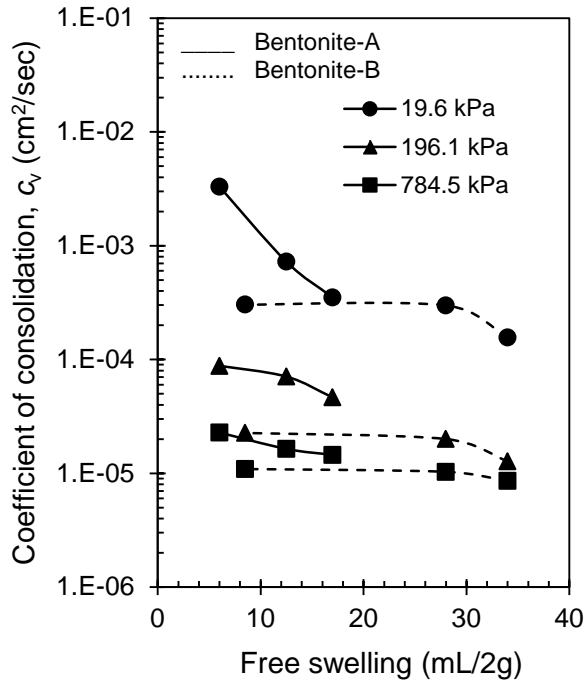
Figure 5.29 shows the relationship between the free swelling and coefficient of consolidation at the vertical pressures of 19.6 kPa, 196.1 kPa and 784.5 kPa for the bentonites. The plot shows that irrespective of the consolidation pressure, the c_v decreased with the increase in the free swelling of the bentonite. The plot shows that the effect of swelling on the c_v was significant at low consolidation pressure. The decrease in c_v with increase in the free swelling was significant for Bentonite-A in comparison to that of Bentonite-B. For Bentonite-A, for samples compacted at OMC-MDD and in presence of Pb^{+2} solution, c_v decreased from $0.003 \text{ cm}^2/\text{sec}$ to $2.28 \times 10^{-5} \text{ cm}^2/\text{sec}$ (131.5 times) with an increase in the free swelling from 9 mL/2g to 17 mL/2g; however, for Bentonite-B the c_v decreased from $0.0002 \text{ cm}^2/\text{sec}$ to $1.03 \times 10^{-5} \text{ cm}^2/\text{sec}$ (19.4 times) with an increase in the free swelling from 16 mL/2g to 34 mL/2g. For Bentonite-A, in presence of Zn^{+2} solution the c_v decreased from $0.003 \text{ cm}^2/\text{sec}$ to $1.45 \times 10^{-5} \text{ cm}^2/\text{sec}$ (206.8 times) with an increase in free swelling from 6 mL/2g to 17 mL/2g; however, for Bentonite-B the c_v decreased from $0.0003 \text{ cm}^2/\text{sec}$ to $8.58 \times 10^{-6} \text{ cm}^2/\text{sec}$ (34.9 times) with an increase in free swelling from 8 mL/2g to 34 mL/2g. Similar observation was made for the bentonites in presence of Cu^{+2} solution.

The reduction in the c_v with an increase in free swelling was higher for the samples compacted at dry of OMC. For Bentonite-A, for samples compacted at 5% dry of OMC-MDD and in presence of Zn^{+2} solution, the c_v decreased from $0.009 \text{ cm}^2/\text{sec}$ to $1.55 \times 10^{-5} \text{ cm}^2/\text{sec}$ (580.6 times) with an increase in free swelling from 6 mL/2g to 17 mL/2g; however for Bentonite-B, c_v decreased from $0.0006 \text{ cm}^2/\text{sec}$ to $8.58 \times 10^{-6} \text{ cm}^2/\text{sec}$ (69.9 times) with an increase in free swelling from 8.5 mL/2g to 34 mL/2g. For Bentonite-A, in presence of Pb^{+2} solution, c_v decreased from $0.011 \text{ cm}^2/\text{sec}$ to $1.55 \times 10^{-5} \text{ cm}^2/\text{sec}$ (709.6 times) with an increase in free swelling from 9.5 mL/2g to 17 mL/2g; however for Bentonite-B, c_v decreased from $0.0002 \text{ cm}^2/\text{sec}$ to $8.58 \times 10^{-6} \text{ cm}^2/\text{sec}$ (23.3 times) with an

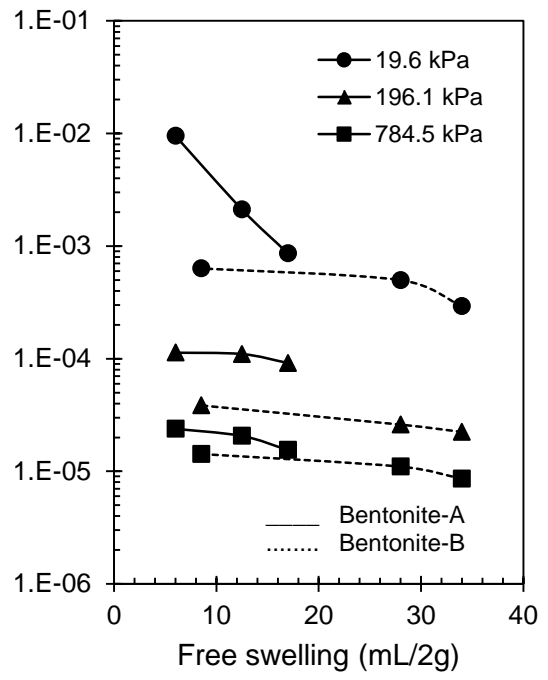
increase in free swelling from 14 mL/2 g to 34 mL/2 g. Similar observation was made for the bentonites in presence of Cu^{+2} solution.

Figure 5.30 shows that irrespective of the consolidation pressure, the c_v decreased with the increase in the liquid limit of the bentonite permeated with heavy metal ions. For Bentonite-A, samples compacted at OMC-MDD and in the presence of Zn^{+2} solution, c_v decreased from 3×10^{-3} cm²/sec to 1.45×10^{-5} cm²/sec with an increase in liquid limit from 165.1 % to 218.0 %; however for Bentonite-B, the c_v decreased from 3×10^{-4} cm²/sec to 8.58×10^{-6} cm²/sec with an increase in liquid limit from 279.1 % to 560.0 %. Similarly for Bentonite-A, in presence of Pb^{+2} solution the c_v decreased from 0.003 cm²/sec to 1.45×10^{-5} cm²/sec with an increase in liquid limit from 170.2 % to 218.0 %; but for Bentonite-B, c_v decreased from 0.0002 cm²/sec to 8.58×10^{-6} cm²/sec with an increase in liquid limit from 286.0 % to 560.0 %.

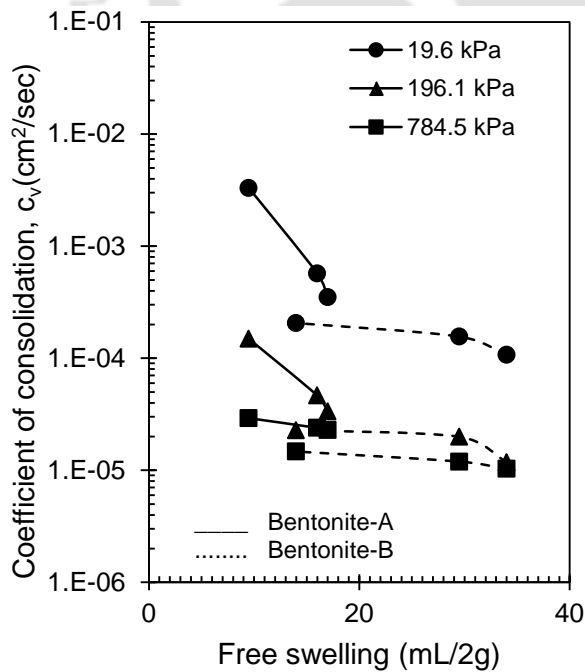
For Bentonite-A, samples compacted at 5% dry of OMC-MDD and in presence of Zn^{+2} solution, c_v decreased from 0.009 cm²/sec to 1.55×10^{-5} cm²/sec with an increase in liquid limit from 165.1 % to 218.0 %; however for Bentonite-B, c_v decreased from 6×10^{-4} cm²/sec to 8.58×10^{-6} cm²/sec with an increase in liquid limit from 279.1 % to 560.0 %. Similarly for Bentonite-A, in presence of Pb^{+2} solution, the c_v decreased from 0.011 cm²/sec to 1.55×10^{-5} cm²/sec due to an increase in liquid limit from 170.2 % to 218.0 %; however for Bentonite-B, c_v decreased from 0.0002 cm²/sec to 8.58×10^{-6} cm²/sec due to an increase in liquid limit from 286.0 % to 560.0 %.



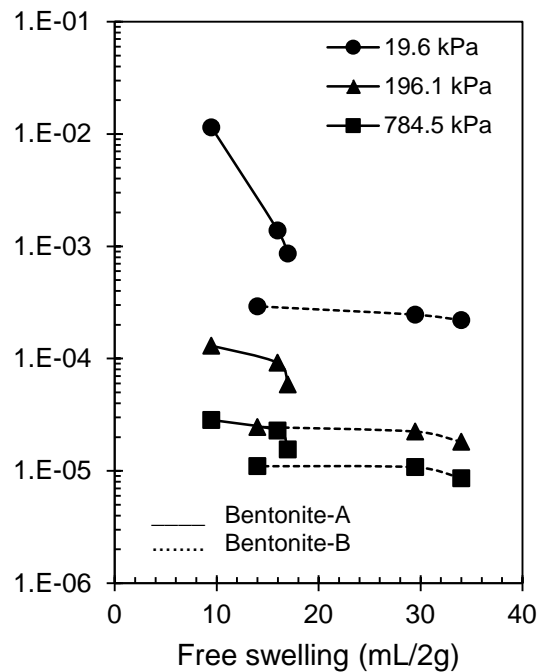
A. At OMC-MDD in presence of Zn^{2+} solution



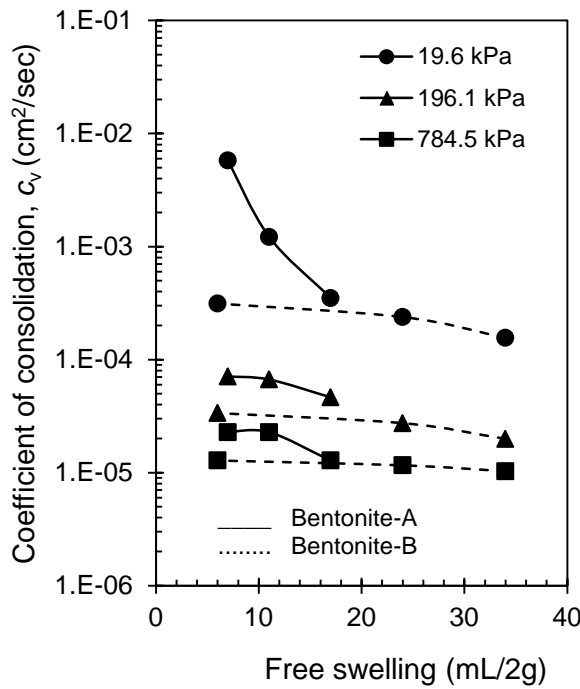
B. At 5% dry of OMC-MDD in presence of Zn^{2+} solution



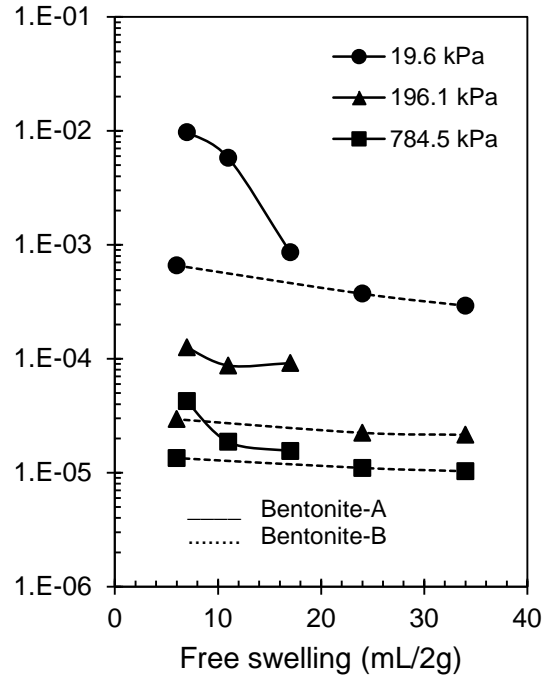
C. At OMC-MDD in presence of Pb^{2+} solution



D. At 5% dry of OMC-MDD in presence of Pb^{2+} solution

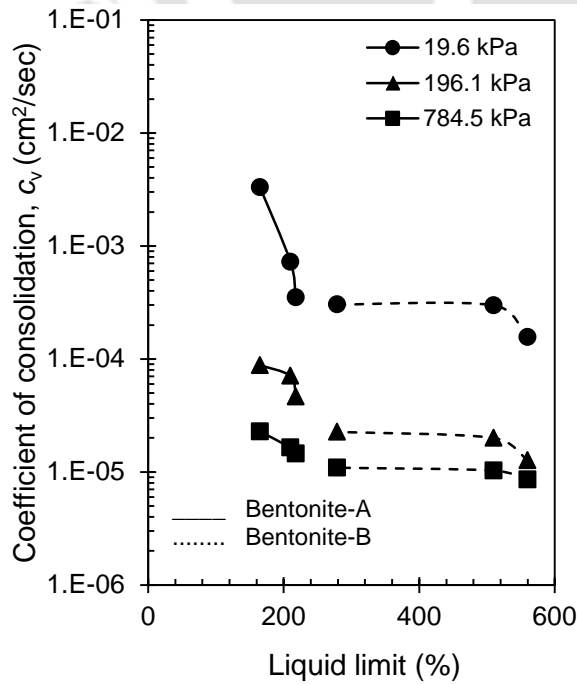


E. At OMC-MDD in presence of Cu^{2+} solution

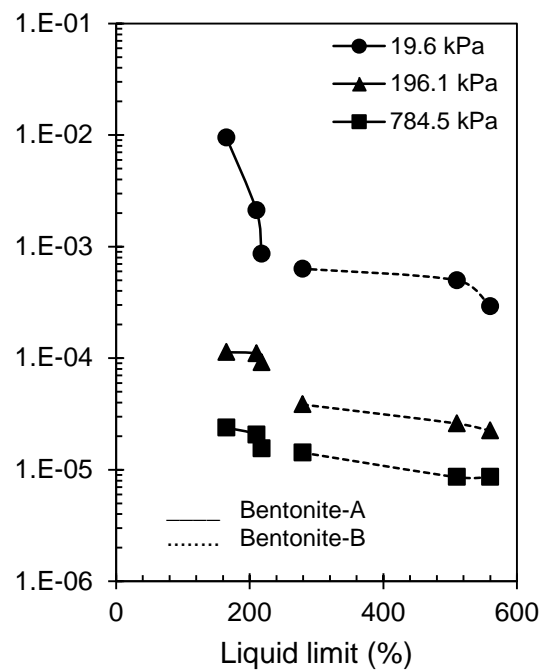


F. At 5% dry of OMC-MDD in presence of Cu^{2+} solution

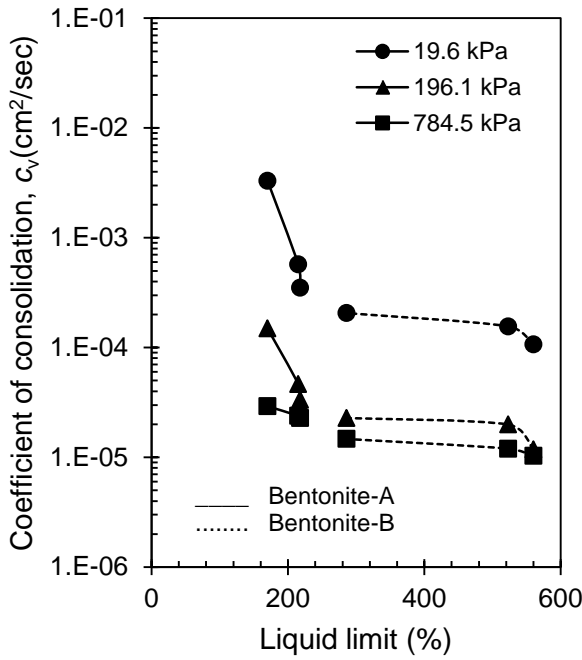
Figure 5.29 Plot between coefficient of consolidation and free swelling for Bentonite-A and -B for different heavy metals at different initial compaction condition



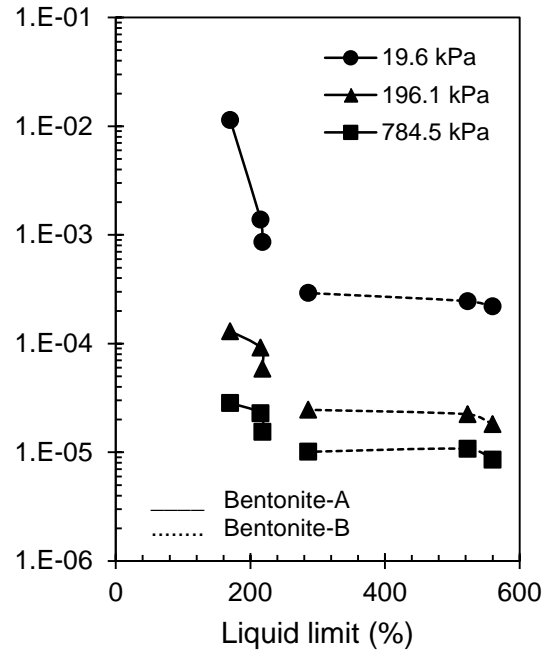
A. At OMC-MDD in presence of Zn^{2+} solution



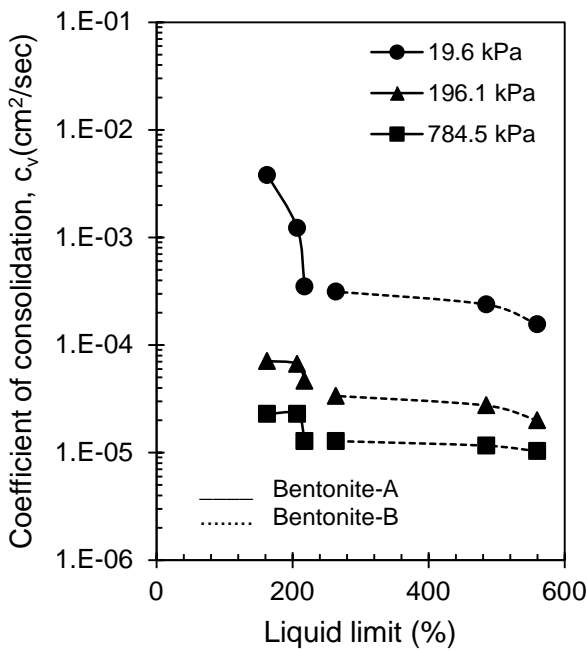
B. At 5% dry of OMC-MDD in presence of Zn^{2+} solution



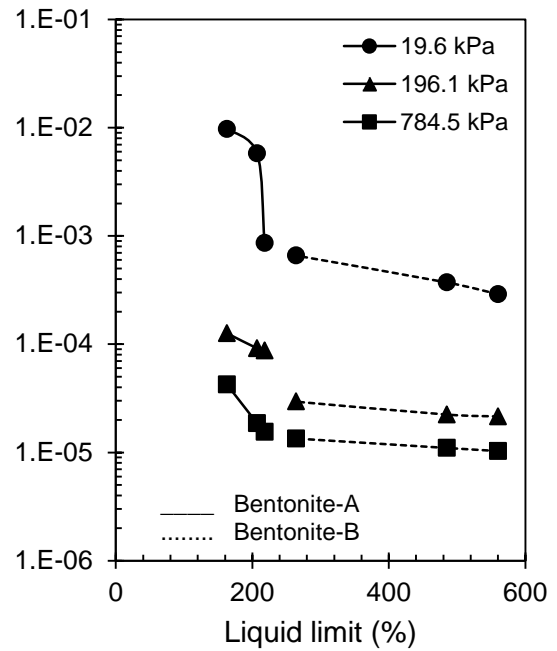
C. At OMC-MDD in presence of Pb^{2+} solution



D. At 5% dry of OMC-MDD in presence of Pb^{2+} solution



E. At OMC-MDD in presence of Cu^{2+} solution



F. At 5% dry of OMC-MDD in presence of Cu^{2+} solution

Figure 5.30 Plot between coefficient of consolidation and the liquid limit for Bentonite-A and -B for different heavy metals at different initial compaction condition

5.2.7.5. Time for 90% of consolidation (t_{90})

Figures 5.31 and 5.32 show the relationship between pressure and time to complete 90% of the consolidation (t_{90}). The plots indicate that with an increase in the consolidation pressure the t_{90} for the sample increases. For both the bentonites, t_{90} decreases with an increase in the concentration of heavy metal ions in the pore fluid. For any given concentration and pressure, a higher value of t_{90} was observed for Bentonite-B in comparison to Bentonite-A. With increase in the pressure from 9.8 kPa to 784.5 kPa the t_{90} for Bentonite-B permeated with 100 ppm of Pb^{2+} increased from 23.1 minutes to 918.1 minutes; whereas, it increased only from 0.3 minutes to 408.0 minutes for Bentonite-A. Similarly, the t_{90} for Bentonite-B permeated with 1000 ppm of Pb^{2+} increased from 37.1 minutes to 875.2 minutes; whereas, it increased only from 0.8 minutes to 361.3 minutes for Bentonite-A

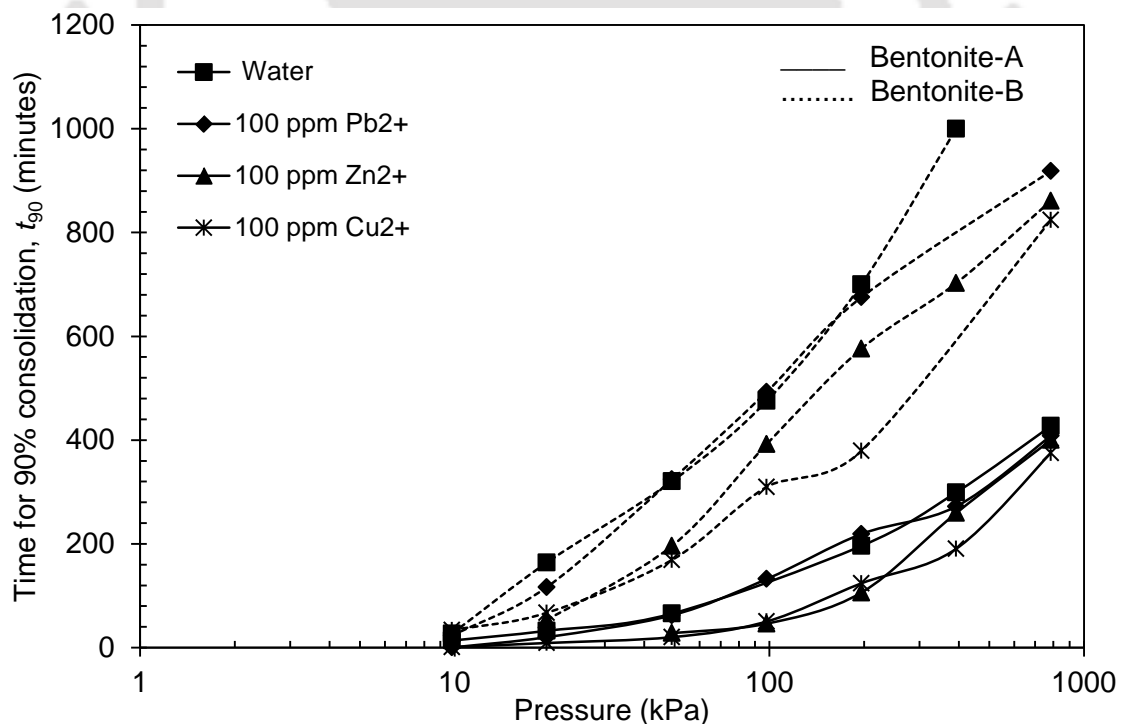


Figure 5.31 Plot between the time for 90% of consolidation and consolidation pressures of Bentonite-A and -B at 100 ppm concentration of heavy metals

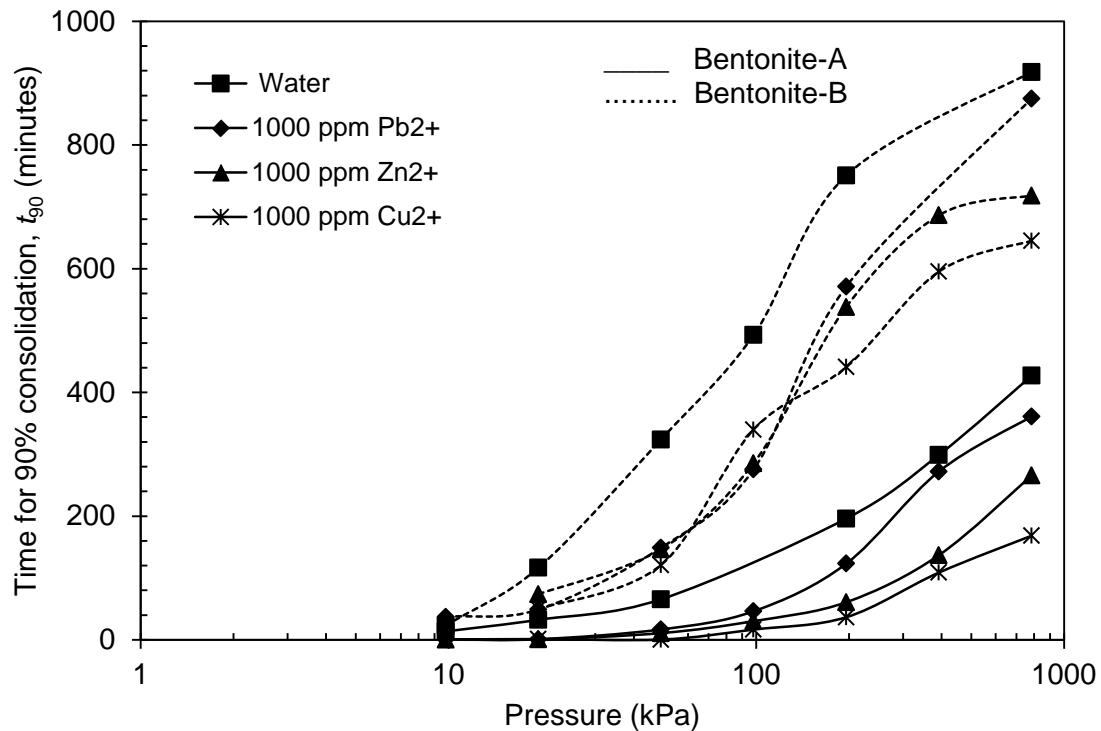
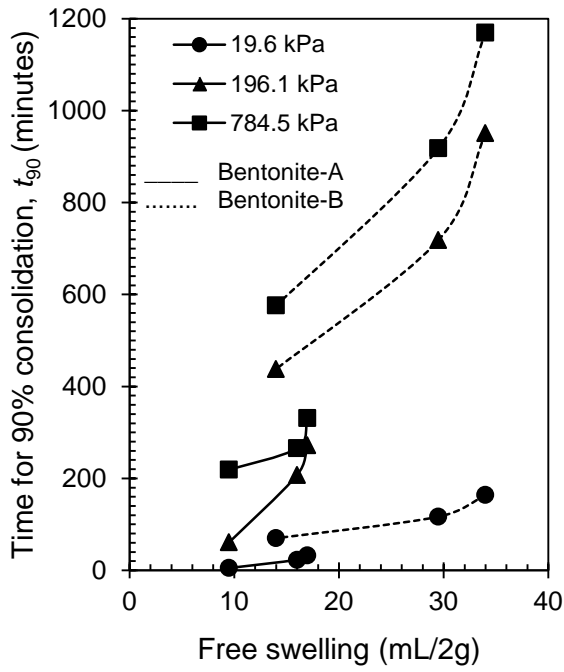
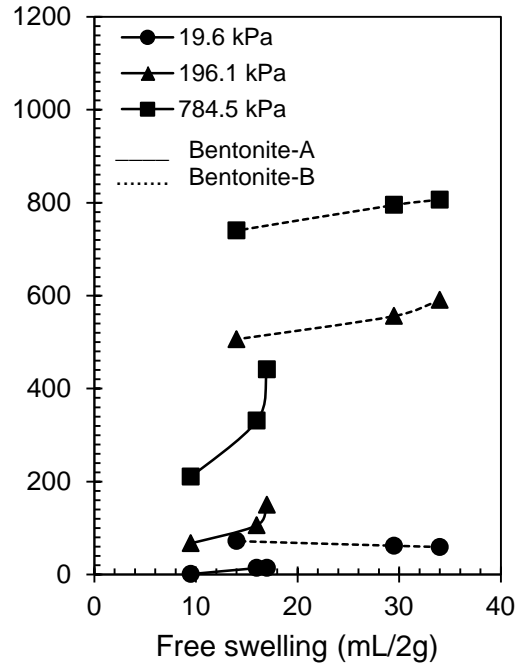


Figure 5.32 Plot between the time for 90% of consolidation and consolidation pressures of Bentonite-A and -B at 1000 ppm concentration of heavy metals

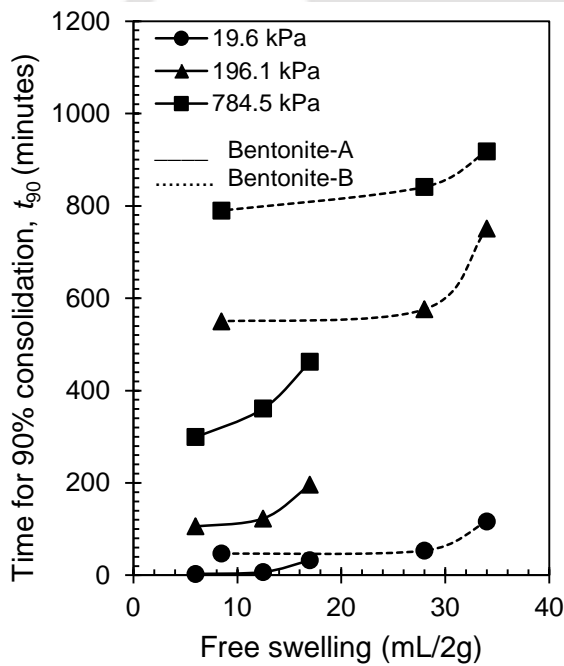
Figure 5.33 shows the relationship between the liquid limit and the time taken to complete 90% of consolidation (t_{90}) at the consolidation pressures of 19.6 kPa, 196.1 kPa and 784.5 kPa. It was observed that irrespective of the consolidation pressure, the t_{90} increased with the increase in the liquid limit of the bentonite. For Bentonite-A, samples compacted at OMC-MDD and in the presence of Zn^{2+} , t_{90} increased from 3.1 minutes to 462.2 minutes with an increase in liquid limit from 165.1 % to 218.0 %; however for Bentonite-B, t_{90} increased from 49.0 minutes to 922.1 minutes with an increase in liquid limit from 279.1 % to 560.0 %. For Bentonite-A, in presence of Cu^{2+} the t_{90} increased from 3.0 minutes to 412.1 minutes with an increase in liquid limit from 163.0 % to 218.0 %; however for Bentonite-B, t_{90} increased from 50.4 minutes to 918.1 minutes with an increase in liquid limit from 264.2 % to 560.0 %. Similar trend for c_v was observed for the bentonites in presence of Pb^{2+} solutions. The plots also show the effect of liquid limit on t_{90} was significant at high consolidation pressure.



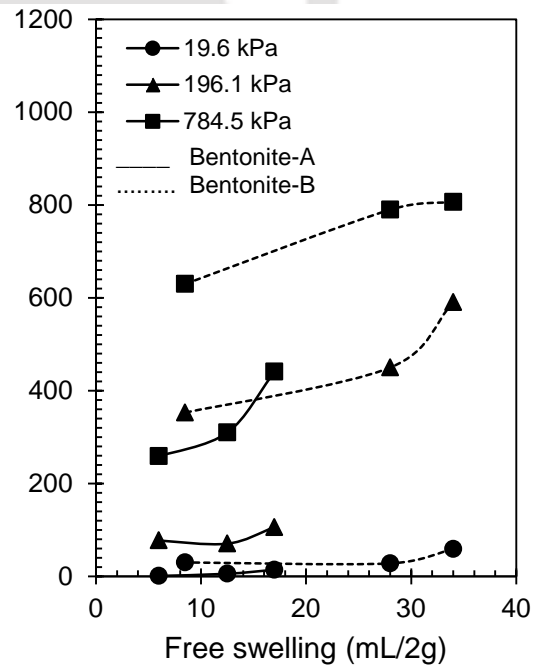
A. At OMC-MDD in presence of Pb^{2+} solution



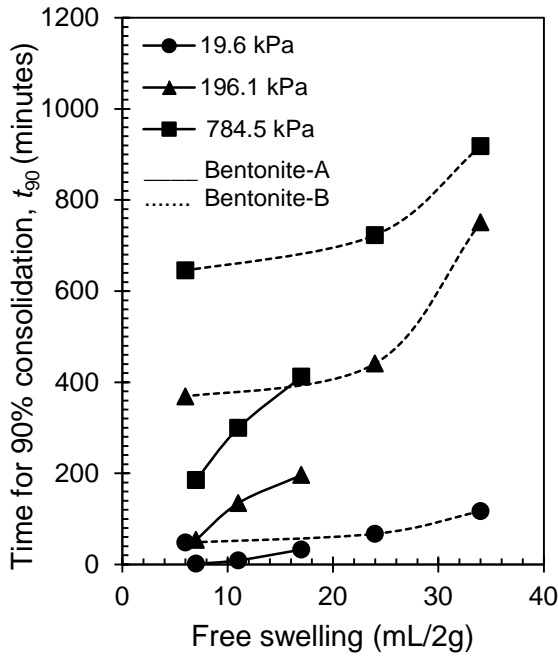
B. At 5% dry of OMC-MDD in presence of Pb^{2+} solution



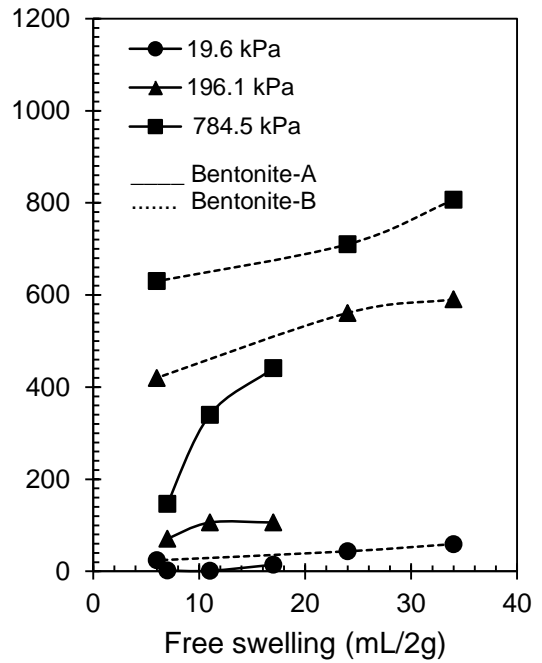
C. At OMC-MDD in presence of Zn^{2+} solution



D. At 5% dry of OMC-MDD in presence of Zn^{2+} solution

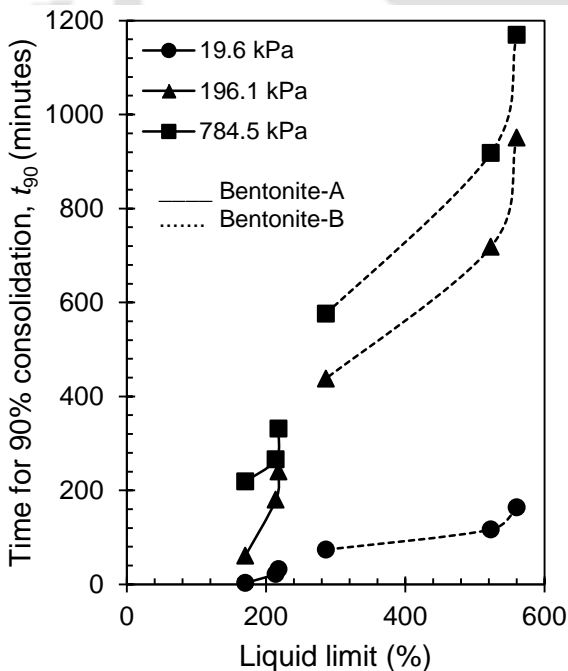


E. At OMC-MDD in presence of Cu^{2+} solution

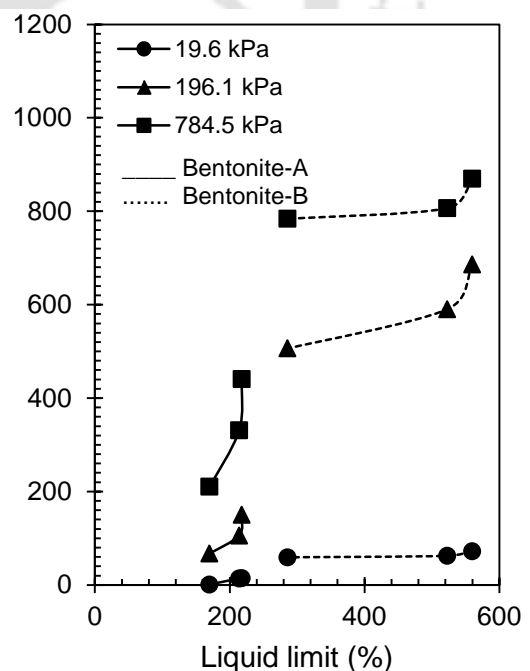


F. At 5% dry of OMC-MDD in presence of Cu^{2+} solution

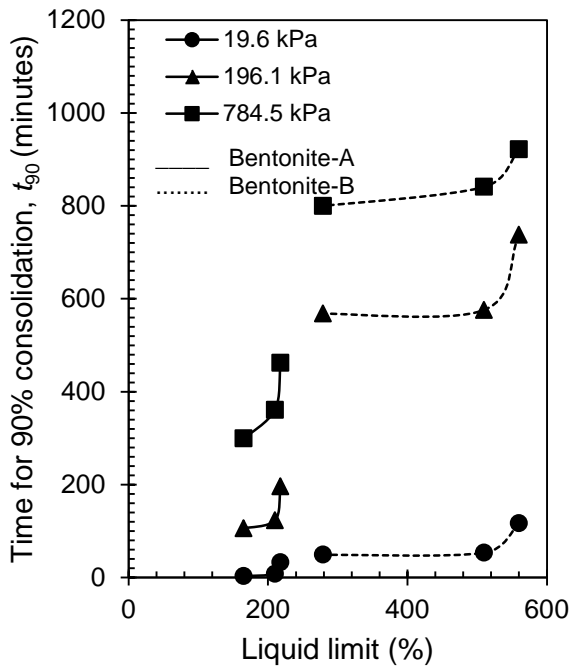
Figure 5.33 Plot between time for 90% consolidation and free swelling for Bentonite-A and -B for different heavy metals at different initial compaction condition



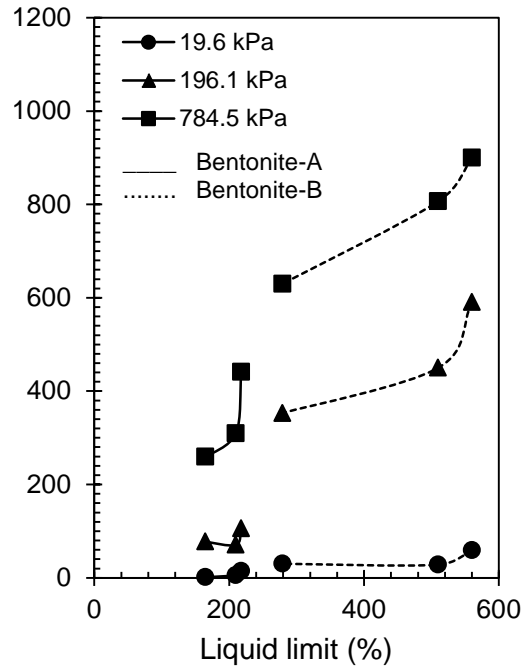
A. At OMC-MDD in presence of Pb^{2+} solution



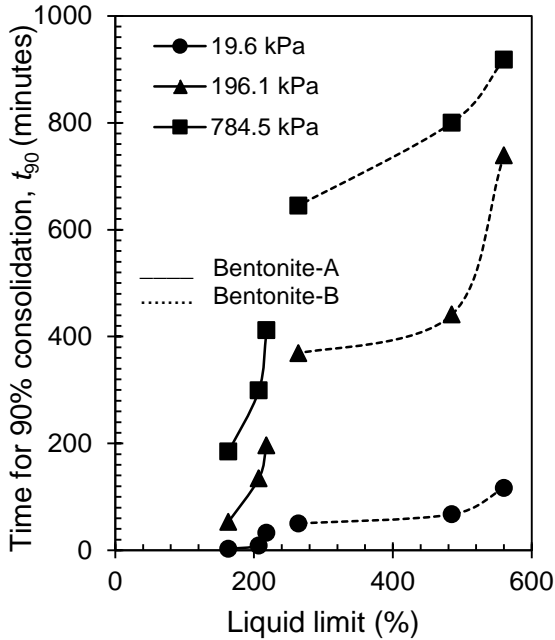
B. At 5% dry of OMC-MDD in presence of Pb^{2+} solution



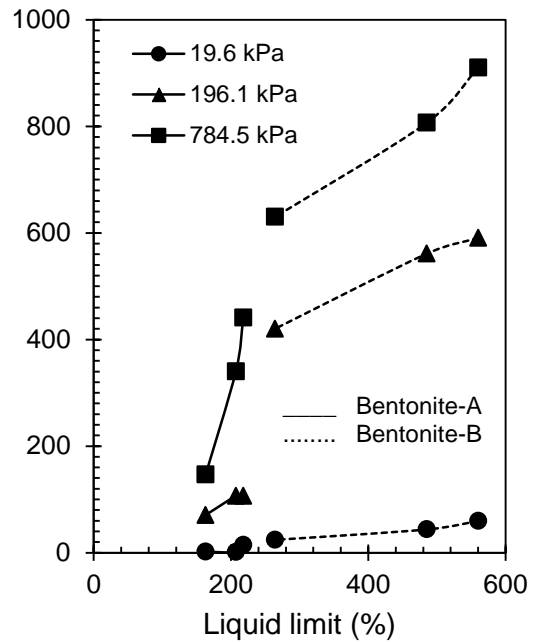
C. At OMC-MDD in presence of Zn^{2+} solution



D. At 5% dry of OMC-MDD in presence of Zn^{2+} solution



E. At OMC-MDD in presence of Cu^{2+} solution



F. At 5% dry of OMC-MDD in presence of Cu^{2+} solution

Figure 5.34 Plot between time for 90% consolidation and the liquid limit for Bentonite-A and -B for different heavy metals at different initial compaction condition

Figure 5.34 shows that the t_{90} for the bentonites increased with the increase in the free swelling capacity of the bentonites. For Bentonite-A, samples compacted at OMC-MDD and in the presence of Zn^{2+} , t_{90} increased from 3.0 minutes to 462.2 minutes with an increase in free swelling from 6 mL/2g to 17 mL/2g; but for Bentonite-B, t_{90} increased from 47.0 minutes to 918.1 minutes with an increase in free swelling from 8 mL/2 g to 34 mL/2g. Similarly for Bentonite-A in presence of Cu^{2+} , t_{90} increased from 1.4 minutes to 412.1 minutes with an increase in free swelling from 7 mL/2g to 17 mL/2g; but for Bentonite-B, t_{90} increased from 48.0 minutes to 918.1 minutes with an increase in free swelling from 6 mL/2g to 34 mL/2g.

For Bentonite-A, samples compacted at 5% dry of OMC-MDD and in presence of Zn^{2+} , t_{90} increased from 1.2 minutes to 441.0 minutes with an increase in free swelling from 6 mL/2g to 17 mL/2g; but for Bentonite-B, t_{90} increased from 30.0 minutes to 806.0 minutes with an increase in free swelling from 8.5 mL/2g to 34 mL/2g. Similarly for Bentonite-A, in presence of Cu^{2+} t_{90} increased from 1.4 minutes to 441.0 minutes with an increase in free swelling from 7 mL/2g to 17 mL/2g but for Bentonite-B, t_{90} increased from 24.0 minutes to 807.1 minutes with an increase in free swelling from 6 mL/2g to 34 mL/2g. Samples compacted at dry of OMC has lower t_{90} values than samples compacted at OMC.

5.2.7.6. Compression index (C_c)

The Fig. 5.35 shows the effect of heavy metal ion concentration on the compression index (C_c) of the bentonites in the presence of various concentrations of heavy metal ions. The plot shows that the C_c of both the bentonites decreased due to permeation of heavy metal ions. For Bentonite-A, the C_c value decreased from 0.699 to 0.588 due to increase in the concentration from 0 to 1000 ppm of heavy metals. The decrease in C_c was significant for Bentonite-B in comparison to Bentonite-A where the C_c decreased from 0.931 to 0.762 due to increase in the concentration from 0 to 1000 ppm of Cu^{2+} solution. For Bentonite-B the

C_c decreased steeply with increase in concentration from 0 to 100 ppm while for Bentonite-A the decrease was significant for an increase in concentration from 100 to 1000 ppm.

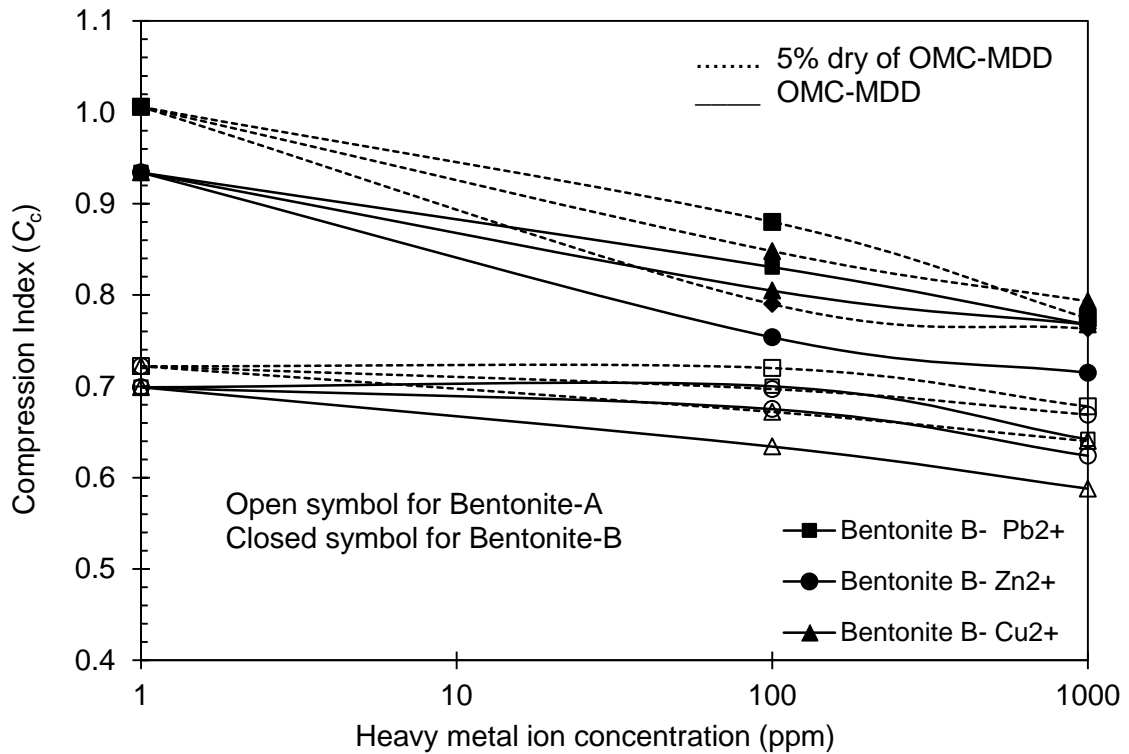


Figure 5.35 Plots for compression index of Bentonite-A and -B for various concentrations of Zn^{2+} , Cu^{2+} and Pb^{2+} solution

5.3. SUMMARY

This study was carried out to investigate the effect of heavy metal ions on the behaviour of bentonites. Two bentonites with different mineralogical properties were studied for their change in the index properties, free swelling, swelling potential, swelling pressure, hydraulic conductivity and consolidation parameters in the presence of heavy metal ions of various concentrations.

The results showed that the liquid limit of the bentonites decreased with increase in the heavy metal concentrations and the effect was more prominent for Bentonite-B in

comparison to Bentonite-A. The plastic limit of the bentonites decreased marginally with increasing heavy metal concentrations.

The free swelling of Bentonite-B was found to decrease significantly due to the increase in the metal ion concentration in comparison to Bentonite-A. For Bentonite-B, the decrease in the free swelling with metal ion concentration was minimal for an increase in concentration from 0 to 100 ppm; however, with a further increase in concentration from 100 ppm to 1000 ppm the swelling decreased significantly. The plot shows that bentonite in the presence of Pb^{2+} ions swelled to a higher value followed by Zn^{2+} and Cu^{2+} ions. Time swelling plots showed that with the increase in the heavy metal ion concentrations, the time taken for the primary swelling reduces.

The results for the swelling pressure showed that the swelling pressure of both the bentonites decreased with the increase in the metal ion concentration in the pore water. Similar to the free swelling and liquid limit behaviour, the swelling pressure of Bentonite-B also found to be significantly affected by the heavy metals in comparison to Bentonite-A. For Bentonite-B, compacted at OMC-MDD, the swelling pressure decreased from a value of 697.2 kPa with DI water to 450.1 kPa due to presence of 1000 ppm of Cu^{2+} solution. The plot also shows that Cu^{+2} have more influence on the swelling pressure in comparison to Pb^{2+} followed by Zn^{+2} . In addition to this, it can also be observed that the difference in the effect is more prominent at 1000 ppm in comparison to 100 ppm.

The data showed that the hydraulic conductivity (k) of the bentonites increased due to addition of heavy metal ions into the pore fluid. Hydraulic conductivity increased marginally when the metal concentration was increased from 0 to 100 ppm, however with a further increase in concentration from 100 ppm to 1000 ppm concentration, k increased significantly. Bentonites compacted at dry side of OMC exhibited a higher value of hydraulic conductivity in comparison to the samples compacted at OMC. A marginally

lower value of hydraulic conductivity was observed for solution containing Pb^{2+} metal ion in comparison to Zn^{2+} and Cu^{2+} ions at any given void ratio.

Results from the void ratio-pressure plots showed that under any given pressure samples with heavy metal ions exhibited a lower value of void ratio and the decrease in the void ratio with the increase in the metal ion concentration was higher for Zn^{2+} and Cu^{2+} solution in comparison to Pb^{2+} solution. Similarly, the compression index (C_c) found to be decreased with increasing the concentration of heavy metals. For Bentonite-B the C_c decreased steeply with increase in concentration from 0 to 100 ppm while for Bentonite-A the decrease was significant for an increase in concentration from 100 to 1000 ppm.

The results for the coefficient of volume change (m_v) showed that the m_v for the bentonites decreased with the increase in the heavy metal ion concentration indicating the compressibility of the bentonite due to application of consolidation pressure decreases in the presence of heavy metals ions in the pore fluid.

From the plots it was observed that coefficient of consolidation (c_v) increased with increase in heavy metal concentrations. A comparison between the values of c_v for the two bentonites at the same concentration and consolidation pressure indicates that Bentonite-B, which has a higher swelling and liquid limit and lower hydraulic conductivity values, exhibited a lower c_v in comparison to Bentonite -A in the presence of heavy metals as well. With increase in the liquid limit and free swelling of the bentonite c_v was found to be decreased irrespective of the consolidation pressure. Samples compacted at dry of OMC exhibited higher c_v and m_v values than the samples compacted at OMC.

With an increase in the consolidation pressure the t_{90} for the sample increases and t_{90} decreases with increase in the concentration of heavy metal ions in pore water. With increase in the liquid limit and free swelling of the bentonite t_{90} was found to be increased irrespective of the consolidation pressure.

COMBINED EFFECT OF INORGANIC SALTS AND HEAVY METALS ON THE BEHAVIOUR OF BENTONITES

6.1. INTRODUCTION

The possible contamination of ground water by the chemicals present in leachates is of serious environmental concern as it leads to a change in the pore water chemistry of the surrounding soil. Compacted bentonites serve as barriers in landfills and prevent the potentially pollutant leachate from contaminating the underlying ground water resources and soil. McNeal (1966) postulated that since swelling of montmorillonite affects the opening and closing of pores, it is the dominant mechanism affecting its hydraulic conductivity. The correlation between hydraulic conductivity and the swelling of bentonite is on account of the volume of water molecules bound to the clay surface. Water in the pores of bentonite is of both mobile and immobile type; mobile water is the freely flowing bulk water that is free to move under a hydraulic gradient; whereas, immobile water is bound to the external and internal (i.e. interlayer) mineral surfaces by strong electrical forces, and act similar to the solid phase in terms of affecting flow. This immobile water is known as diffuse double layer (DDL). When the DDL in the system increases, the fraction of the pore space comprised of freely flowing bulk water decreases and pathways for flow become smaller and more tortuous. With an increase in the volume of the bound water, the swelling volume increases and the hydraulic conductivity decreases. However, various salts present in the leachate suppress the thickness of diffuse double layer which in turn shrinks the bentonite. As the bentonite shrinks, the flow path becomes open and the hydraulic conductivity increases.

Bentonite used in liners comes in contact with multiple salts present in the leachate. The mechanism of interactions between the bentonite and the salt ions collectively is complicated as the ions are of various valence, sizes and concentration. Kjeldsen et al. (2002) categorized the pollutants in municipal solid waste (MSW) landfill leachate into four groups- Dissolved organic matter such as Chemical Oxygen Demand (COD) or Total Organic Carbon (TOC); Inorganic macro-components like Ca^{2+} , Mg^{2+} , Na^+ , K^+ ; Heavy metals like Cu^{2+} , Pb^{2+} , Zn^{2+} , Cd^{2+} ; and Xenobiotic organic compounds (XOCs).

Few studies have been carried out in the past to investigate the effect of various inorganic salts and heavy metals present in leachate on the behaviour of clayey soils. McNeal et al. (1968) studied the factors influencing the hydraulic conductivity of soils with different clay content but nearly uniform clay-fraction mineralogy in the presence of mixed salt solutions and observed that the relative hydraulic conductivity in the presence of mixed salt solutions decreases markedly with increasing clay content, particularly at the lowest salt concentrations employed. Peirce et al. (1987) investigated the effects of ferric chloride and nickel nitrate and observed that the materials with high clay fractions was the least responsive to test permeants and thus could be most suitable as liner material. Malik et al. (1992) studied the effect of mixed solution of Na^+ and Ca^{2+} salts of various concentrations on the swelling and hydraulic conductivity of two unsaturated clays containing montmorillonite as dominant mineral and concluded that swelling increases and the hydraulic conductivity decreases as the concentration decreases or the sodium adsorption ratio (SAR) increases. In their studies Ruhl and Daniel (1997) observed a higher value of hydraulic conductivity for a GCL permeated directly with simulated MSW leachate rich in calcium or a strong acid or base in comparison to the GCL permeated with a real MSW leachate. Shackelford et al. (2000) evaluated the hydraulic conductivity of GCLs permeated with non-standard liquids and observed that the liquids containing both high

concentrations of monovalent cations (e.g., 0.6 M NaCl) as well as low concentrations of divalent cations (e.g. 0.0125 M CaCl₂) can cause significant increases in hydraulic conductivity provided the test is performed sufficiently long to allow for exchange of adsorbed cations. Li (2003) examined the adsorptivity of different combinations of lead, copper and cadmium ions onto the clay mineral kaolinite. Results of single Pb²⁺, Cu²⁺ and Cd²⁺ solutions were compared with those of binary Pb²⁺+Cu²⁺, Pb²⁺+Cd²⁺, Cu²⁺+Cd²⁺ and ternary Pb²⁺+Cu²⁺+Cd²⁺ solutions and concluded that the adsorptivity of heavy metal ions is slightly lower in binary and ternary solutions than for single ion species in the solution. Bouazza et al. (2013) investigated the effect of strong acidic leachates on hydraulic conductivity of a needle punched GCL and concluded that hydraulic conductivity of GCLs tend to increase with increasing acid concentration.

A critical review of the literature shows that although few studies have been carried out in the past to investigate the effect of mixture of inorganic salts or heavy metals on the behaviour of bentonites, no study has been carried out to investigate the effect of mixture of inorganic salts and heavy metals on the behaviour of bentonites compacted at OMC-MDD. Since the leachates generated from the waste consists of various inorganic salts as well as heavy metals, the effect of mixed salt solutions on swelling and conductivity behaviour of bentonite is more complex in comparison to the effect of single salt. In a multiple ion system, the ions react and compete with each other for adsorbing sites on the exchange complex of the soil and prevent others from being retained. In such cases the ion exchange is a governing mechanism, but it is influenced by relative concentrations and replacing power and the valence of individual ions.

This study has been carried out to compare the combined effect of inorganic salts and heavy metals on two different bentonites. Two bentonites with varying mineralogical composition were evaluated for their swelling pressure, swelling potential, hydraulic

conductivity and consolidation behaviour in the presence of various combinations of inorganic salts and heavy metals. Different concentrations of NaCl and CaCl₂ and heavy metals (i.e. Pb²⁺, Zn²⁺ and Cu²⁺) were chosen for the study.

6.1.1. Various combinations of salts used for the study

Since leachates generated from the waste consists of various inorganic salts, i.e. NaCl and CaCl₂, as well as heavy metals, i.e. Zn²⁺, Pb²⁺ and Cu²⁺ were combined in various proportions and study was carried out to investigate the combined effect of inorganic salts and heavy metals on the behaviour of compacted bentonites. Table 6.1 shows the combinations that have been carried out on the two bentonites.

Table 6.1 The various combinations of inorganic salts and heavy metals

Combination of salt solutions	pH
DI water	7.0
0.1 N CaCl ₂ + 0.1 N NaCl	6.8
0.1 N NaCl + 1 N CaCl ₂	6.7
0.1 N CaCl ₂ + 1 N NaCl	6.7
100 ppm all HM (i.e. Pb ²⁺ + Zn ²⁺ + Cu ²⁺)	5.5
1000 ppm all HM (i.e. Pb ²⁺ + Zn ²⁺ + Cu ²⁺)	4.9
0.1 N NaCl + 0.1 N CaCl ₂ + 100 ppm all HM	4.8
0.1 N NaCl + 0.1 N CaCl ₂ + 1000 ppm all HM	4.5
1 N CaCl ₂ + 0.1 N NaCl + 100 ppm all HM	5.1
1 N CaCl ₂ + 0.1 N NaCl + 1000 ppm all HM	4.4
1 N NaCl + 0.1 N CaCl ₂ + 100 ppm all HM	5.2
1 N NaCl + 0.1 N CaCl ₂ + 1000 ppm all HM	4.5

*HM = Heavy Metals

6.2. RESULTS AND DISCUSSIONS

6.2.1. Liquid Limit

The combined effect of various concentrations of NaCl, CaCl₂ and Pb²⁺, Zn²⁺ and Cu²⁺ on the liquid limits of Bentonite-A and -B is shown in Table 6.2. The data shows that the

combined effect of salts has a significant impact on the liquid limit of both the bentonites in comparison to the individual salt solution indicating an additive effect of salt on the liquid limit. The combined effect of salts was found to be more significant in Bentonite-B in comparison to Bentonite-A. The data in the Table 6.2 shows that the liquid limit of the Bentonite-B in the presence of 0.1 N CaCl_2 +0.1 N NaCl was observed to be 129.0 %, whereas, it was found to be 252.0 % for 0.1 N of NaCl and 200.0 % for 0.1 N of CaCl_2 solution (from Fig. 4.1). Similarly, the liquid limit of the Bentonite-A in the presence of 0.1 N CaCl_2 +0.1 N NaCl was observed to be 98.0 %, whereas, it was found to be 128.3 % for 0.1 N of NaCl and 116.2 % for 0.1 N of CaCl_2 solutions. However, the additive effect becomes marginal when either of one or both salts is of 1 N concentration. When one of the salts in the mixture was of 1 N concentration, the liquid limit value of the bentonites was found to be slightly lower than the liquid limit of the corresponding bentonite with 1 N concentration. The data in the Table 6.2 shows that the liquid limit of Bentonite-B with 1 N CaCl_2 +0.1 N NaCl and 0.1 N CaCl_2 +1 N NaCl was found to be 105.0 % and 101.0 %, respectively. The liquid limit of Bentonite-B with 1 N of CaCl_2 and 1 N NaCl of was found to be 107.0 % and 112.0 %, respectively. Data also shows that the difference in the liquid limit value of the two bentonites decreases significantly due to the combined effect of NaCl and CaCl_2 solution.

Similarly, the data in Table 6.2 shows that the combined effect of heavy metals on liquid limit of the bentonites were significant in comparison to the individual effect. The liquid limit of Bentonite-B in the presence of 1000 ppm of Cu^{2+} , Zn^{2+} and Pb^{2+} was found to be 264.0 %, 279.0 % and 286.0 %, respectively (from Fig 5.1); however, due to presence of the mixture of Cu^{2+} , Zn^{2+} and Pb^{2+} of individual concentration of 1000 ppm the liquid limit of Bentonite-B decreased to 159.1 %. Similar behaviour was also observed for Bentonite-A.

Table 6.2 Liquid limit of Bentonite-A and -B in presence of the combined salt solutions

Combinations of salt solutions	Bentonite-A	Bentonite-B
DI water	218.0%	560.0%
0.1 N CaCl ₂ + 0.1 N NaCl	98.0%	129.0%
1 N NaCl + 0.1N CaCl ₂	90.0%	105.0%
1 N CaCl ₂ + 0.1N NaCl	87.0%	101.0%
100 ppm of all HM	179.0%	390.0%
1000 ppm of all HM	124.0%	159.1%
0.1 N NaCl + 0.1 N CaCl ₂ + 100 ppm of all HM	96.5%	119.5%
0.1 N NaCl + 0.1 N CaCl ₂ + 1000 ppm of all HM	95.5%	118.5%
1N CaCl ₂ + 0.1 N NaCl + 100 ppm of all HM	86.6%	99.0%
1N CaCl ₂ + 0.1 N NaCl + 1000 ppm of all HM	85.8%	98.5%
1N NaCl + 0.1 N CaCl ₂ + 100 ppm of all HM	89.4%	104.0%
1N NaCl + 0.1 N CaCl ₂ + 1000 ppm of all HM	88.0%	101.5%

The effect of addition of all the heavy metals to the mixture of inorganics salts (i.e. NaCl + CaCl₂) did not produce any significant impact on the liquid limit of both the bentonites. The data shows that the liquid limit of Bentonite-B decreased marginally from 129.0 % to 118.5 % due to addition of 1000 ppm of all the heavy metals (individually) to the 0.1 N NaCl + 0.1 N CaCl₂ solution. Similar observation was also observed for Bentonite-A.

6.2.2. Free swelling

The combined effect of various concentrations of inorganic salts and heavy metals on the free swelling of Bentonite-A and -B is shown in Table 6.3. The large swelling volume measured for DI water is due to the greater tendency for particle dispersion and unit layer disassociation while reduced interlayer swelling was observed for the samples in presence

of the combined solutions. Table 6.3 shows that swelling was most effectively suppressed in the high concentration combination solutions and thus at high concentrations of the combination solutions, free swelling values for both bentonites were nearly equal.

Table 6.3 Free swelling of Bentonite-A and -B in presence of the solutions

Combinations of salt solutions	Free swelling (mL/2g)	
	Bentonite-A	Bentonite-B
DI water	17	34
0.1 N CaCl ₂ + 0.1N NaCl	5	6
0.1 N NaCl + 1N CaCl ₂	5	6
0.1 N CaCl ₂ + 1N NaCl	5	6
100 ppm all HM (i.e. Pb ²⁺ + Zn ²⁺ + Cu ²⁺)	5	6
1000 ppm all HM (i.e. Pb ²⁺ + Zn ²⁺ + Cu ²⁺)	5	6
0.1 N NaCl + 0.1 N CaCl ₂ + 100 ppm of all HM	5	6
0.1 N NaCl + 0.1N CaCl ₂ + 1000 ppm of all HM	5	6
1 N CaCl ₂ + 0.1 N NaCl + 100 ppm of all HM	5	6
1 N CaCl ₂ + 0.1 N NaCl + 1000 ppm of all HM	5	6
1 N NaCl + 0.1 N CaCl ₂ + 100 ppm of all HM	5	6
1 N NaCl + 0.1 N CaCl ₂ + 1000 ppm of all HM	5	6

6.2.3. Swelling pressure and Swelling potential

Swelling pressure is an important parameter for the design of structures like liners, as its swelling behaviour gets affected in presence of leachates. In order to prevent opening of cracks and fissures, liners must possess a high value of swelling pressure in order to suffice as impermeable barriers.

Table 6.4 and 6.5 shows the effect of the mixed salt solutions on the swelling potential and swelling pressure of both the bentonites. The data in Table 6.4 shows that the swelling pressure and swelling potential of both the bentonites decreased significantly due to interaction with the mixed salt solution. The effect of mixed salt solution on Bentonite-B

was more significant in comparison to Bentonite-A. The swelling pressure of Bentonite-B was decreased from 697.2 kPa to 271.7 kPa due to increase in the concentration from 0 (i.e. DI water) to 1 N CaCl_2 +0.1 N NaCl solution.

Similar to the observation made in the liquid limit, a comparison between the data in Table 6.4 and Fig. 4.11 shows that the combined effect of salts has a significant impact on the swelling pressure of both the bentonites in comparison to the individual salt solution indicating an additive effect of salt on swelling pressure. The data in the Table 6.4 shows that the swelling pressure of the Bentonite-B in the presence of 0.1 N CaCl_2 +0.1 N NaCl was determined to be 350.1 kPa, whereas, it was found to be 418.7 kPa for 0.1 N of NaCl and 392.1 kPa for 0.1 N of CaCl_2 solution (from Fig. 4.11). Similarly, the swelling pressure of the Bentonite-A in the presence of 0.1 N CaCl_2 +0.1 N NaCl was found to be 190.2 kPa, whereas, it was found to be 186.3 kPa for 0.1 N of NaCl and 176.5 kPa for 0.1 N of CaCl_2 solution.

The data for the swelling pressure for both the bentonites in presence of heavy metals shows that the combined effect of the heavy metals was quite significant in comparison to the individual effect. The data in Table 6.4 shows that the swelling pressure of Bentonite-B was 409.8 kPa with a mixture of 1000 ppm of solution of Cu^{2+} , Zn^{2+} and Pb^{2+} as the pore fluid, whereas, for the individual solution of 1000 ppm of Cu^{2+} , Zn^{2+} and Pb^{2+} it was 441.2, 519.9 and 580.1 kPa, respectively indicating an additive effect of heavy metals on the swelling pressure of the bentonites as well.

However when 1000 ppm of the Cu^{2+} , Zn^{2+} and Pb^{2+} was added with 1 N CaCl_2 + 0.1 N NaCl and 1 N NaCl+0.1 N CaCl_2 , the swelling pressure of the bentonites decreased considerably. From the data in the Table 6.4 it can be seen that the swelling pressure of Bentonite-B decreased from 271.7 kPa to 221.6 kPa due to the addition of 1000 ppm of Cu^{2+} , Zn^{2+} and Pb^{2+} solution to 1 N CaCl_2 + 0.1 N NaCl solution. This observation was

contrary to the observation made for the liquid limit where a marginal decrease due to addition of 1000 ppm of Cu^{2+} , Zn^{2+} and Pb^{2+} was observed.

Table 6.4 Swelling pressure of Bentonite-A and -B in presence of the solutions

Combinations of salt solutions	Swelling pressure (kPa)	
	Bentonite-A	Bentonite-B
DI water	267.7	697.2
0.1 N CaCl_2 + 0.1 N NaCl	190.2	350.1
1 N CaCl_2 + 0.1 N NaCl	180.3	271.7
1 N NaCl + 0.1 N CaCl_2	210.0	315.0
100 ppm of all HM	227.1	583.4
1000 ppm of all HM	205.9	409.8
1 N CaCl_2 + 0.1 N NaCl + 100 ppm of all HM	176.2	268.6
1 N CaCl_2 + 0.1 N NaCl + 1000 ppm of all HM	168.6	221.6
1 N NaCl + 0.1 N CaCl_2 + 100 ppm of all HM	202.9	312.8
1 N NaCl + 0.1 N CaCl_2 + 1000 ppm of all HM	200.1	250.1
0.1 N NaCl + 0.1 N CaCl_2 + 100 ppm of all HM	184.0	348.1
0.1 N NaCl + 0.1 N CaCl_2 + 1000 ppm of all HM	174.5	293.2

However, the data in Table 6.5 on the effect of mixed salt solution on the swelling potential indicates that the mixed salt solution decreased the swelling potential marginally in comparison to the individual salt solution. Bentonite-B exhibited a swelling potential of 28.9 % due to the permeation of 0.1 N CaCl_2 +0.1 N NaCl in comparison to 29.0 % for 0.1 N of NaCl and 31.1 % for 0.1 N CaCl_2 solutions (Fig. 4.8). Similarly, the swelling potential of Bentonite-B in the presence of 1 N CaCl_2 +0.1 N NaCl was observed to be 18.3 %, whereas, for 1 N of CaCl_2 it was 21.4 % (Fig. 4.8).

Table 6.5 Swelling potential of Bentonite-A and -B in presence of the solutions

Combinations of salt solutions	Swelling potential (%)	
	Bentonite-A	Bentonite-B
DI water	22.1	48.4
0.1 N CaCl ₂ + 0.1 N NaCl	21.4	28.9
1 N CaCl ₂ + 0.1 N NaCl	15.3	18.3
1 N NaCl + 0.1 N CaCl ₂	16.3	19
100 ppm of all HM	21.9	43.4
1000 ppm of all HM	20.9	33.9
1 N CaCl ₂ + 0.1 N NaCl + 100 ppm of all HM	14.7	17.3
1 N CaCl ₂ + 0.1 N NaCl + 1000 ppm of all HM	14.1	16.6
1 N NaCl + 0.1 N CaCl ₂ + 100 ppm of all HM	15.8	16.8
1 N NaCl + 0.1 N CaCl ₂ + 1000 ppm of all HM	15.4	16.1
0.1 N NaCl + 0.1 N CaCl ₂ + 100 ppm of all HM	20.9	27.0
0.1 N NaCl + 0.1 N CaCl ₂ + 1000 ppm of all HM	19.5	24.6

The data for the heavy metals in Table 6.5 shows that the swelling potential for the mixture of 100 ppm of Cu²⁺, Zn²⁺ and Pb²⁺ solution was observed to be 43.4 % for Bentonite-B. For the individual concentration of 100 ppm of Cu²⁺, Zn²⁺ and Pb²⁺ solution swelling potential value of 42.4 %, 42.8 % and 45.4 % was observed respectively (Fig. 5.5). Similarly, the swelling potential with the mixture of 100 ppm of Cu²⁺, Zn²⁺ and Pb²⁺ solution was observed to be 21.9 % for Bentonite-A. For the individual concentration of 100 ppm of Cu²⁺, Zn²⁺ and Pb²⁺ solution 20.9 %, 20.8 % and 21.2 % of swelling potential value was observed respectively. Similar to the effect on the swelling pressure, the addition of the mixtures of 1000 ppm of Cu²⁺, Zn²⁺ and Pb²⁺ solution to the 1 N NaCl+0.1 N CaCl₂ and 0.1 N NaCl+1 N CaCl₂ produced a significant decrease in the swelling potential. With the addition of mixture of 1000 ppm of Cu²⁺, Zn²⁺ and Pb²⁺ solution to the 1 N NaCl+0.1 N CaCl₂ decreased the swelling potential of Bentonite-B from 19 % to 16.1 %. With the

addition of 1000 ppm of Cu^{2+} , Zn^{2+} and Pb^{2+} solution to the 0.1 N NaCl+0.1 N CaCl_2 decreased the swelling potential of Bentonite-B from 28.9% to 24.6%.

6.2.4. Time swelling relationship

Figures 6.1 and 6.2 show the swelling percentage versus time elapsed for the bentonites in presence of the mixture various salt solutions. The plots show that in presence of the various salts, the time taken to complete the primary swelling reduces. A comparison between the two bentonites in the time-swelling plot shows that at the same time elapsed, the percentage of swelling was more for Bentonite-B in comparison to Bentonite-A. Irrespective of the bentonite quality, swelling was found to be least in the presence of combination of the high concentration solutions. In case of the combinations having 0.1 N CaCl_2 or 0.1 N NaCl, the percentage of swelling over time elapsed was more for Bentonite-B in comparison to Bentonite-A, whereas for the solutions having combinations of heavy metals along with 1 N NaCl or 1 N CaCl_2 solution, the swelling for both the bentonites were nearly equal. The difference in the swelling values for both the bentonites reduced with the increase in concentration of the mixed salt solutions. The swelling reduced marginally due to the addition of 1000 ppm of Cu^{2+} , Zn^{2+} and Pb^{2+} solution in comparison to that of DI water. However, when individual concentration of 1000 ppm of Cu^{2+} , Zn^{2+} and Pb^{2+} was added with 1 N CaCl_2 + 0.1 N NaCl or 1 N NaCl+0.1 N CaCl_2 the swelling percentage decreased considerably indicating an additive effect of salts on the swelling of the bentonites. The time taken to complete the primary swelling decreased significantly in presence of these mixtures.

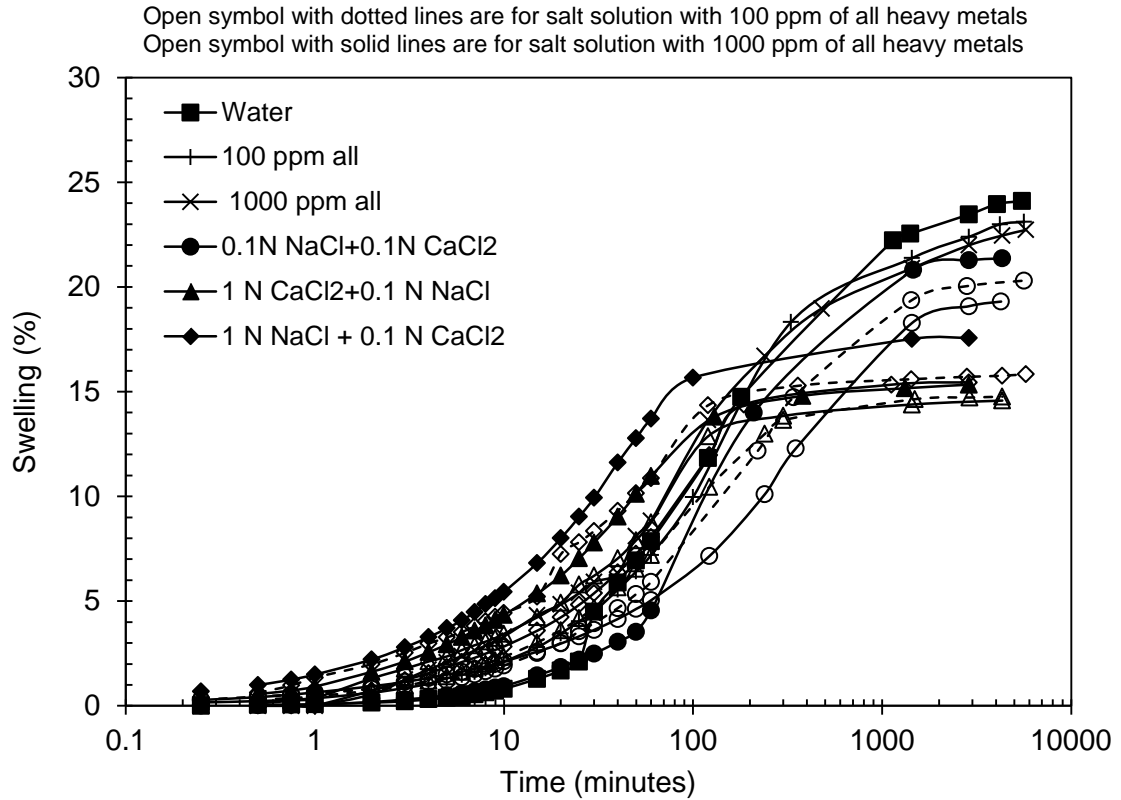


Figure 6.1 Time–swelling plots for Bentonite-A in presence of the combined salt solutions

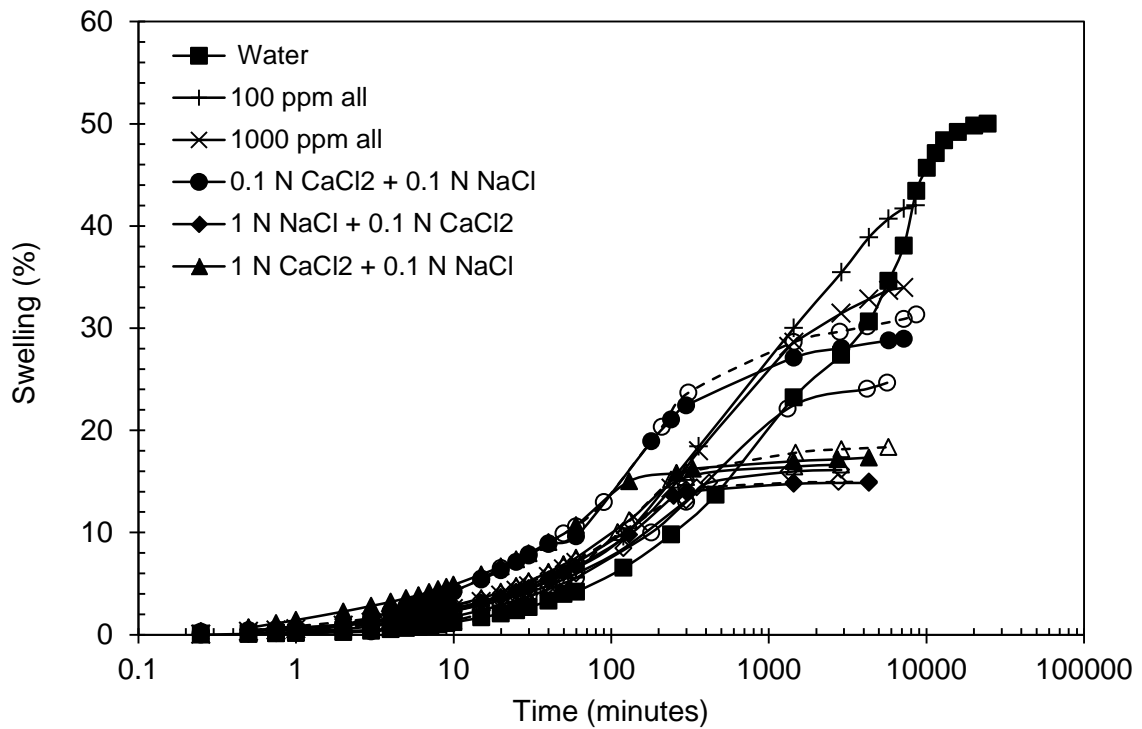


Figure 6.2 Time–swelling plots for Bentonite-B in presence of the combined salt solutions

6.2.5. Hydraulic conductivity

Figures 6.3 to 6.14 shows the void ratio-hydraulic conductivity relationship for the bentonites in the presence of various combinations of inorganic and heavy metal salt solution. Figures 6.3 to 6.4 and 6.5 to 6.8 compares the hydraulic conductivity of the bentonites in the presence of combinations of inorganic salts and combinations of heavy metals, respectively with their single species; while, Figs. 6.9 to 6.14 show the hydraulic conductivity in presence of combination of inorganic and heavy metals solutions. It was observed that the hydraulic conductivity of the bentonite in the presence of the mixture of the salt solutions were higher than when the salts were applied as individual species. When solutions of inorganic salts and heavy metals were applied to the bentonite together, the total concentrations of the ions were higher than when they were applied individually as single species. The higher the concentration of ions in the solution, the more the metal cations bind with the hydroxyl group on the broken edges on bentonite to maintain an equilibrium of positive and negative charges on the soil surface (Sparks, 1995). When more ions are bound to the clay surface, the diffuse double layer shrinks resulting in a tendency towards a more flocculated fabric and a high hydraulic conductivity value. Since the pH of permeant also has an effect on the hydraulic conductivity (Mitchell and Soga, 2005), it can also be seen that the hydraulic conductivity of bentonite considerably gets affected significantly due to the change in the pH of the salt solution. As pH of the solution increases, the net proton charge decreases (Sposito, 1989) and there will be a higher demand for positive ions on the clay particle surface. This movement of particles from the acids or bases creates the chance of (i) increase in hydraulic conductivity due to an increase in pore space or (ii) a decrease in hydraulic conductivity because of pore clogging.

The extent of increase in hydraulic conductivity due to addition of salt solution was different for the different combination of solutions. For Bentonite-A, the hydraulic

conductivity increased by 7.1 to 10.1 times due to permeation of 1 N NaCl and 1 N CaCl₂ solution individually, whereas, it increased from 14.5 to 25.1 times due to permeation of the combination of 1 N CaCl₂+0.1 N NaCl+1000 ppm of heavy metals signifying the effect of combination of salts on the hydraulic conductivity. Similarly for Bentonite-B, the hydraulic conductivity increased by 150.2 to 300.0 times due to permeation of 1 N CaCl₂ solution, whereas, due to permeation of 1 N CaCl₂+0.1 N NaCl+1000 ppm the increase in the hydraulic conductivity was from 142.2 to 326.2 times that of the hydraulic conductivity when permeated with DI water

When the pore fluid contains the combined solution of Pb²⁺, Zn²⁺ and Cu²⁺, each of 100 ppm concentration, the hydraulic conductivity of Bentonite-A increased by about 2 times in comparison to that with DI water. When the concentration of individual heavy metal ions increased to 1000 ppm, the hydraulic conductivity increased by about 4 times than that with DI water. Similarly for Bentonite-B, the hydraulic conductivity at 100 ppm increased about 3 times, whereas, with 1000 ppm it was more than 7 times that of the hydraulic conductivity permeated with DI water. The increase due to permeation of 1000 ppm all heavy metal ions was higher in comparison to the presence of individual species of heavy metal ions in pore DI water.

A comparison between the two bentonite showed that the hydraulic conductivity of Bentonite-B was severely affected in comparison to Bentonite-A due to the presence of the combined solutions. For Bentonite-A, the hydraulic conductivity increased by 14.1 to 22.2 times due to permeation of 1 N CaCl₂ +0.1 N NaCl, whereas, it increased by 100.1 to 300.0 times for Bentonite-B. Similarly for Bentonite-A, the hydraulic conductivity increased by 7.1 to 9.2 times due to permeation of 0.1 N CaCl₂ +0.1 N NaCl solution, whereas, it increased by 14.0 to 34.2 times when permeated with DI water for Bentonite-B.

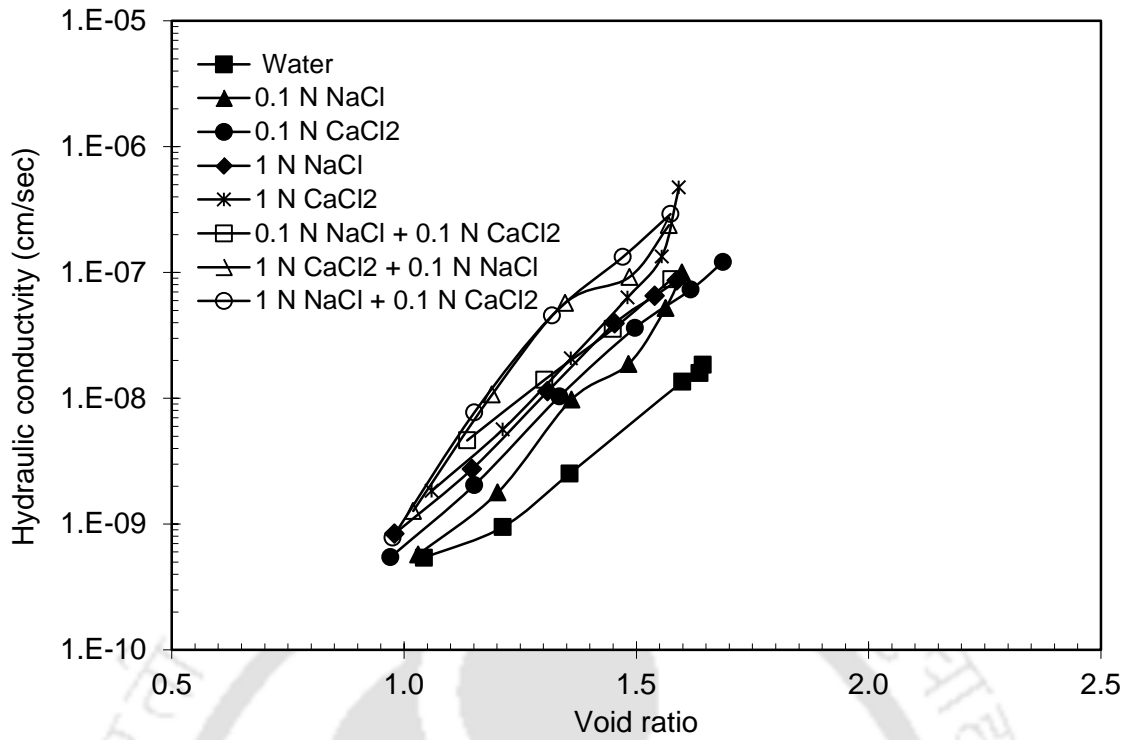


Figure 6.3 Void ratio-hydraulic conductivity comparison plots of combination of inorganic salts for Bentonite-A

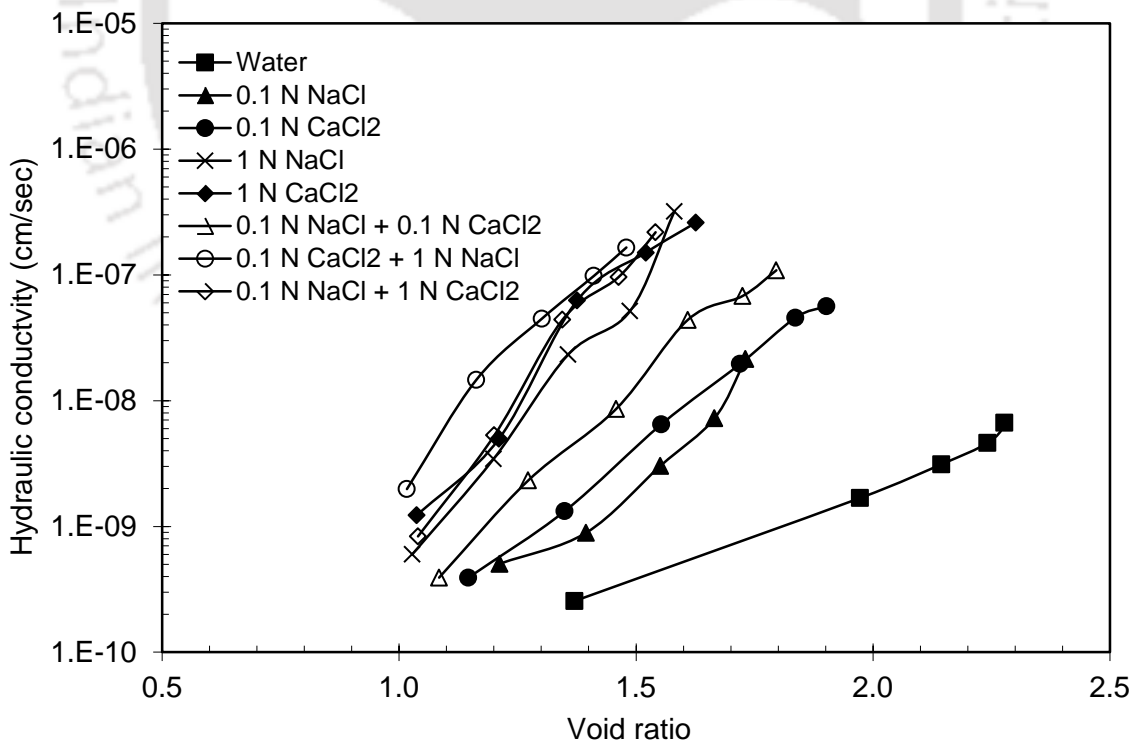


Figure 6.4 Void ratio-hydraulic conductivity comparison plots of combination of inorganic salts for Bentonite-B

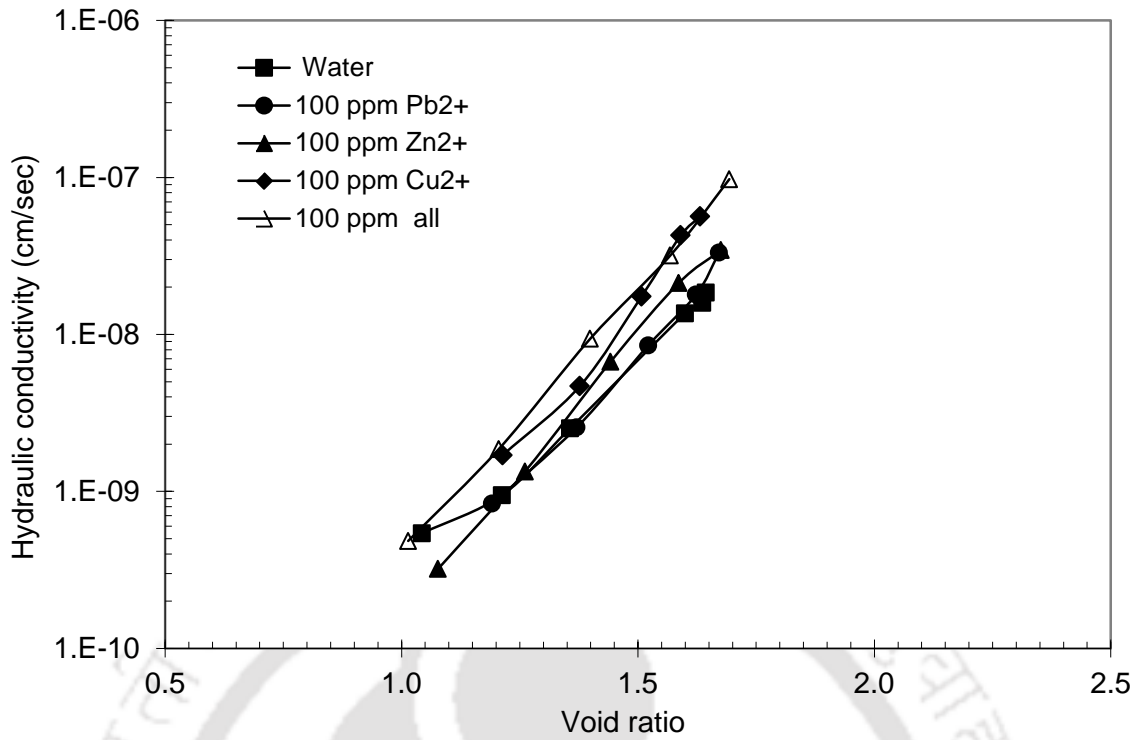


Figure 6.5 Void ratio-hydraulic conductivity comparison plots of combination of heavy metals (100 ppm) for Bentonite-A

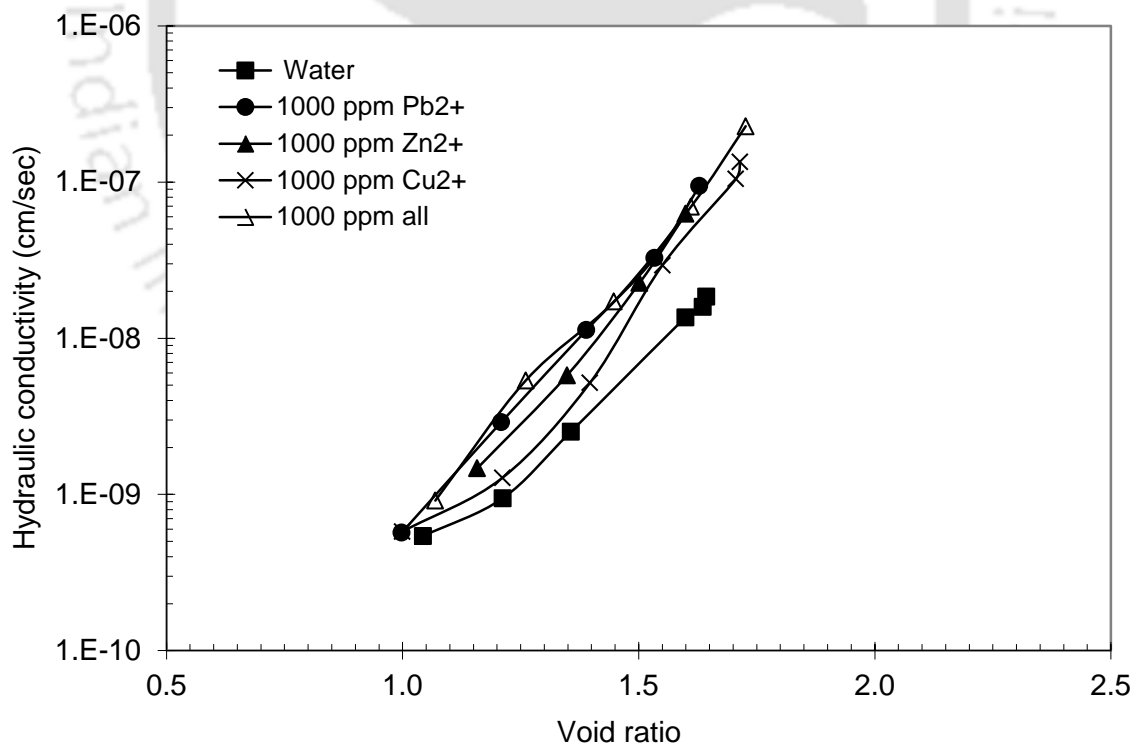


Figure 6.6 Void ratio-hydraulic conductivity comparison plots of combination of heavy metals (1000 ppm) for Bentonite-A

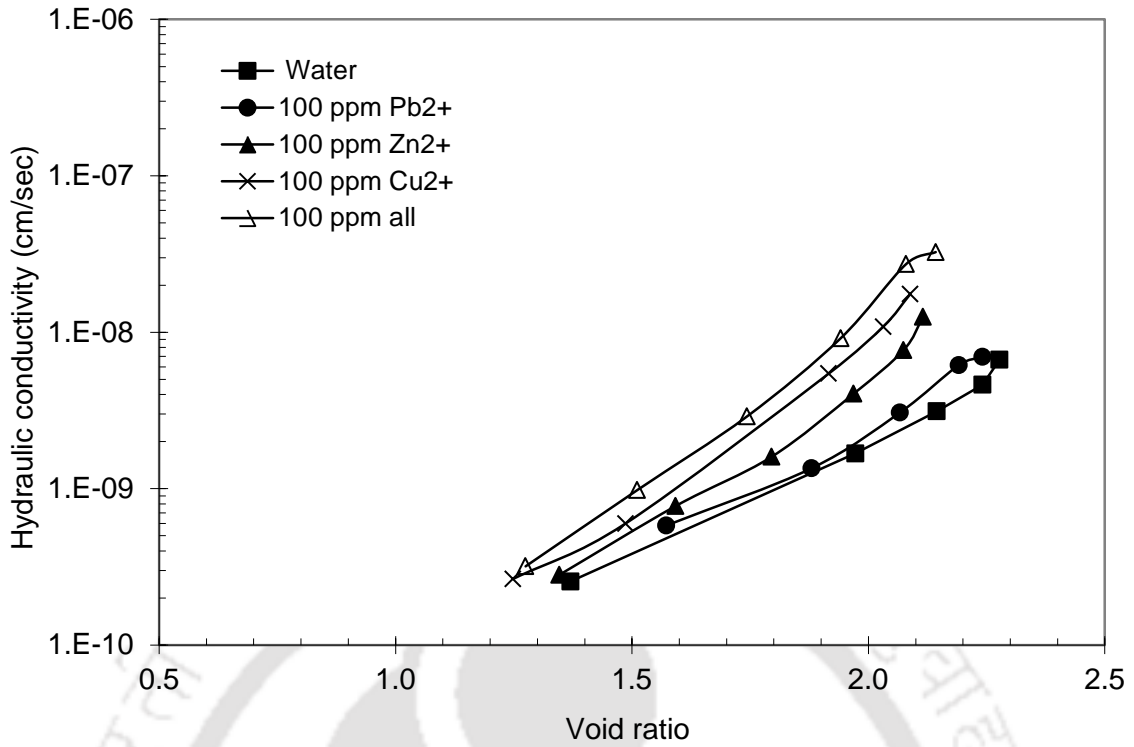


Figure 6.7 Void ratio-hydraulic conductivity comparison plots of combination of heavy metals (100 ppm) for Bentonite-B

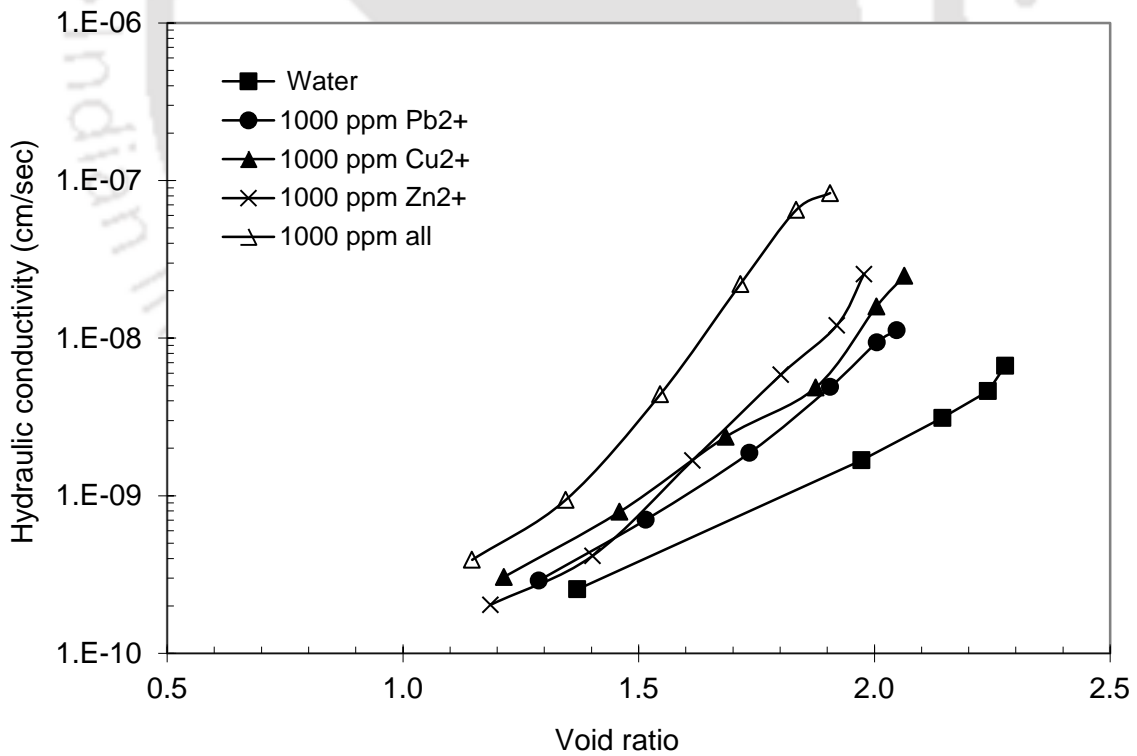


Figure 6.8 Void ratio-hydraulic conductivity comparison plots of combination of heavy metals (1000 ppm) for Bentonite-B

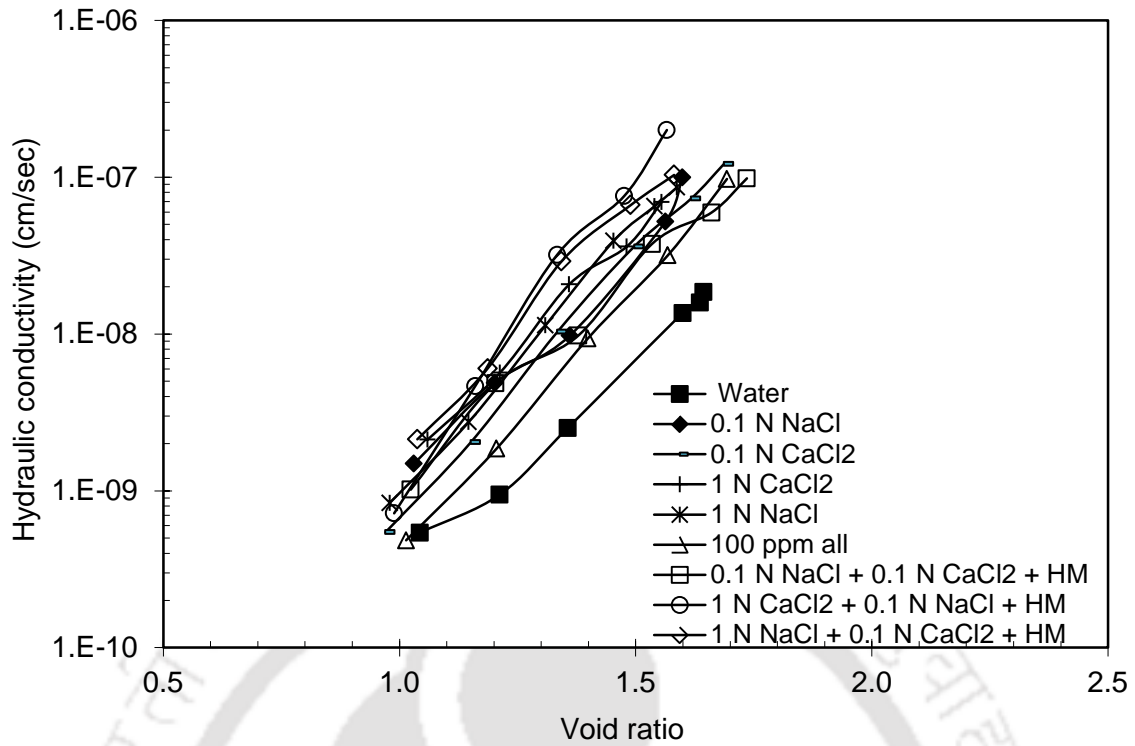


Figure 6.9 Void ratio-hydraulic conductivity comparison plots of combination of inorganic salts and heavy metals (100 ppm) for Bentonite-A

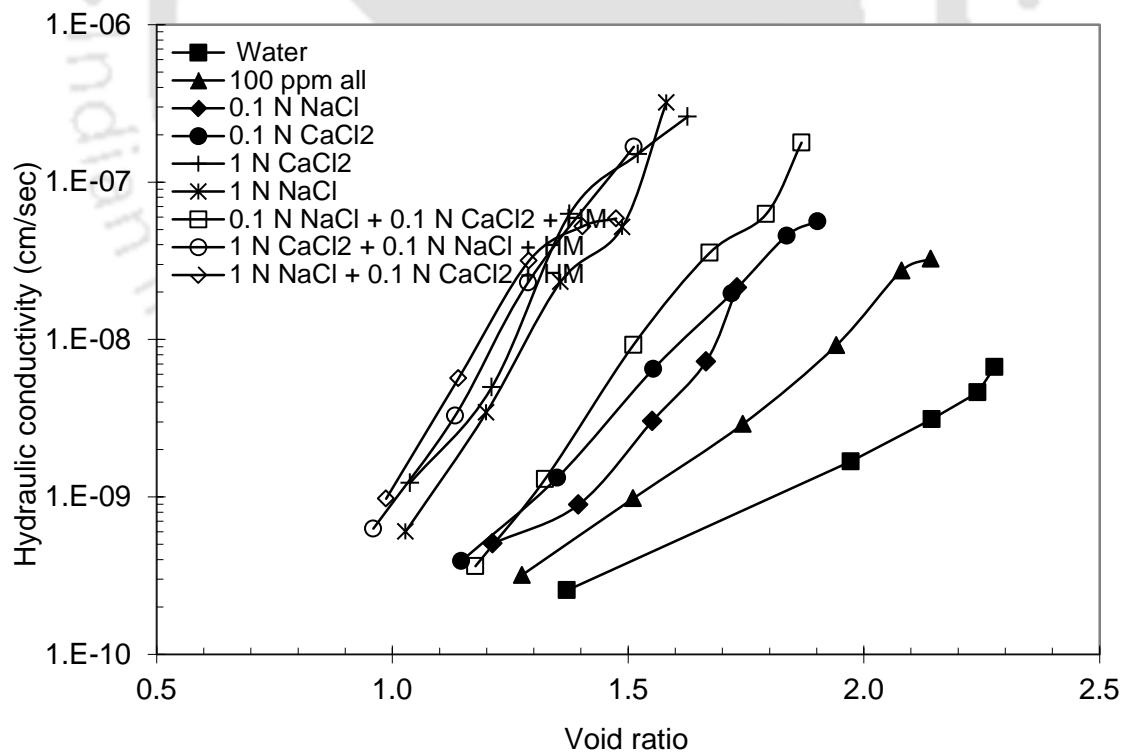


Figure 6.10 Void ratio-hydraulic conductivity comparison plots of combination of inorganic salts and heavy metals (100ppm) for Bentonite-B

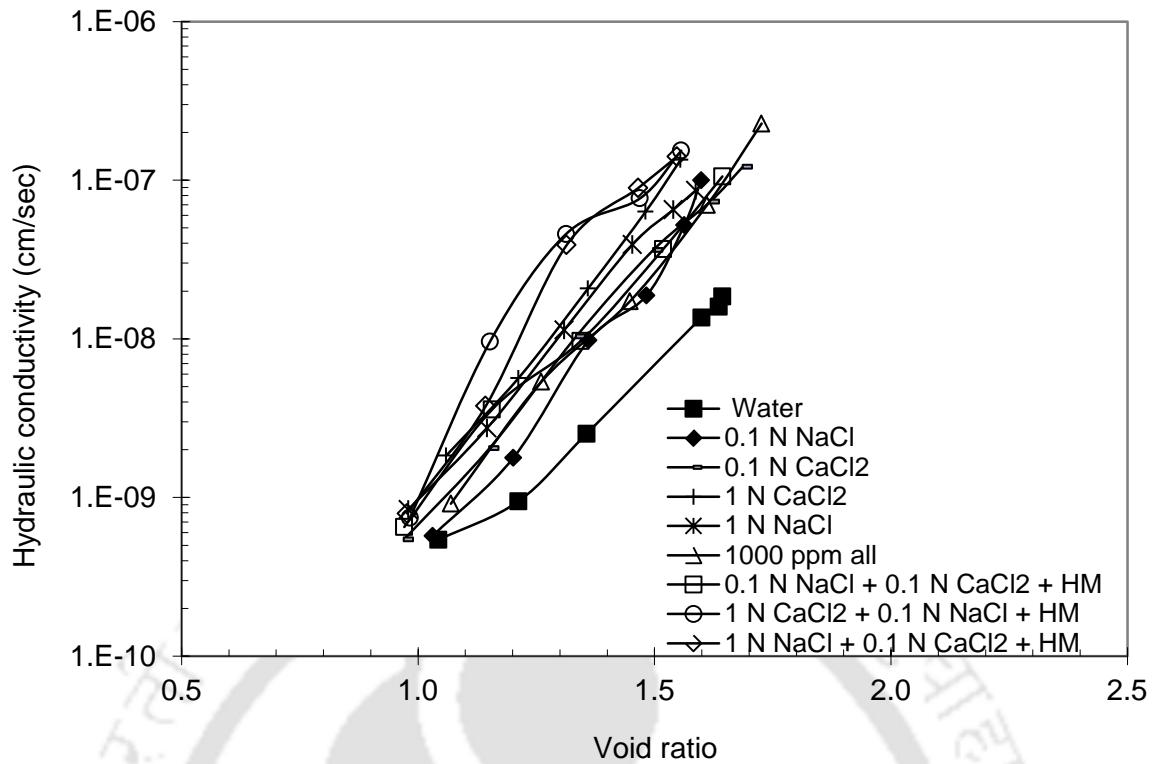


Figure 6.11 Void ratio-hydraulic conductivity comparison plots of combination of inorganic salts and heavy metals (1000 ppm) for Bentonite-A

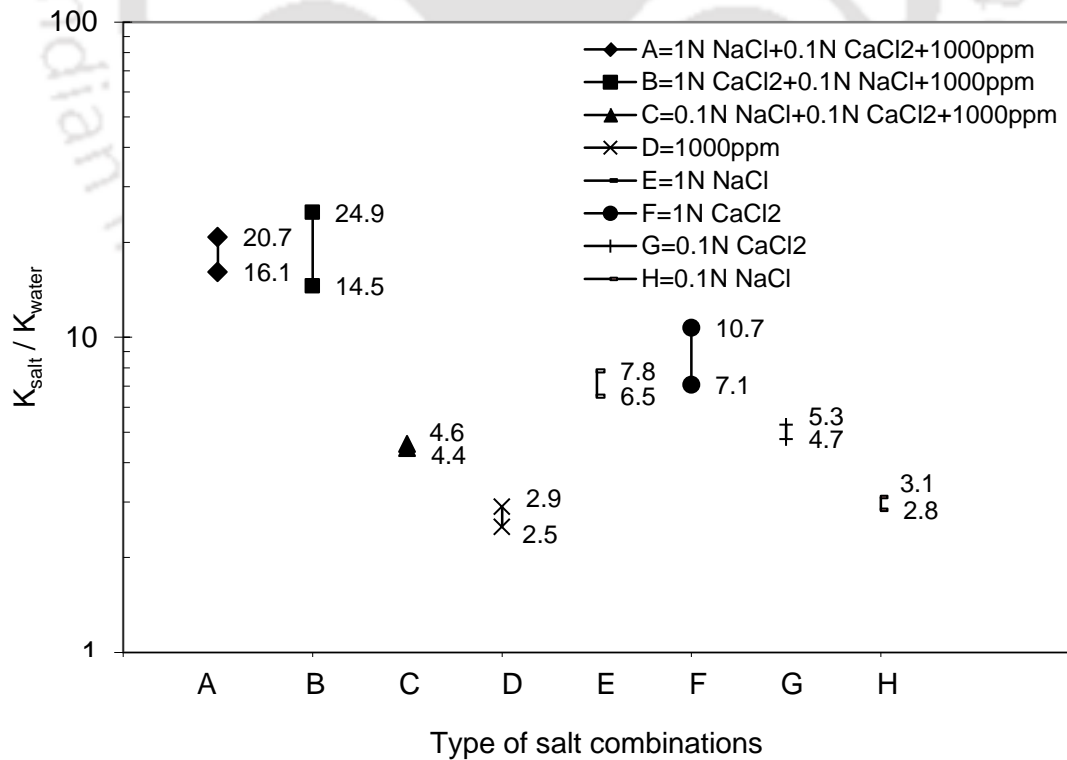


Figure 6.12 Plot for range in increase in the hydraulic conductivity of Bentonite-A

Figure 6.12 shows the range of increase in the hydraulic conductivity of Bentonite-A in presence of the combination of heavy metals (1000 ppm) and inorganic salts for a range of void ratio 1.3 to 1.6. The increase in the hydraulic conductivity due to permeation of salts is represented in the plot by the ratio between the hydraulic conductivity for any salt concentration (k_{salt}) and the hydraulic conductivity in DI water (k_{water}) at a given void ratio. It was observed that the bentonite in the presence of mixture of 1 N CaCl_2 +0.1 N NaCl +1000 ppm solution undergoes a large change in hydraulic conductivity. The hydraulic conductivity of the bentonite permeated with the solution increased from 14.5 to 24.9 times.

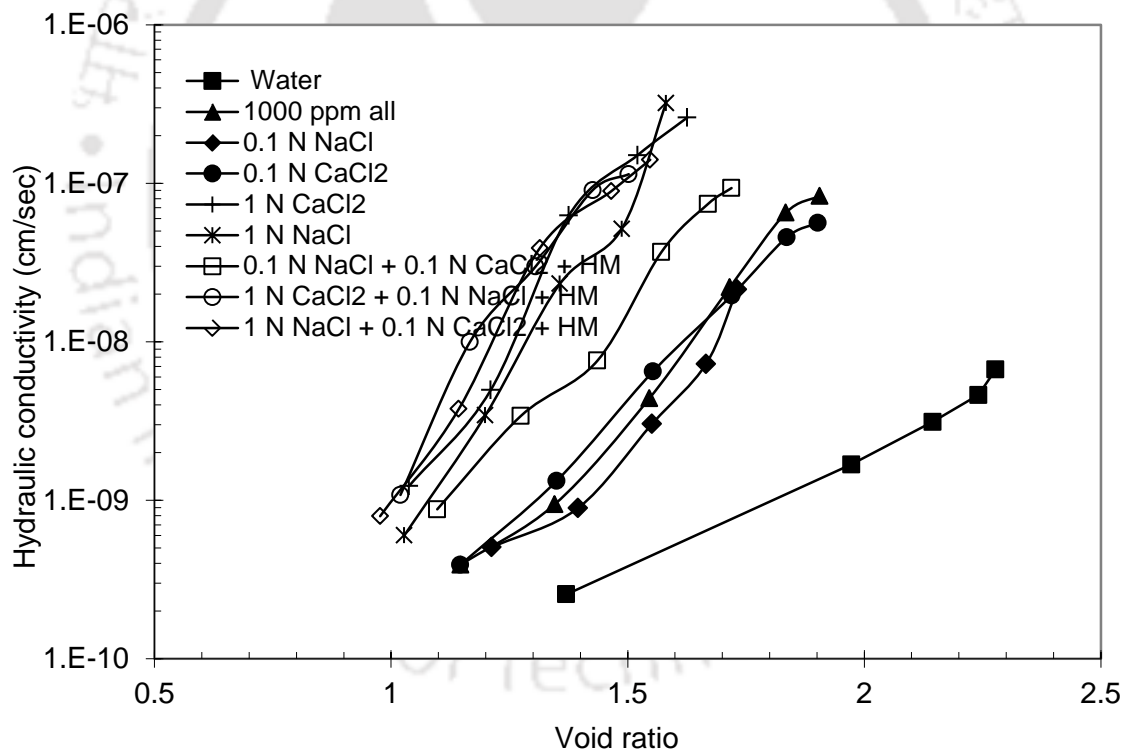


Figure 6.13 Void ratio-hydraulic conductivity comparison plots of combination of inorganic salts and heavy metals (1000 ppm) for Bentonite-B

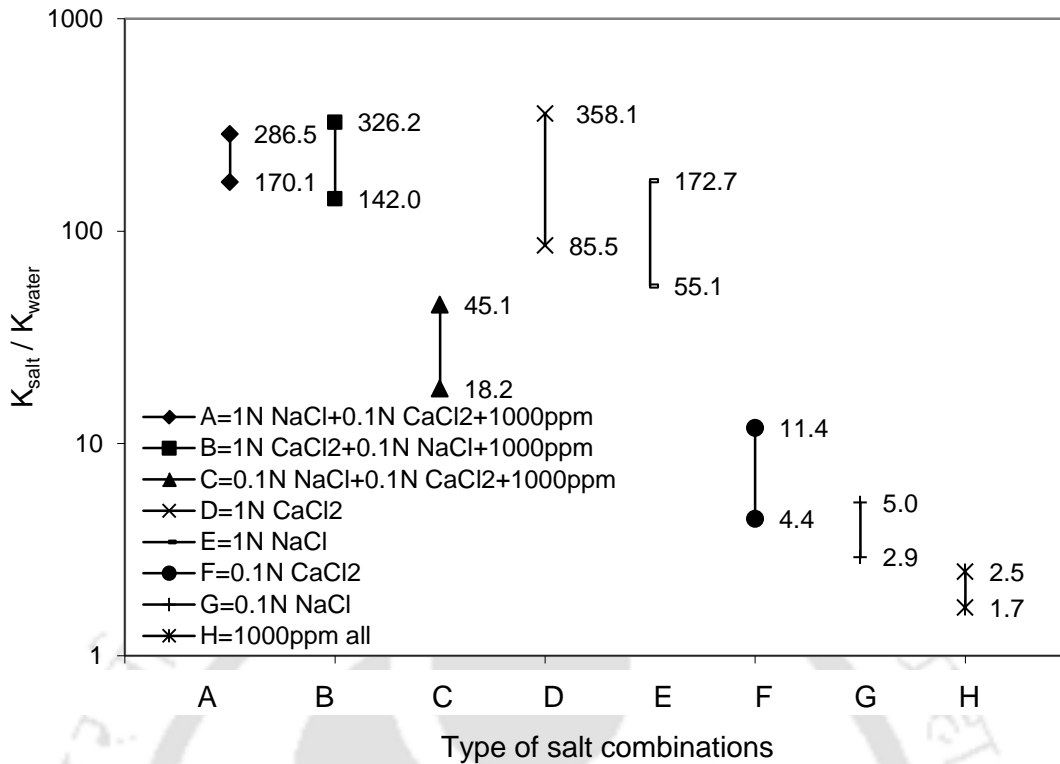


Figure 6.14 Plot for range in increase in the hydraulic conductivity of Bentonite-B

Figure 6.14 shows the range of increase in the hydraulic conductivity for Bentonite-B in the presence of the combination of heavy metals (1000 ppm) and inorganic salts for a range of void ratio 1.3 to 1.6. It is observed that the bentonite in the presence of salt solution containing 1 N $\text{CaCl}_2 + 0.1 \text{ N NaCl} + 1000 \text{ ppm}$ undergoes a large change in hydraulic conductivity and the hydraulic conductivity of the bentonite permeated with the solution increased from 142.0 to 326.2 times.

6.2.6. Consolidation parameters

6.2.6.1. Void ratio-pressure relationship

Figures 6.15 and 6.16 show the void ratio-pressure relationships of the bentonites in presence of the mixture of various salt solutions. From the plots it is observed that there was a significant decrease in void ratio in presence combination of high concentration salt solutions. The compression of Bentonite-B was more than Bentonite-A in presence of the solutions.

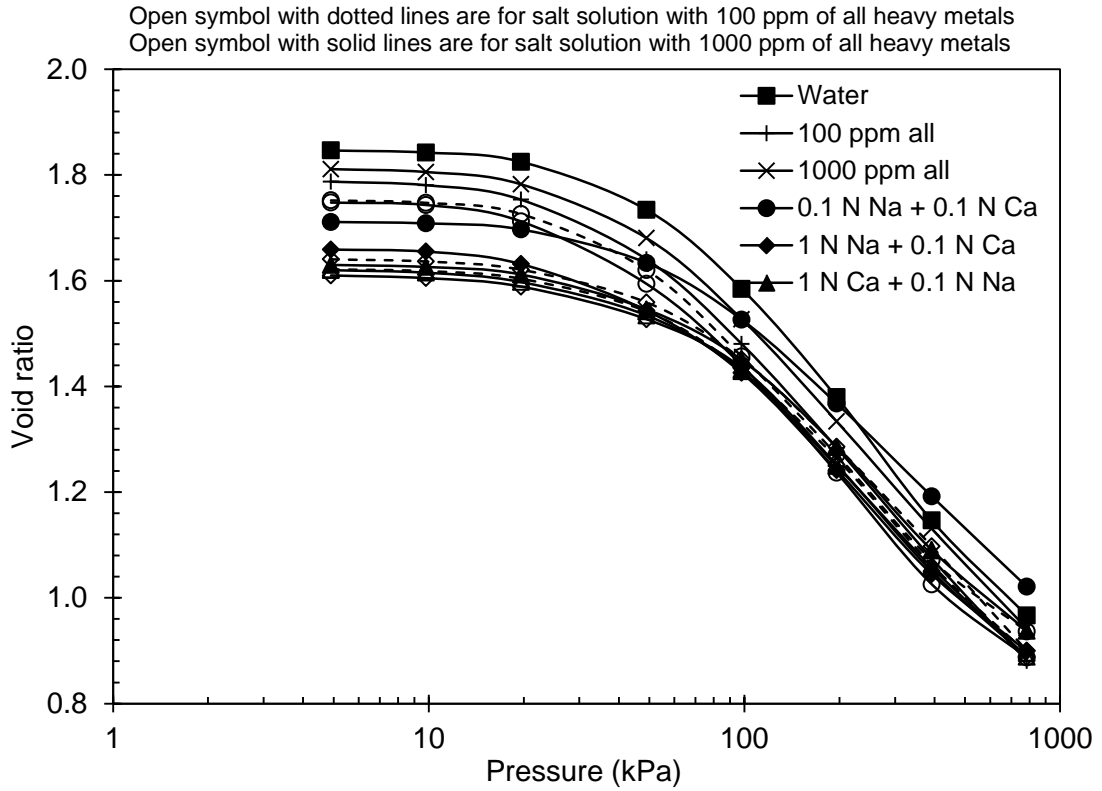


Figure 6.15 Void ratio-pressure plots of Bentonite-A in presence of the combined solutions

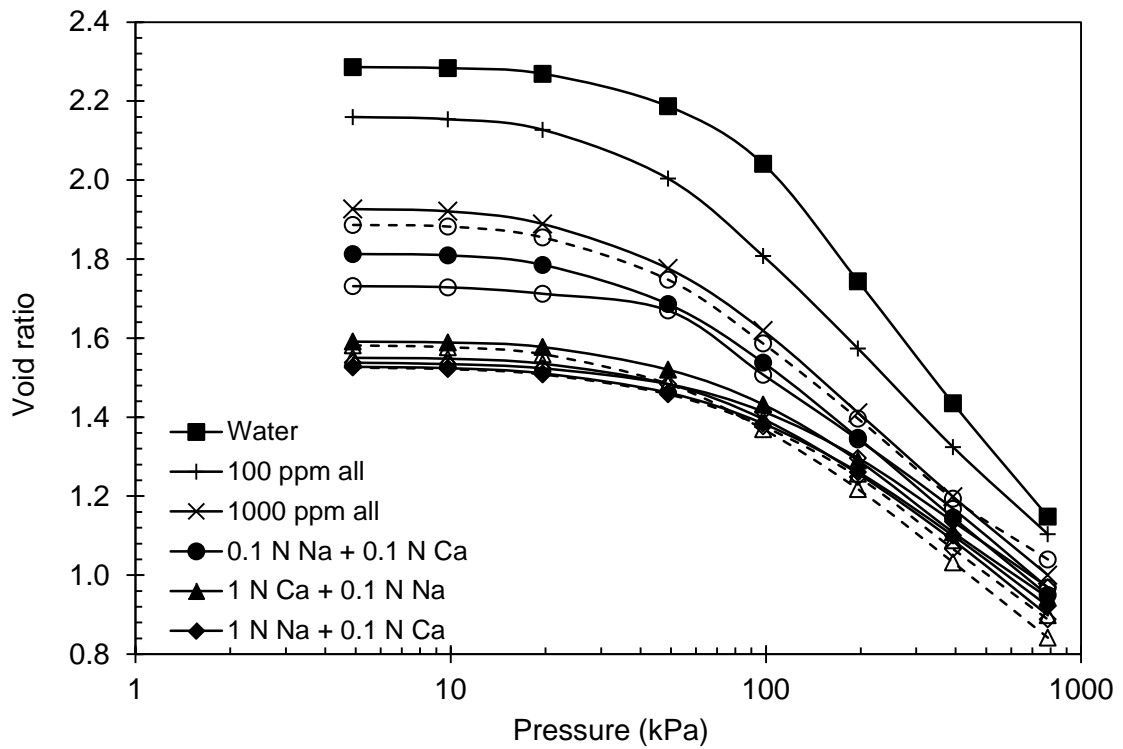


Figure 6.16 Void ratio-pressure plots of Bentonite-B in presence of the combined solutions

Bentonites in the presence of lower concentration exhibited a higher degree of compressibility behaviour than the bentonites subjected to a higher pore fluid concentrations and this difference can be attributed to the internal swelling forces generated by clay-pore fluid interactions that provide resistance to the compressive stresses. As salts get diffused into the bentonite, the inter-particle repulsive stresses between clay particles decreases, thus the clay is compressed to a lower void ratio. Decrease in the void ratio due to an increase in the consolidation pressure was highest for DI water followed by 100 ppm or 1000 ppm combination of heavy metals where the compression decreased marginally. However when added with 1 N $\text{CaCl}_2 + 0.1 \text{ N NaCl}$ and 1 N $\text{NaCl} + 0.1 \text{ N CaCl}_2$, 1000 ppm of the mixtures of all Cu^{2+} , Zn^{2+} and Pb^{2+} solution decreased the compressibility of the bentonites considerably. The combinations of high concentrations of the salts, viz. 1 N $\text{NaCl} + 0.1 \text{ N CaCl}_2 + 1000 \text{ ppm}$ or 1 N $\text{CaCl}_2 + 0.1 \text{ N NaCl} + 1000 \text{ ppm}$, produced the least compressibility for the bentonites. These can be attributed to the reduction in diffuse double layer thickness due to an increase in the salt concentration (Olson and Mesri, 1970; Sridharan et al., 1986b; Mitchell and Soga, 2005).

6.2.6.2. Coefficient of volume change (m_v)

Figures 6.17 and 6.18 show the relationship between coefficient of volume change and consolidating pressures of the bentonites in presence of the mixture of various salt solutions. From the plots, it can be observed that irrespective of the type of permeating fluid, the m_v of the bentonites decreased with the increase in the concentration of mixture of salt solution. The m_v increased initially and then decreased with an increase in the pressure. At lower consolidation pressures, when the void ratio was high, with an increase in pressure a larger reduction in the void spaces took place resulting in a higher m_v . After reaching a peak value, the rate of volume change decreased with a further increase in pressure.

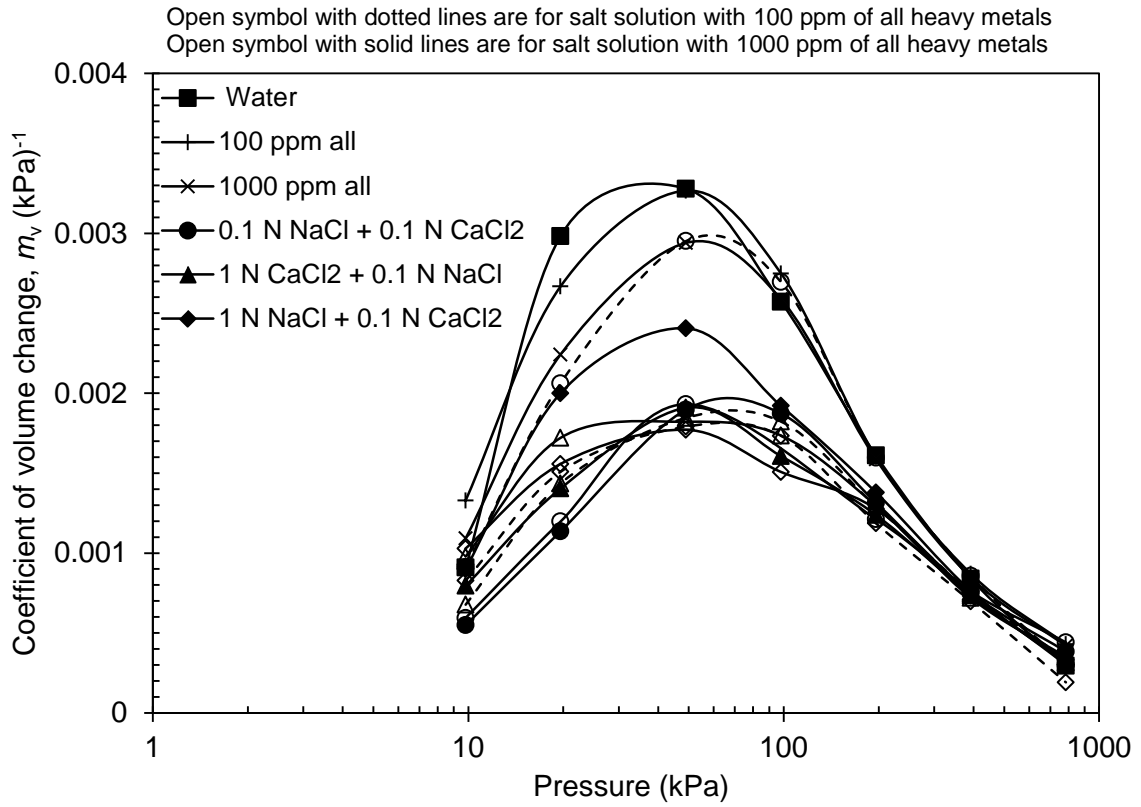


Figure 6.17 Plots between coefficient of volume change and consolidation pressures of Bentonite-A in presence of the combined salt solutions

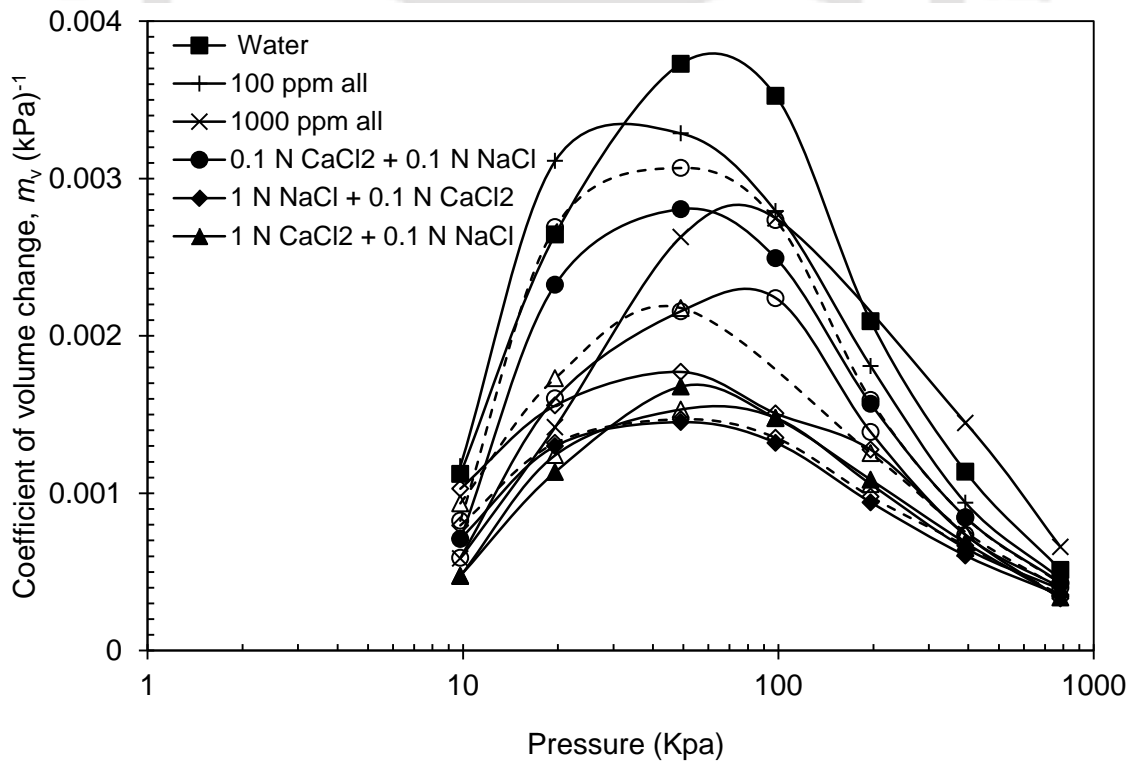


Figure 6.18 Plots between coefficient of volume change and consolidation pressures of Bentonite-B in presence of the combined salt solutions

The combined salts have a pronounced effect on the m_v of both the bentonites in comparison to the individual salt solution. The m_v values of Bentonite-B were higher than that of Bentonite-A, however, at the combination high concentration solutions, m_v values were nearly equal for both bentonites. However, due to permeation of combined salt solution the m_v decreased marginally. When 1000 ppm of heavy metals was added to inorganic salts, the m_v decreased considerably. The decreased in m_v was significant in the presence of combinations of solution having 1 N NaCl or 1 N CaCl₂.

6.2.6.3. Coefficient of consolidation (c_v)

Figures 6.19 and 6.20 show the relationship between coefficient of consolidation and consolidation pressures of the bentonites in the presence of the inorganic salts and heavy metals solutions mixed in different combination. From the plots it is observed that c_v values decreased with increase in the consolidation pressure. The plot also shows that the decrease in c_v with increase in the pressure was significantly affected by the presence of mixed salts. In presence of DI water, with an increase in the pressure from 19.6 kPa to 784.5 kPa, the c_v decreased from 1.60×10^{-4} cm²/sec to 2.28×10^{-5} cm²/sec (7.0 times) for Bentonite-A. However, for the similar range of increase in the pressure the c_v decreased from 2.7×10^{-3} cm²/sec to 6.7×10^{-5} cm²/sec (40.3 times) when Bentonite-A was permeated with the high concentration combination solution. Similarly for Bentonite-B when permeated with DI water, the c_v decreased from 5.48×10^{-5} cm²/sec to 1.03×10^{-5} cm²/sec (5.3 times) due to an increase in the pressure from 19.6 kPa to 784.5 kPa. However, when permeated with the mixed salts, the c_v decreased from 2.90×10^{-3} cm²/sec to 4.14×10^{-5} cm²/sec (70.0 times).

From Figs. 6.19 and 6.20 and, it is also observed that c_v values increased with increase in concentration of the salts. With the increase in the salt concentration the diffuse double layer thickness reduces resulting in higher value of hydraulic conductivity which in turn

increases the c_v of the sample. For Bentonite-A, at a consolidation pressure of 196 kPa, c_v increased from 0.48×10^{-4} cm²/sec in presence of DI water to 0.63×10^{-3} cm²/sec (13.1 times) in presence of 1 N CaCl₂+0.1 N NaCl solution, whereas, it increased to 0.83×10^{-3} cm²/sec (17.3 times) in presence of 1 N CaCl₂+0.1 N NaCl+1000 ppm. When one of the salts was of 1 N concentration, the c_v value of the bentonites were found to be higher than with combinations of 0.1 N solution. The c_v increased from 0.48×10^{-4} cm²/sec in presence of DI water to 0.98×10^{-4} cm²/sec (2.0 times) in presence of 0.1 N NaCl+0.1 N CaCl₂, it increased to 0.83×10^{-3} cm²/sec (17.3 times) in presence of 1 N CaCl₂+0.1 N NaCl and it increased to 0.54×10^{-3} cm²/sec (11.3 times) in presence of 1 N NaCl+0.1 N CaCl₂. The c_v increases marginally in presence of combination of heavy metals. The c_v increased from 0.48×10^{-4} cm²/sec to 0.86×10^{-4} cm²/sec (1.7 times) in presence of 1000 ppm combination of heavy metals. Similarly for Bentonite-B, at a consolidation pressure of 196 kPa, the c_v increased from 0.22×10^{-4} cm²/sec in presence of DI water to 0.67×10^{-3} cm²/sec (30 times) in presence of 1 N CaCl₂+0.1 N NaCl, whereas, it increased to 0.47×10^{-3} cm²/sec (21.3 times) in presence of 1 N CaCl₂+0.1 N NaCl+1000 ppm solution. When one of the salts was of 1 N concentration, the c_v value of the bentonites were found to be higher than that with a combinations of 0.1 N. The c_v value increased from 0.21×10^{-4} cm²/sec in presence of DI water to 0.12×10^{-3} cm²/sec (5.7 times) in presence of 0.1 N NaCl+0.1 N CaCl₂, it increased to 0.67×10^{-3} cm²/sec (31.9 times) in presence of 1 N CaCl₂+0.1 N NaCl and it increased to 0.86×10^{-3} cm²/sec (40.9 times) in presence of 1 N NaCl+0.1 N CaCl₂. The c_v increases marginally in presence of combination of heavy metals. The c_v increased from 0.214×10^{-4} cm²/sec to 0.53×10^{-4} cm²/sec (2.5 times) in presence of 1000 ppm combination of heavy metals. A comparison between the values of the c_v for the two bentonites at the same concentration and consolidation pressure indicates that the Bentonite-B, which has a higher

swelling and liquid limit and lower hydraulic conductivity values, exhibited a lower c_v in comparison to Bentonite-A.

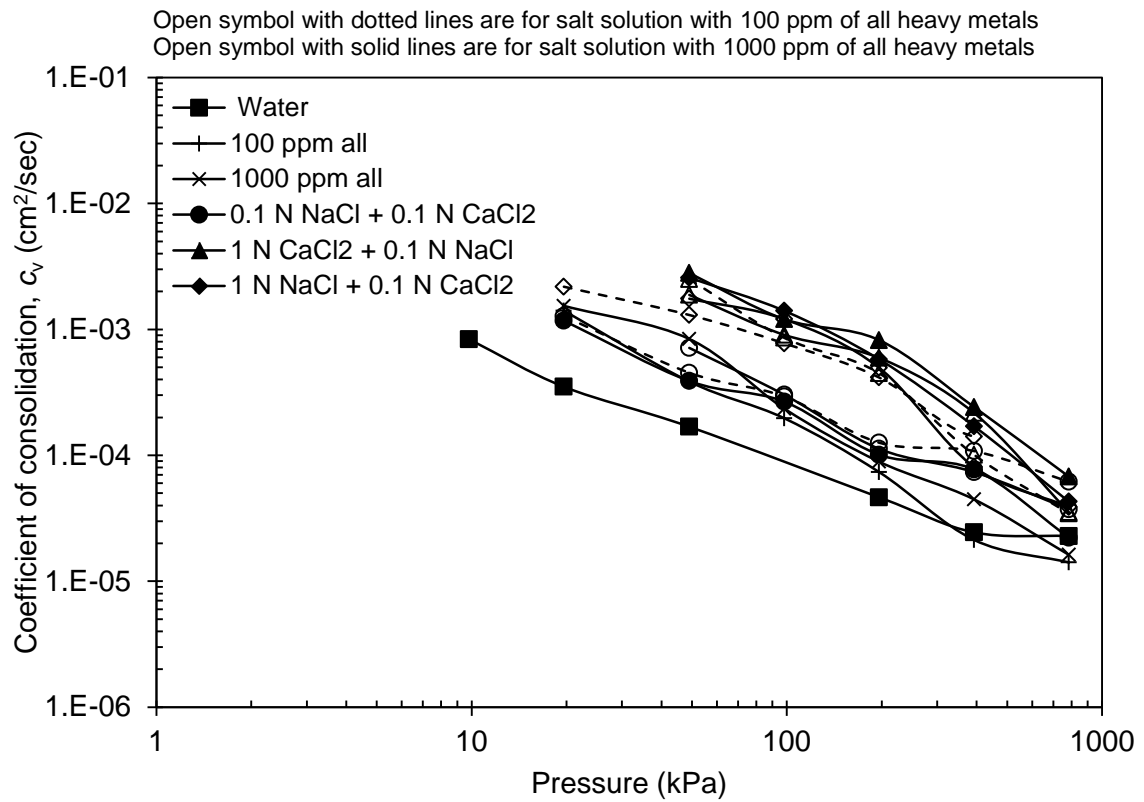


Figure 6.19 Plots between coefficient of consolidation and consolidation pressures of Bentonite-A in presence of the combined solutions

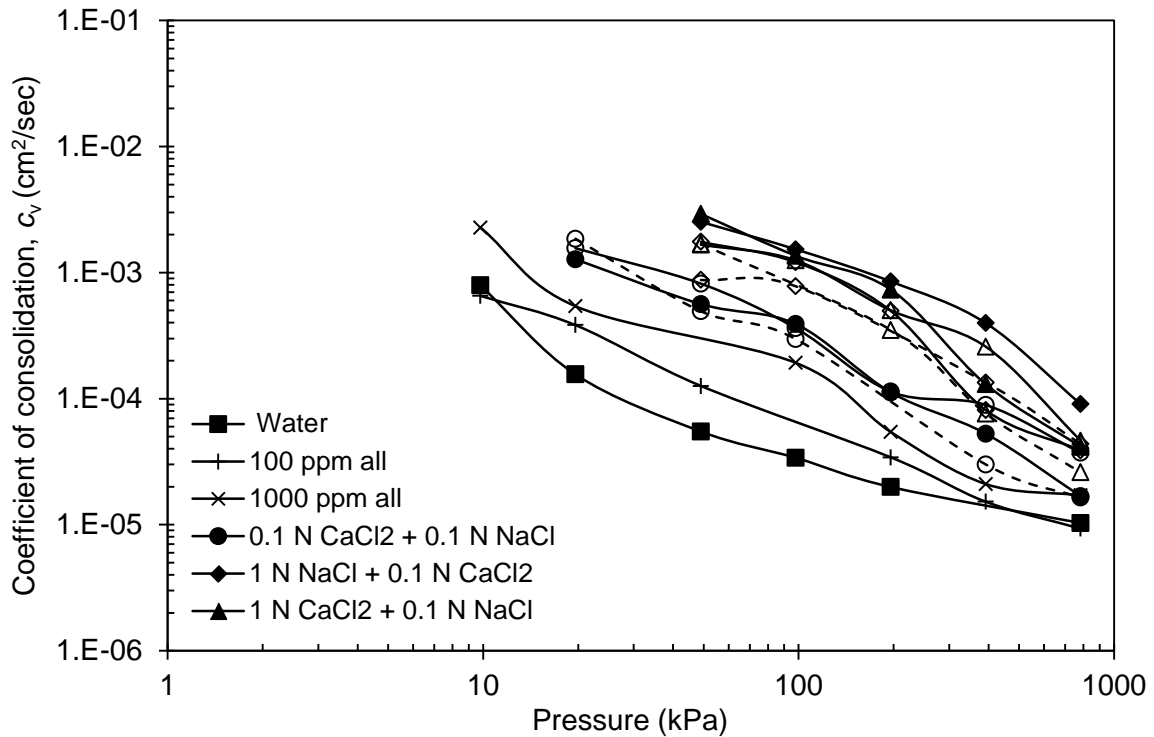


Figure 6.20 Plots between coefficient of consolidation and consolidation pressures of Bentonite-B in presence of the combined solutions

Figures 6.21 and 6.22 shows the relationship between the coefficient of consolidation and liquid limit of the bentonites. The plots show that irrespective of the consolidation pressure, the c_v decreased with the increase in the liquid limit of the bentonite. The decrease in c_v with increase in the liquid limit was prominent at low consolidation pressure compared to at high consolidation pressure. For Bentonite-A, in presence of the permeating liquids and under a consolidation pressure of 784.5 kPa, c_v decreased from 3.54×10^{-5} cm²/sec to 2.28×10^{-5} cm²/sec when the liquid limit increased from 85.8 % to 218.0 %; whereas, under a consolidation pressure of 49.1 kPa, the c_v decreased from 1.87×10^{-3} cm²/sec to 3.5×10^{-4} cm²/sec. For Bentonite-B, in presence of the salt as permeating liquids and under a consolidation pressure of 784.5 kPa, the c_v decreased from 9.03×10^{-5} cm²/sec to 1.03×10^{-5} cm²/sec when the liquid limit increased from 98.5 % to 560.0 %; whereas, under a consolidation pressure of 49.1 kPa, c_v decreased from 2.53×10^{-3} cm²/sec to 1.56×10^{-4} cm²/sec.

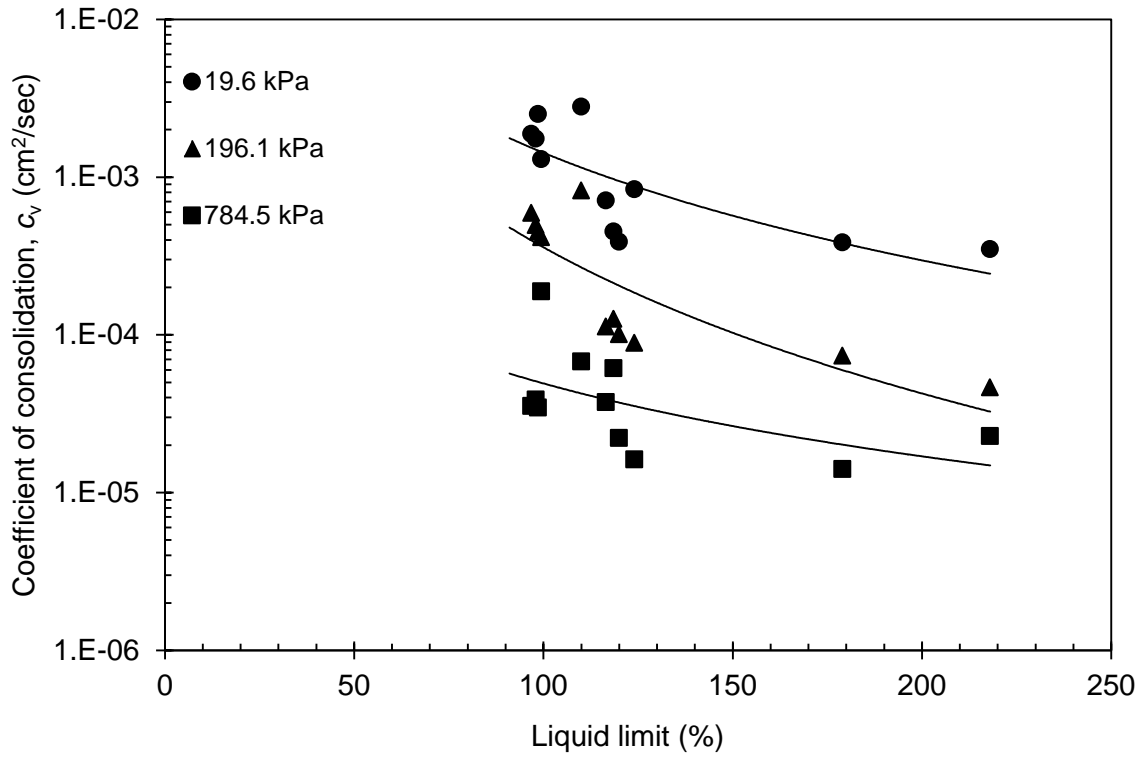


Figure 6.21 Plots between the coefficient of consolidation and the liquid limit of Bentonite-A in presence of the combined solutions

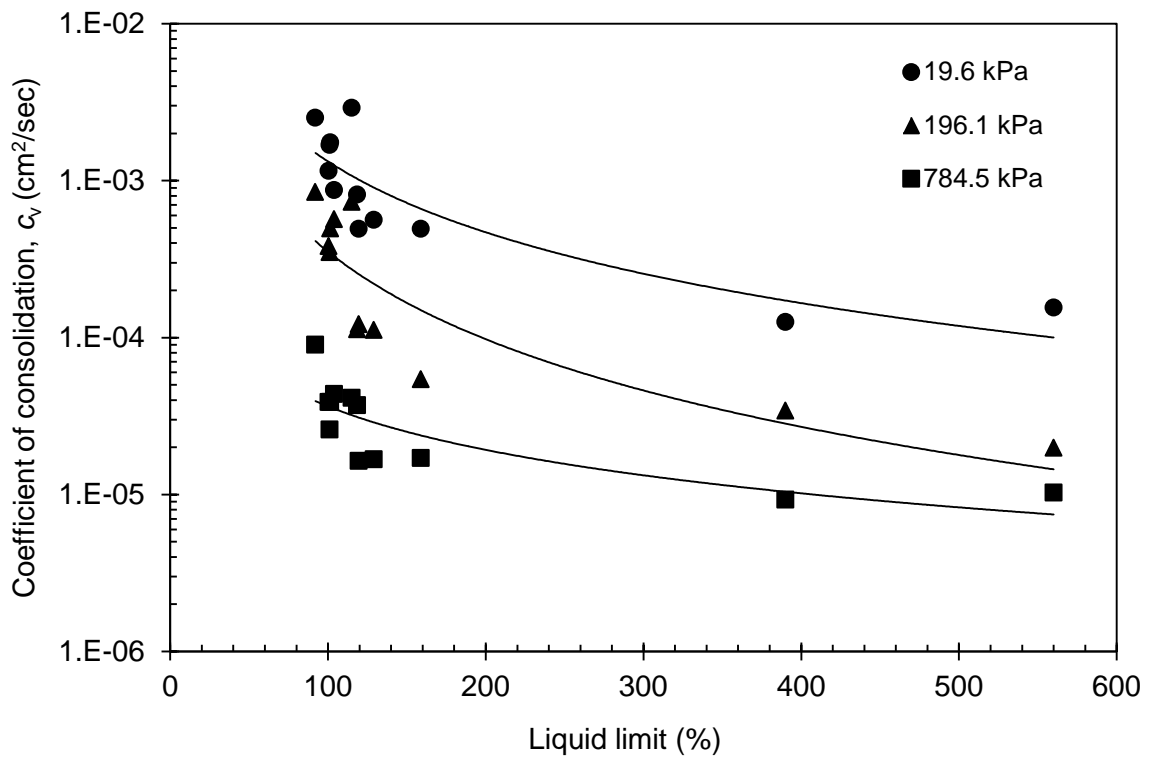


Figure 6.22 Plots between the coefficient of consolidation and the liquid limit of Bentonite-B in presence of the combined solutions

6.2.6.4. Time for 90% of consolidation (t_{90})

Figures 6.23 and 6.24 show the relationship between consolidating pressure and time to complete 90% of consolidation (t_{90}). The plots indicate that with an increase in the consolidation pressure the t_{90} for the sample increases in the presence of the salt solutions. For any given concentration and pressure, a higher value of t_{90} was observed for the Bentonite-B in comparison to Bentonite-A. The plots also show that the increase in t_{90} with the consolidation pressure was gradual in the beginning and significant at higher pressures. However, the increase in t_{90} with the consolidation pressure was less in presence of the salt solutions in comparison to that of DI water. With an increase in the consolidation pressure from 9.8 kPa to 784.5 kPa the t_{90} for the Bentonite-B permeated with DI water increased from 24.0 minutes to 918.1 minutes; whereas, it increased only from 9.1 minutes to 74.0 minutes for combination solutions of high concentrations of heavy metals and inorganic salts. Similarly, for Bentonite-A the t_{90} increased from 13.6 minutes to 445.1 minutes when

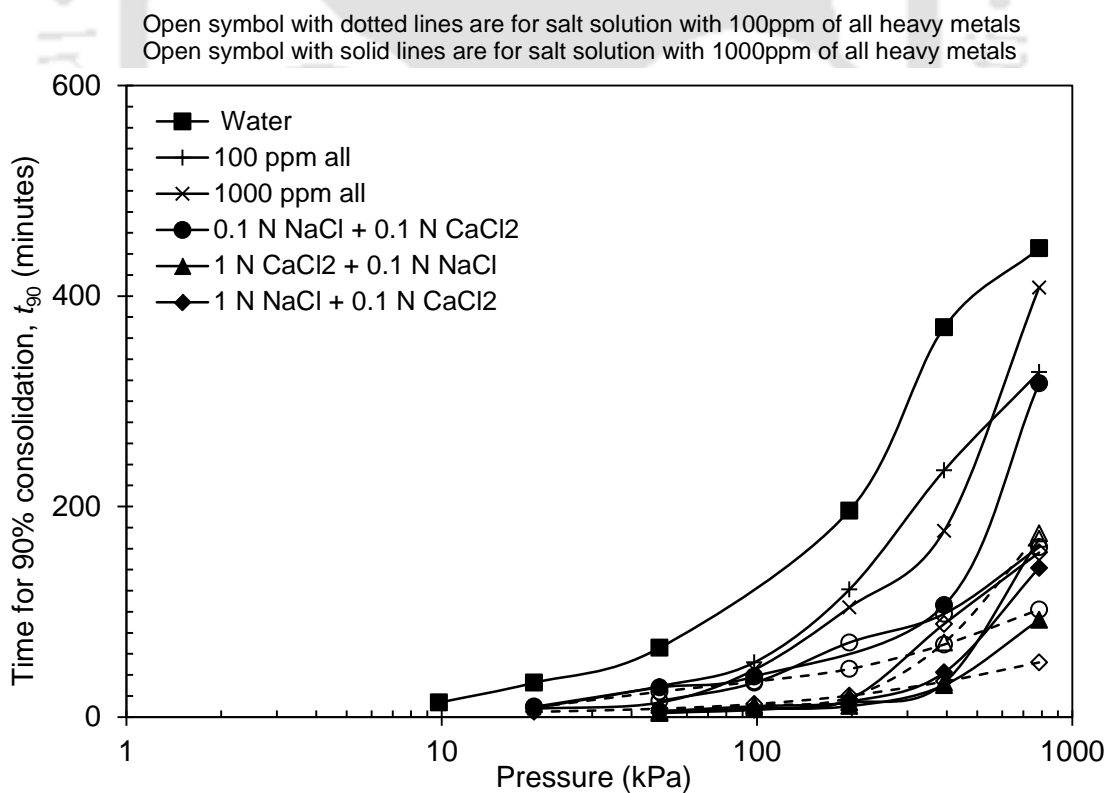


Figure 6.23 Plots between the time for 90% of consolidation and consolidation pressures of Bentonite-A in presence of the combined solutions

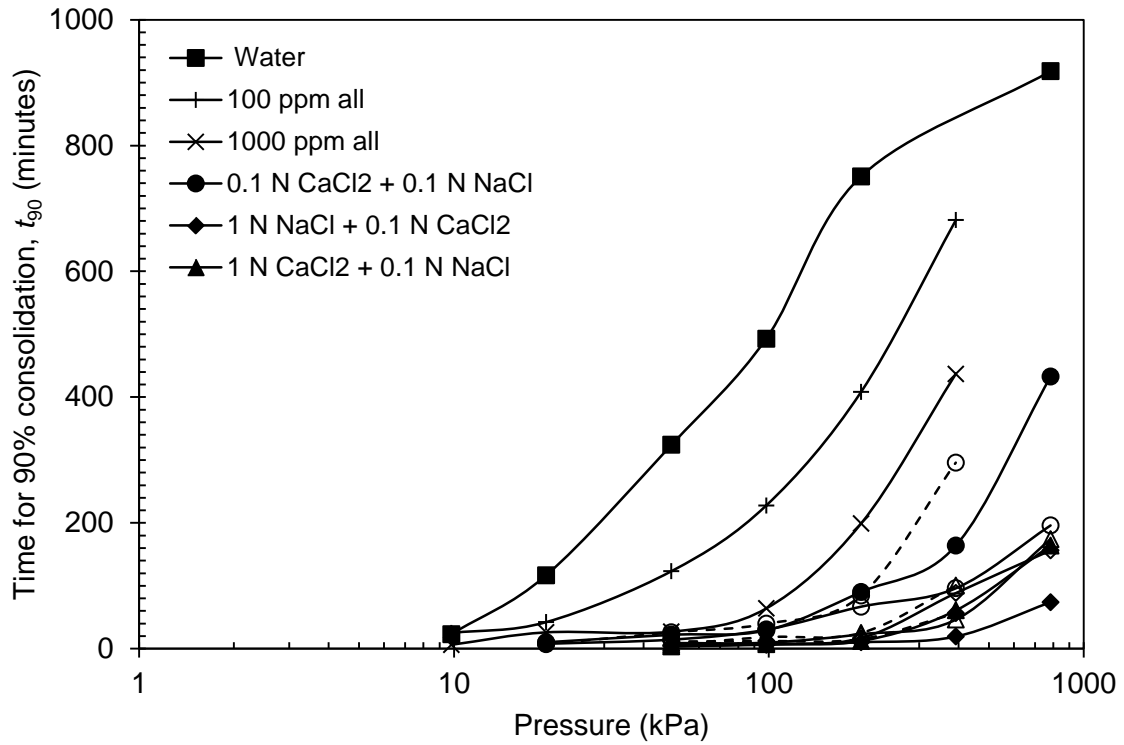


Figure 6.24 Plots between the time for 90% of consolidation and consolidation pressures of Bentonite-B in presence of the combined solutions

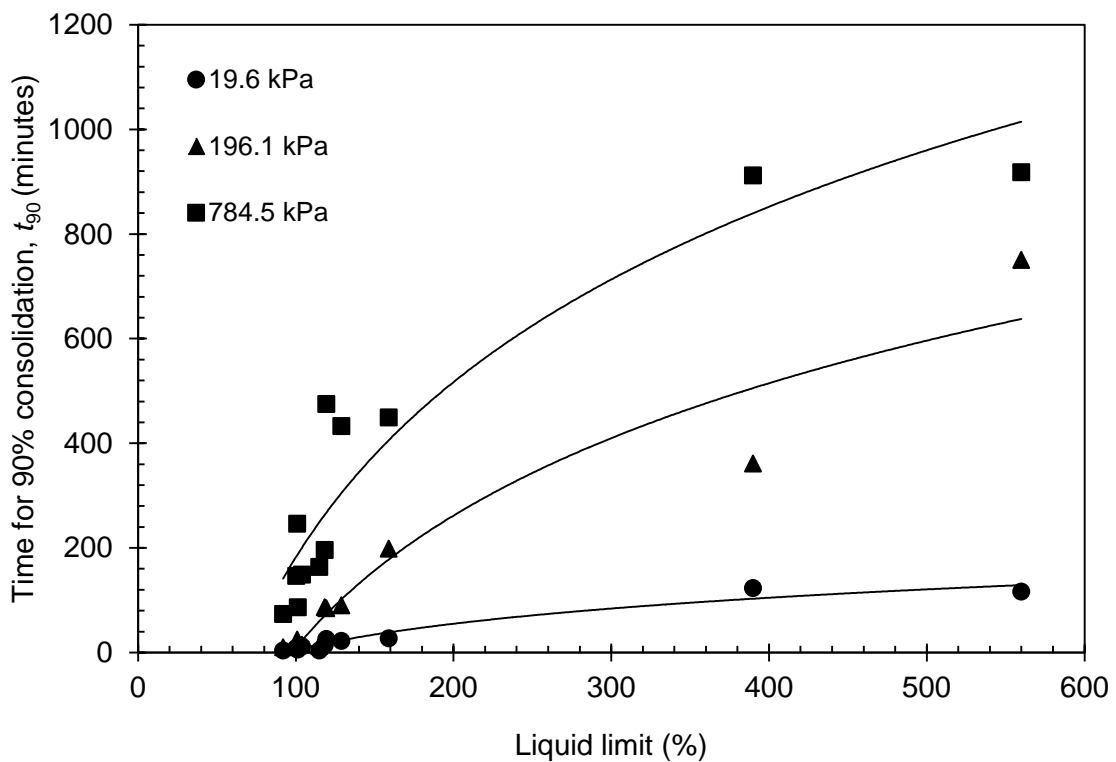


Figure 6.25 Plots between the time for 90% of consolidation and the liquid limit of Bentonite-B in presence of the combined solutions

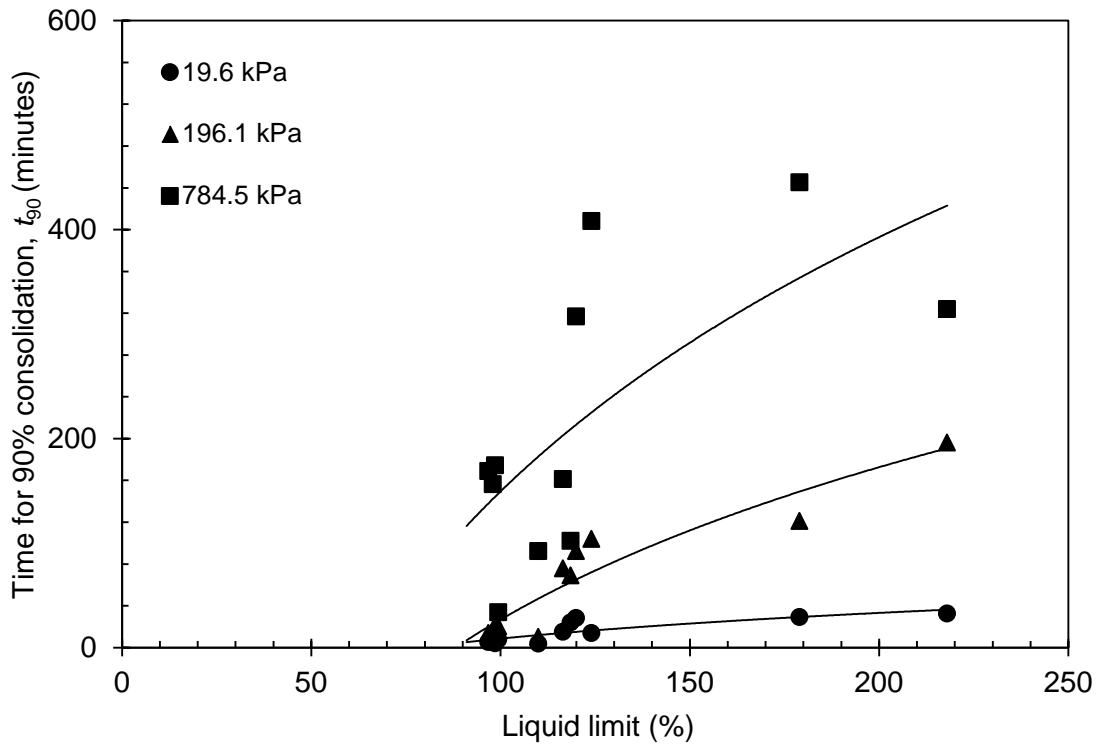


Figure 6.26 Plots between the time for 90% of consolidation and the liquid limit of Bentonite-A in presence of the combined solutions

permeated with DI water. However, on permeation with 1 N of inorganic salts and 1000 ppm of heavy metals it increased only from 12.2 minutes to 52.0 minutes.

Figures 6.25 and 6.26 show the relationship between time for 90% of consolidation and liquid limit of the bentonites. From the plots it is observed that irrespective of the consolidation pressure, the t_{90} increased with the increase in the liquid limit of the bentonite. However, the increase in the t_{90} with the liquid limit was prominent at high consolidation pressure compared to that at low consolidation pressure. For Bentonite-B at a consolidation pressure of 49.1 kPa, with an increase in the liquid limit from 98.5 % to 560.0 % the t_{90} increased from 4.0 minutes to 116.6 minutes; whereas, at consolidation pressure of 784.5 kPa, t_{90} increased from 73.9 minutes to 918.0 minutes. Similarly, for Bentonite-A at a consolidation pressure of 49.1 kPa, t_{90} increased from 5.3 minutes to 32.5 minutes when liquid limit increased from 85.8 % to 218.0 %; whereas, at a consolidation pressure of 784.5 kPa, t_{90} increased from 169.1 minutes to 324.2 minutes.

6.2.6.5. Compression index (C_c)

Similar to the hydraulic conductivity, compression index is an important parameter which needs to be understood for settlement analysis. The data in Table 6.6 shows that C_c decreased marginally due to presence of the mixture of salt solution in comparison to the individual salts. A comparison in the data in Table 6.6 and Fig. 4.41 shows that C_c of the Bentonite-B in presence of 0.1 N CaCl_2 decreased marginally from 0.707 to 0.696 due to addition of 0.1 N NaCl to 0.1 N CaCl_2 solution. For Bentonite-A, the sample exhibited a C_c of 0.699 when permeated with DI water and it decreased to 0.462 (33.1 % decrease) in presence of 1 N CaCl_2 +0.1 N NaCl +1000 ppm. Similarly, for Bentonite-B, the sample exhibited a C_c of 0.934 when permeated with DI water and it decreased to 0.587 (37.2 % decrease) due to permeation of 1 N CaCl_2 +0.1N NaCl +1000 ppm solution. The C_c of Bentonite-B decreased to 0.697 due to permeation of mixtures of 1000 ppm of mixture of Zn^{2+} , Cu^{2+} and Pb^{2+} from a value of 0.715, 0.768 and 0.771 due to permeation of 100 ppm of Zn^{2+} , Cu^{2+} and Pb^{2+} solution respectively.

Table 6.6 Compression index of Bentonite-A and -B in presence of the solutions

Combinations of salt solutions	Bentonite A	Bentonite B
DI water	0.699	0.934
0.1 N CaCl_2 +0.1 N NaCl	0.536	0.696
0.1 N CaCl_2 +1 N NaCl	0.520	0.693
1 N CaCl_2 +0.1 N NaCl	0.570	0.651
100 ppm all HM	0.674	0.802
1000 ppm all HM	0.658	0.697
1 N CaCl_2 +0.1 N NaCl +100 ppm	0.559	0.616
1 N CaCl_2 +0.1 N NaCl +1000 ppm	0.462	0.587
1 N NaCl +0.1 N CaCl_2 +100 ppm	0.515	0.638
1 N NaCl +0.1 N CaCl_2 +1000 ppm	0.509	0.555
0.1 N NaCl +0.1 N CaCl_2 +100 ppm	0.639	0.687
0.1 N NaCl +0.1 N CaCl_2 +1000 ppm	0.564	0.652

6.3. SUMMARY

Since the electrolyte concentration in waste liquids result from concentrations of various chemicals, this study was carried out to investigate the combined effect of inorganic salts and heavy metals on the behaviour of bentonites. Bentonites were studied for their change in the swelling potential, swelling pressure, hydraulic conductivity and consolidation parameters due to the presence of various combinations of mixtures of inorganic salts and heavy metals of various concentrations. The data showed that the combined effect of salts had a significant impact on the liquid limits of both the bentonites in comparison to the effect due to the individual salt solution indicating an additive effect of salt on the liquid limit. Similar to the earlier observation, the effect of combined salt was more significant in Bentonite-B in comparison to Bentonite-A. However, the additive effect becomes marginal when either one or both of the salts is of 1 N concentration. When one of the salts in the mixture was of 1 N concentration, the liquid limit value of the bentonites were found to be slightly lower than the liquid limit of the corresponding bentonite with 1 N concentration. Similarly, the data showed that the combined effect of heavy metals on liquid limit of the bentonites were significant in comparison to the individual effect.

The results showed that the swelling pressure and swelling potential of both the bentonites decreased significantly due to interaction with the mixed salt solution. The effect of mixed salt solution on Bentonite-B was more significant in comparison to Bentonite-A. The combined effect of salts has a significant impact on the swelling pressure of both the bentonites in comparison to the individual salt solution indicating an additive effect of salt on swelling pressure.

The data for the swelling pressure for both the bentonites in presence of heavy metals showed that the combined effect of the heavy metals was quite significant in comparison to the individual effect. However when added with 1 N CaCl_2 + 0.1 N NaCl and 1 N

NaCl+0.1 N CaCl₂, 1000 ppm of the mixtures of all Cu²⁺, Zn²⁺ and Pb²⁺ decreased the swelling pressure considerably. However, the data on the effect of mixed salt solution on the swelling potential indicates that the mixed salt decreased the swelling potential marginally in comparison to the individual salt solution.

The data for the heavy metals concluded that the swelling potential for the mixture of 100 ppm of Cu²⁺, Zn²⁺ and Pb²⁺ solution was observed to be 43.4 % for Bentonite-B. For the individual concentration of 100 ppm of Cu²⁺, Zn²⁺ and Pb²⁺ solution 42.4 %, 42.8 % and 45.4 % swelling potential value was observed respectively (Fig. 6.5). Similar to the effect on the swelling pressure, the addition of the mixtures of 1000 ppm of Cu²⁺, Zn²⁺ and Pb²⁺ solution to the 1 N NaCl+0.1 N CaCl₂ and 0.1 N NaCl+1 N CaCl₂ produced a significant decrease in the swelling potential.

Plots showed that with the increase in the salt concentrations the time taken for the primary swelling reduces. A comparison between the two bentonites in the time-swelling plot showed that at the same time elapsed, the percentage of swelling was more for Bentonite-B in comparison to Bentonite-A. Irrespective of the bentonite quality, swelling was least in presence of high concentration combination solutions. In case of the combinations having 0.1 N CaCl₂ or 0.1 N NaCl or the heavy metals combined, the percentage of swelling over time elapsed was more for Bentonite-B compared to Bentonite-A, whereas for the solutions having combinations of 1 N NaCl or 1 N CaCl₂ and heavy metals, the swelling for both the bentonites are nearly equal.

It was observed from the plots that there was a significant decrease in void ratio in presence of high concentration combination solutions. Bentonites in presence of less electrolyte pore fluid concentrations show higher compression than the bentonite samples subjected to high electrolyte pore fluid concentrations because of the internal swelling forces generated by clay-pore fluid interactions that provide resistance to the compressive stresses. As salts get

diffused into the bentonite, the inter-particle repulsive stresses between clay particles decreases, thus the clay is compressed to a lower void ratio.

The results showed that the hydraulic conductivity increased in presence of the mixed solutions and the hydraulic conductivity for the combination mixture were higher than when the salts are applied as single species and the extent of increase in hydraulic conductivity due to addition of salt solution was different for the different combination solutions.. When solutions of inorganic salts and heavy metals are applied in a combined manner, the total concentrations of the ions were higher in comparison to when they were applied individually as single species.

The data for the compression index (C_c) shows that the C_c decreased marginally due to presence of the mixture of salt solution in comparison to the individual salts. The combined salts are found to have a pronounced effect on coefficient of volume change (m_v) of both the bentonites in comparison to the individual salt solution. The m_v values of Bentonite-B were higher than that of Bentonite-A, however, at the combination of high concentration of solutions, m_v was observed to be nearly equal for both bentonites. From the results it was concluded that the coefficient of consolidation (c_v) increased due to addition of the mixtures of inorganic salt solution, however, it increased marginally in presence of combination of heavy metals.

From the combination of salts, it was concluded that the hydraulic, swelling and compressibility behaviour of bentonites depend more on the quality of the bentonite at low concentrations of the permeant whereas for high concentrations, the quality of bentonite is dominated by the concentrations of the permeant.

CONCLUSIONS AND SCOPE FOR THE FUTURE WORK**7.1. CONCLUSIONS**

This study was carried out to investigate the effect of inorganic salts and heavy metals on the behaviour of bentonites. Bentonites were studied for their change in the Atterberg limits, free swelling, swelling potential, swelling pressure, hydraulic conductivity and consolidation parameters due to the presence of various inorganic salts and heavy metals of various concentrations, individually as well as combination of each other. To study the influence of bentonite's mineralogical properties on these parameters in the presence of salt solution, two bentonites of different mineralogical composition were chosen. Similarly, to study the impact of initial compaction water content on the behaviour of bentonite, bentonite samples were compacted at their respective maximum dry density (MDD)-optimum moisture content (OMC) and MDD-5% dry of OMC. Following are the major conclusions from the present study;

- 1) The liquid limit and free swelling of the bentonites decreased significantly due to the inclusion of inorganic salt and heavy metals in the pore liquid. However, the plastic limit increased for inorganic salts. Bentonite with NaCl solution exhibited a higher liquid limit and plastic limit in comparison to the same concentration of CaCl₂ solution. The liquid limit and free swelling of the Bentonite-B, which is marked as a high quality bentonite, decreased considerably in comparison to Bentonite-A due to the increase in the salt concentration.
- 2) The swelling pressure and swelling potential of the bentonites decreased with the increase in the salts and metal ion concentration. For a given concentration, swelling pressure of Bentonite-B, a high quality bentonite marked by higher cation exchange

capacity, swelling capacity and exchangeable sodium percentage, was higher than that of the Bentonite-A which was a low quality bentonite. The swelling pressure and swelling potential for the samples compacted on dry side of OMC was higher than for samples compacted at OMC.

- 3) Irrespective of the initial compaction condition, the hydraulic conductivity of the bentonites increased with an increase in the inorganic salt and heavy metal ion concentrations. The effect of CaCl_2 solution on the hydraulic conductivity was more significant in comparison to NaCl solution. The increase in the hydraulic conductivity with metal ion concentration is more prominent at higher salt concentration. The hydraulic conductivity values of low swelling bentonite (i.e. Bentonite-A) on permeation with the solutions were higher than those of high swelling bentonite (i.e. Bentonite-B). Higher value of hydraulic conductivity was observed for bentonites compacted at dry of OMC in comparison to the samples compacted at OMC.
- 4) From the void ratio versus pressure relationships for both the bentonites it was observed that the decrease in the void ratio due to the consolidation pressure was higher for the samples with lower salt concentration and the overall compression decreased with increasing the salt concentration.
- 5) A higher value of theoretical void ratio obtained for both the bentonites from the diffuse double layer theory at lower consolidation pressure; however, with an increase in the consolidation pressure the value of theoretically obtained void ratio exceeds the experimentally obtained value. However, with the salt as a pore fluid a lower value of theoretical void ratio was obtained for both the bentonites.
- 6) Time swelling plots showed that with the increase in inorganic salt and heavy metal ion concentrations, the time taken for the primary swelling reduces. Irrespective of the bentonite quality, swelling was least in presence of high concentration solutions. The

bentonites compacted at dry of OMC exhibited a higher percentage of swelling in comparison to the samples compacted at OMC indicating the influence of the initial compaction condition on the swelling behaviour.

- 7) Result showed that the consolidation parameters such as compression index (C_c), coefficient of volume change (m_v), coefficient of consolidation (c_v) and time required for the 90% of consolidation (t_{90}) depends upon the mineralogical properties of the bentonite, pore water chemistry and the consolidation pressure. It was observed that the C_c , m_v and t_{90} of the bentonites decreased; whereas, c_v increased with the increase in salt concentration indicating specimens consolidated faster in salt solution in comparison to DI water. Irrespective of the salt solution present in pore water, c_v was found to decrease whereas t_{90} increased with increase in the consolidation pressure. It was also observed that the bentonite of higher quality exhibited higher values of t_{90} , m_v and C_c in comparison to lower quality bentonite. With increase in the liquid limit and free swelling of the bentonite c_v was found to be decreased, whereas, the t_{90} increased irrespective of the overburden pressure. Samples compacted at dry of OMC has higher c_v , m_v values than samples compacted at OMC.
- 8) The combined effect of salts had a significant impact on the liquid limits, swelling pressure and swelling potential of both the bentonites in comparison to the effect due to the individual salt solution indicating an additive effect of salt on these properties. Irrespective of the bentonite quality, swelling was least in presence of high concentration combination solutions. From the combination of salts, it was observed that the hydraulic, swelling and compressibility behaviour of bentonites depend more on the quality of the bentonite at low concentrations of the permeant whereas for high concentrations, the quality of bentonite is dominated by the concentrations of the permeant. The results showed that the hydraulic conductivity increased in presence of

the mixed solutions and the hydraulic conductivity for the combination solutions were higher than when the salts are applied as single species and the extent of increase in hydraulic conductivity due to addition of salt solution was different for the different combination solutions.

- 9) A comparison between the two bentonites concluded that salt has a significant effect on Bentonite-B. Bentonite-B, which has a high liquid limit, swelling capacity, SSA, CEC and ESP and termed as high quality bentonite, undergoes a large change in liquid limit, free swelling, swelling pressure and hydraulic conductivity due to increase in the salt concentration and metal ion concentration. It was also observed that the effect of the salt on the properties of the bentonites depends on the mineralogical composition of bentonite, salt type, salt concentration, pH value and initial compaction condition of the bentonite.

7.2. SCOPE FOR THE FUTURE WORK

The study of the behaviour of the bentonites is far from being a closed issue. Further work should be concentrated in the following area:

- 1) Since the clay liner generally consists of layers of compacted bentonite along with geosynthetic clay liners (GCL), further studies need to be carried out to investigate the behaviour of bentonite combined with GCL in presence of salt solutions.
- 2) Shear strength and shrinkage are the two other important factors which control the suitability of a material for the use as a landfill liner material; further tests can be conducted to investigate these parameters of the bentonites in presence of salt solutions.
- 3) Since the clay liner is generally get exposed to various kind of leachates produced by various kind of wastes, further tests should be carried out study the effect of different leachates on the behaviour of bentonite.

REFERENCES

- Abollino, O., Aceto, M., Malandrino, M., Sarzanini, C. and Mentasti, E. (2003). Adsorption of heavy metals on Na-Montmorillonite, Effect of pH and organic substances, *Water Research*, 37, 1619-1627.
- Alther, G., Evans, J.C., Fang, H.Y. and Witmer, K. (1985). Influence of inorganic permeants upon the permeability of bentonite, *Hydraulic barriers in soil and rock*, ASTM STP 874, 64-73.
- ASTM (2000). Standard test methods for liquid limit, plastic limit, and plasticity index of soils, D 4318, American Society for Testing and Materials, Philadelphia.
- ASTM (2001). Standard test method for swell index of clay mineral component of geosynthetic clay liners, D 5890, American Society for Testing and Materials, Philadelphia.
- ASTM (1996). Standard test method for one-dimensional consolidation properties of soils, D 2435, American Society for Testing and Materials, Philadelphia.
- ASTM (2012). Standard test methods for laboratory compaction characteristics of soil using standard effort, D 698, American Society for Testing and Materials, Philadelphia.
- Baille, W., Tripathy, S. and Schanz, T. (2010). Swelling pressures and one-dimensional compressibility behaviour of bentonite at large pressures, *Applied Clay Science*, 48, 324-333.
- Barbour, S. and Fredlund, D. (1989). Mechanism of osmotic flow and volume change in clay soils, *Canadian Geotechnical Journal*, 26(4), 551-562.
- Barbour, S.L. and Yang, N. (1993). A review of the influence of clay-brine interactions on the geotechnical properties of Ca-montmorillonitic clayey soils from western Canada, *Canadian Geotechnical Journal*, 30(6), 920-934.
- Beede, D.N. and Bloom, D.E. (1995). The economics of municipal solid waste, *World Bank Research Observer*, 10(2), 113-150.
- Bohnhoff, G. and Shackelford, C. (2014). Consolidation behaviour of polymerized bentonite-amended backfills, *Journal of Geotechnical and Geoenvironmental Engineering*, 140(5), 04013055.
- Bolt, G.H. (1956). Physico and chemical analysis of the compressibility of pure clays, *Geotechnique*, 6(1), 86-93.
- Bouazza, A., Liu, Y. and Gates, W.P. (2013). Effect of strong acidic leachates on hydraulic conductivity of a needle punched GCL, *Heapleach Conference*, Vancouver, Canada.
- Burland, J.B. (1990). On the compressibility and shear strength of natural clays, *Geotechnique*, 40(3), 329-378.

Castellanos, E., Villar, M.V., Romero, E., Lloret, A. and Gens, A. (2008). Chemical impact on the hydro-mechanical behaviour of high-density FEBEX bentonite, *Physics and Chemistry of the Earth*, 33, 516–526.

Cerato, A.B. and Lutenecker, A.J. (2002). Determination of surface area of fine-grained soils by the ethylene glycol monoethyl ether (EGME) method, *Geotechnical Testing Journal*, 25, 1–7.

Chalmin, P. and Gaillochet, C. (2009). From waste to resource, An abstract of world waste survey, Cyclope, Veolia Environmental Services, Edition Economica, France.

Chapman, D.L. (1913). A contribution to the theory of electrocapillarity, *Philosophical Magazine*, 25(6), 475–481.

Chapman, H.D. (1965). Cation exchange capacity. In: *methods of soil analysis, part 2 Chemical and microbiological properties*, 2nd edition, Soil Science Society of America, Madison, Wisconsin, USA, 891-895.

Chen, F.H. (1975). *Foundation on Expansive Soils*, *Developments in Geotechnical Engineering* 12, Elsevier Scientific, New York.

Christensen, T.H. and Kjeldsen, P. (1989). Basic biochemical processes in landfills, Chapter 2.1 in *Sanitary Landfilling: Process, Technology and Environmental Impact*, Christensen, T.H., Cossu, R., and Stegmann, R., Eds., Academic Press, London, UK, 29.

Daniel, D.E. (1984). Predicting hydraulic conductivity of clay liners, *Journal of Geotechnical Engineering*, ASCE, 110(4), 465-478.

Daniel, D.E. and Benson, C.H. (1990). Water content-density criteria for compacted soil liners, *Journal of Geotechnical engineering*, ASCE, 116(12), 1811-1830.

Daniel, D.E. and Wu, Y.K. (1993). Compacted Clay Liners and Covers for Arid Sites, *Journal of Geotechnical Engineering*, ASCE, 119(2), 223-237

Das, B.M. (2006). *Principles of Geotechnical Engineering*, 5th edition, Thomson, Toronto.

Du, Y.J., Fan, R.D., Reddy, K.R., Liu, S.Y. and Yang, Y.L. (2015). Impacts of presence of lead contamination in clayey soil-calcium bentonite cutoff wall backfills, *Applied Clay Science*, 108, 111-122.

Egloffstein, T.A. (1995). Properties and test methods to assess bentonite used in geosynthetic clay liners, *Geosynthetic Clay Liners*, Balkema, Rotterdam, The Netherlands, 51–72.

Egloffstein, T.A. (1997). Ion exchange in geosynthetic clay liners, *Geotechnical Fabrics Report*, 15(5), June/July 1997, St. Paul, USA.

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

Gouy, G. (1910). Sur la constitution de la charge a la surface d'un electrolyte, *Journal of Physics*, 9(4), 457-468.

Grim, R.E. (1968). *Clay Mineralogy*, 2nd edition, McGraw-Hill, New York.

Grim, R.E. and Guven, N. (1978). *Bentonites: Geology, mineralogy, property and uses*, *Developments in Sedimentology*, 24, Elsevier, Amsterdam.

Haug, M. D. and Boldt-Leppin, B. (1994). Influence of polymers on the hydraulic conductivity of marginal quality bentonite-sand mixtures, *Hydraulic conductivity and waste contaminant transport in soil*, ASTM STP 1142, D. E. Daniel and S. J. Trautwein, eds., ASTM, 407–421.

Hoornweg, D. and Bhada-Tata, P. (2012). *What a waste: A global review of solid waste management*, Washington D.C., World Bank, Urban Development & Local Government Unit, March 2012, No. 15, 98.

Hotz, W.G. and Gibbs, J.J. (1956). Engineering properties of expansive clays, *ASCE Transaction Paper No 2814(121)*, 641-677.

Howell, J.L. and Shackelford, C.D. (1997). Hydraulic conductivity of sand admixed processed clay mixtures, In: *Proceedings of 14th international conference on soil mechanics and foundation engineering*, Hamburg, 1, Balkema Publishers, Rotterdam, 307–310.

Chai, J.C. and Miura, N. (2002). Comparing the performance of landfill liner systems, *Journal of Material Cycles and Waste Management*, 4,135-142.

Jefferson, I. and Rogers, C.D.F. (1998). Liquid limit and the temperature sensitivity of clays, *Engineering Geology*, 4(9), 95-109.

Jo, Y. H., Katsumi, T., Benson, C.H. and Edil, T.B. (2001). Hydraulic conductivity and swelling of non-prehydrated GCLs permeated with single-species salt solutions, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 127(7), 557-567.

John, R.A. and Evangeline, Y.S. (2009). Variation in Engineering Properties of Different Bentonites due to Acetic Acid, *10th National Conference on Technological Trends*, 78-81.

Kashir, M. and Yanful, E.K. (2001). Hydraulic conductivity of bentonite permeated with acid mine drainage, *Canadian Geotechnical Journal*, 38, 1034-1048.

Kittrick, J.A. (1969). Interlayer forces in montmorillonite and vermiculite, *Soil Science Society of America Proceedings*, 33, 217–222.

Kjeldsen, P., Barlaz, M.A., Rooker, A.P., Baun, A., Ledin, A., and Christensen, T.H. (2002). Present and long-term composition of MSW landfill leachate: A review, *Critical Reviews in Environmental Science and Technology*, 32(4), 297–336.

Kjellander, R., Marcelja, S. and Quirk, J. (1988). Attractive double layer interactions between calcium clay particles, *Journal of Colloid and Interface Science*, 126(1), 194–211.

Kolstad, D.C., Benson, C.H. and Edil, T.B. (2004). Hydraulic conductivity and swell of nonprehydrated geosynthetic clay liners permeated with multispecies inorganic solutions, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 130(12), 1236-1249.

Komine, H. and Ogata, N. (1996). Prediction for swelling characteristics of compacted bentonite, *Canadian Geotechnical Journal*, 33,11-22.

Komine, H. (2008). Theoretical equations on hydraulic conductivities of bentonite-based buffer and backfill for underground disposal of radioactive wastes, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 134(4), 497-508.

Laird, D.A. (2006). Influence of layer charge on swelling of smectites, *Applied Clay Science*, 34, 74-87.

Laird, D.A. (1996). Model for crystalline swelling of 2:1 phyllosilicates, *Clays and Clay Minerals*, 44, 553–559.

Lambe, T.W. (1954). The permeability of compacted fine-grained soils, *Special Technical Publication*, 163, ASTM, Philadelphia, 56-67.

Lambe, T.W. (1958a). The structure of compacted clay, *Journal of the Soil Mechanics & Foundations Division*, ASCE, 84, SM2, 1654-1-34.

Lambe, T.W. (1958b). The engineering behaviour of compacted clay, *Journal of the Soil Mechanics & Foundations Division*, ASCE, 84, SM2, 1655-1-35.

Lee, J. M. and Shackelford, D. (2005). Impact of bentonite quality on hydraulic conductivity of geosynthetic clay liners, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 131(1), 64–77.

Li, L.Y. (2003). Multi-component of heavy metal contaminants adsorptivity and compatibility onto variable charge clay mineral, *Clay Science*, 12,73-80.

Li, L.Y. and Li, F. (2001). Heavy metal sorption and hydraulic conductivity studies using three types of Bentonite Admixes, *Journal of Environmental Engineering*, 127(5), 420-429.

Lin, L. and Benson, C. (2000). Effect of wet-dry cycling on swelling and hydraulic conductivity of GCLs, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 126(1), 40–49.

Lo, I., Luk, A. and Yang, X. (2004). Migration of heavy metals in saturated sand and bentonite / soil admixture, *Journal of Environmental Engineering*, ASCE, 130(8), 906-909.

Ludwig, H. (1979). A study of some aspects of dispersive clay particle interaction. Master thesis, Department of Civil Engineering and Applied Mechanics, McGill University, 201.

Lutz, J. F. and Kemper, W. D. (1958). Intrinsic permeability of clay as affected by clay-water interaction, *Soil Science*, 88, 83–90.

Madsen, F. T. and Vonmoos, M. (1989). The swelling behaviour of clays, *Applied Clay Science*, 4(2), 143–156.

Madsen, F.T. and Mitchell, J.K. (1989). Chemical effects on clay fabric and hydraulic conductivity, *The Landfill, Lecture Notes in Earth Sciences*, 20, 201-251.

Malik, M., Mustafa, M. A. and Letey, J. (1992). Effect of mixed Na/Ca solutions on swelling, dispersion, and transient water flow in unsaturated montmorillonitic soils, *Geoderma*, 52, 17–28.

Martin, J.P., Richards, S.J. and Pratt, P.F. (1964). Relationship of exchangeable Na percentage at different soil pH levels to hydraulic conductivity, *Proceedings of Soil Science Society of America Journal*, 28, 620–622.

Mc Neal, B.L., Layfield, D.A., Norvell, W.A. and Rhoades, J.D. (1968). Factors influencing hydraulic conductivity of soils in the presence of mixed salt solutions, *Soil Science Society of America Proceedings*, 32, 187-190.

Mc Bride, M. (1994). *Environmental chemistry of soils*, Oxford University Press, New York.

Mc Neal, B. L., Norwell, W. A. and Coleman, N. T. (1966). Effect of solution composition on the swelling of extracted soil clays, *Soil Science Society of America Proceedings*, 30, 313–317.

Mesri, G. and Olson, R.E. (1971a). Consolidation characteristics of montmorillonite, *Geotechnique*, 21(4), 341-352.

Mesri, G. and Olson, R.E. (1971b). Mechanisms controlling the permeability of clays, *Clay and Clay Minerals*, 19, 151-158.

Mishra, A.K., Dhawan, S. and Rao, S.M. (2008). Analysis of swelling and shrinkage behaviour of compacted clays, *Geotechnical and Geological Engineering*, 26(3), 289-298.

Mishra, A. K., Ohtsubo, M., Li, L. and Higashi, T. (2011). Controlling factors of the swelling of various bentonites and their correlations with the hydraulic conductivity of soil-bentonite mixtures, *Applied Clay Science*, 52, 78–84.

Mishra, A. K., Ohtsubo, M., Li, L., Higashi, T. and Park, J. (2009). Effect of salt of various concentrations on liquid limit, and hydraulic conductivity of different soil-bentonite mixtures, *Environmental Geology*, 57(5), 1145-1153.

Mishra, A.K., Ohtsubo, M., Li, L. and Higashi, T. (2005). Effect of salt concentrations on the permeability and compressibility of soil-bentonite mixtures, *Journal of the faculty of agriculture, Kyushu university, Fukuoka, Japan*, 50(2), 837-849.

Mishra, A.K., Ohtsubo, M., Li, L.Y. and Higashi, T. (2010). Influence of the bentonite on the consolidation behaviour of soil-bentonite mixtures, *Carbonates and Evaporites*, 25, 43-49.

Mitchell, J. K. and Jaber, M. (1990). Factors controlling the long-term properties of clay liners, Waste Containment Systems, Geotechnical Special Publication No. 26, ASCE, 84–105.

Mitchell J. K. and Soga, K. (2005). Fundamentals of soil behavior, 3rd edition, Wiley, New York.

Murray, H.H. (2000). Traditional and new applications for kaolin, smectite and palygorskite: A general overview, Applied Clay Science, 17, 207-221.

Nakano, A., Li, L.Y., Ohtsubo, M. and Mishra, A.K. (2008). Lead retention mechanisms and hydraulic conductivity studies of various bentonites for geoenvironment applications, Environmental Technology, 29, 505-514.

Norrish, K. (1954). The swelling of montmorillonites, Discussions of Faraday Society, 18, 120–134.

Norrish, K. and Quirk, J. (1954). Crystalline swelling of montmorillonite; use of electrolyte to control swelling, Nature, 173, 255–257.

Olgun, M. and Yildiz, M. (2010). Effect of organic fluids on the geotechnical behaviour of a highly plastic clayey soil, Applied Clay Science, 48, 615-621.

Olson, R. E. and Mesri, G. (1970). Mechanisms controlling the compressibility of clay, Journal of the Soil Mechanics and Foundations Division, ASCE, 96(6), 1863–1878.

Onikata, M., Kondo, M., Hayashi, N. and Yamanaka, S. (1999). Complex formation of cation-exchanged montmorillonites with propylene carbonate: Osmotic swelling in aqueous electrolyte solutions, Clays and Clay Minerals, 47(5), 672–677.

Ouhadi, V.R. and Sedighi, M. (2003). Variation of experimental results of oedometer testing due to the changes of pore fluid, In Deformation Characteristics of Geomaterials, Taylor & Francis, 299-304.

Ouhadi, V.R., Yong, R.N. and Sedighi, M. (2006). Influence of heavy metal contaminants at variable pH regimes on rheological behaviour of bentonite, Applied Clay Science, 32, 217-231.

Peirce, J.J., Sallfors, G., Peel, T.A. and Witter K.A. (1987). Effects of selected inorganic leachates on clay permeability, Journal of Geotechnical Engineering, ASCE, 113(8), 915-919.

Petrov, R.J. and Rowe, R.K. (1997). Geosynthetic clay liner (GCL) chemical compatibility by hydraulic conductivity testing and factors impacting its performance, Canadian Geotechnical Journal, 34, 863–885.

Posner, A. and Quirk, J. (1964). Changes in basal spacing of montmorillonite in electrolyte solutions, Journal of Colloid Science, 19(9), 798–812.

Pratt, M. (1965). Potassium and sodium. In: Black, C.A. (Ed.), *Methods of soil Analysis*. Amer. Soc. Agronomy, Inc. Madison, Wisconsin, EE. UU. 2, 1022-1234.

Prost, R., Koutit, T., Benchara, A. and Huard, E. (1998). State and location of water adsorbed on clay minerals: Consequences of the hydration and swelling-shrinkage phenomena, *Clays and Clay Minerals*, 46(2), 117–131.

Prudent, P., Domeizel, M. and Massiani, C. (1996). Chemical sequential extraction as a decision-making tool: application to municipal solid waste and its individual constituents, *Science of the Total Environment*, 178, 55-61.

Qian, X., Koerner, R.M. and Gray, D.H. (2002). *Geotechnical aspects of landfill design and construction*, Prentice Hall, New Jersey.

Quirk, J. P. and Schofield, R. K. (1955). The effect of electrolyte concentration on soil Permeability, *Journal of Soil Science*, 6(2), 163-178.

Rao, S. M., Thyagaraj, T. and Thomas, H. R. (2006). Swelling of compacted clay under osmotic gradients, *Geotechnique*, 56 (10), 707–713.

Rao, S.M. (2006). *Identification and classification of expansive soils*, Expansive Soils, Taylor & Francis Group, London, U.K.

Rao, S.N. and Mathew, P.K. (1995). Effects of exchangeable cations on hydraulic conductivity of a marine clay, *Clays and Clay Minerals*, 43 (4), 433-437.

Robinson, R.G. and Allam, M.M. (1998). Effect of clay mineralogy on coefficient of consolidation, *Clays and Clay Minerals*, 46(5), 596–600.

Rowe, R.K., Quigley, R.M. and Booker, J.R. (1995). *Clayey barrier systems for waste disposal facilities*, Chapman & Hall, London.

Ruhl, J. L. and Daniel, D. E. (1997). Geosynthetic clay liners permeated with chemical solutions and leachates, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 123(4), 369–381.

Ryan, C.R. (1987). Vertical barriers in soil for pollution contaminant, ASCE, *Geotechnical Special Publication*, 13, 182-204.

Salas, J. A. J. and Serratosa, J. M. (1953). Compressibility of clays, In: *Proceedings of 3rd International Conference of Soil Mechanics and Foundation Engineering*, Zurich, 1, 192–198.

Seed, H. B., Woodward, R. J. and Lundgren, R. (1962). Prediction of swelling potential for compacted clays, *Journal of Soil Mechanics and Foundation Engineering*, *Proceedings of the American Society of Civil Engineers*, 88, SM3, 53-87.

Shackelford, C. D., Benson, C. H., Katsumi, T., Edil, T. B. and Lin, L. (2000). Evaluating the hydraulic conductivity of GCLs permeated with non-standard liquids, *Geotextiles and Geomembranes*, 18, 133–162.

Shackelford, C. D. and Daniel, D. E. (1991). Diffusion in saturated soil. 1: Background, *Journal of Geotechnical Engineering*, ASCE, 117(3), 467– 484.

Shariatmadari, N., Salami, M. and Karimpour, M.F. (2011). Effect of inorganic salt solutions on some geotechnical properties of soil bentonite mixtures as barriers, *International Journal of Civil Engineering*, 9 (2), 103-110.

Shirazi S.M., Wimat, S., Kazama, H., Kuwano, J. and Shaaban M.G. (2011). Salinity effect of swelling characteristics of compacted bentonite, *Environment Protection Engineering*, 37(2), 65-74.

Singh, S. and Prasad, A. (2007). Effect of chemicals on compacted clay liner, *Electronic Journal of Geotechnical Engineering*, 12, Bundle D, 1-15.

Skempton, A. W. (1944). Notes on the compressibility of clays, *Quarterly Journal of Geological Society*, 100, 119–135.

Sparks, Donald L. (1995). *Environmental soil chemistry*, Academic Press, San Diego.

Sposito, G. (1981). *The thermodynamics of soil solutions*, Oxford University Press, New York.

Sposito, G. (1984). *The surface chemistry of soils*, Oxford University Press, New York.

Sposito, G. (1989). *The chemistry of soils*, Oxford University Press, New York.

Sridharan, A. and Rao, G.V. (1975). Mechanism controlling liquid limit of clays, *Proceeding of the Istanbul conference on soil mechanics and foundation engineering* 1, 75–84.

Sridharan, A. and Rao, G.V. (1973). Mechanisms controlling volume change of saturated clays and the role of the effective stress concept, *Geotechnique*, 23(3), 359-382.

Sridharan, A. and Jayadeva, M.S. (1982). Double layer theory and compressibility of clays, *Geotechnique*, 32(2), 133-144.

Sridharan, A., Rao, A.S. and Sivapullaiah, P.V. (1986a). Swelling Pressure of Clays, *ASTM Geotechnical Testing Journal*, 9(1), 23-33.

Sridharan, A., Rao, S.M. and Murthy, N.S. (1986b). Compressibility behaviour of homoionised bentonites, *Geotechnique*, 36(4), 551-564.

Suocheng, D., Tong, K.W., and Yuping, W. (2001). Municipal solid waste management in China: using commercial management to solve a growing problem, *Utility Policy* 10(1), 7-11.

Taylor, D.W. (1942). *Research on consolidation of clays*, Serial 82, Massachusetts Institute of Technology, Department of Civil Engineering, Cambridge.

Taylor, D. W. (1948). *Fundamentals of soil mechanics*, John Wiley and Sons, New York,

- Terzaghi, K. (1943). Theoretical soil mechanics, John Wiley & Sons, New York.
- Thammathiwat, A. and Chimoye, W. (2010). Effect of permeant liquid on the swell volume and permeability of geosynthetic clay liners, *Electronic Journal of Geotechnical Engineering*, 15, 1183-1197.
- UNEP (2010). Framework of global partnership on waste management, Note by Secretariat, http://www.unep.or.jp/Ietc/SPC/news-nov10/3_FrameworkOfGPWM.pdf
- Van Olphen, H. (1965). Thermodynamics of interlayer adsorption of water in clays, *Journal of Colloid Science*, 20, 822-837.
- van Olphen, H. (1977). An introduction to clay colloid chemistry, 2nd edition, John Wiley Interscience, New York.
- Warkentin, B.P. (1961). Interpretation of the upper plastic limit of clays, *Nature*, 190, 287-288.
- Xue, Q., Zhang, Q. and Liu, L. (2012). Impact of high concentration solutions on hydraulic properties of geosynthetic clay liner materials, *Materials*, 5, 2326-2341.
- Yong, R.N. and Warkentin, B.P. (1975). Soil properties and behaviour, Elsevier, New York.
- Yong, R.N. and Di Perno, N. (1991). Source and characteristics of waste with specific reference to Canada, Geoenvironmental series 91-1, Geotechnical Research Centre, McGill University.
- Zhang, F., Low, P. and Roth, C. (1995). Effects of monovalent exchangeable cations and electrolytes on the relation between swelling pressure and interlayer distance in montmorillonite, *Journal of Colloid Interface Science*, 173,34-41.
- Zhang, F., Ye, W.M., Chen, B., Chen, Y.G., Wang, Q. And Cui, Y.J. (2014). Effects of salt solutions on the hydro-mechanical behaviour of compacted GMZ01 bentonite, *Environmental Earth Science*, 72, 2621-2630.
- Zhu, C.M., Ye, W.M., Chen, Y.G., Chen, B. And Cui, Y.J. (2013). Influence of salt solutions on the swelling pressure and hydraulic conductivity of compacted GMZ01 bentonite, *Engineering Geology*, 166, 74-80.

LIST OF PUBLICATIONS BASED ON THIS RESEARCH WORK

Journals:

- Dutta, J. and Mishra, A.K. (2016). Consolidation Behaviour of Bentonites in the presence of salt solutions, *Applied Clay Science*, Elsevier, 120, 61-69.
- Dutta, J. and Mishra, A.K. (2015). A study on the influence of inorganic salts on the behaviour of compacted bentonites. *Applied Clay Science*, Elsevier, 116-117, 85-92.
- Mishra, A.K., Dutta, J., Chingtham, R. (2015). A study on the behaviour of the compacted bentonite in the presence of salt solutions. *International Journal of Geotechnical Engineering*, Taylor and Francis, 9(4), 354-362.

Paper under review:

- Dutta, J. and Mishra, A.K. (Under Review). Influence of heavy metals on the behaviour of bentonites, *Environmental Earth Science*.

Conferences:

- Mishra, Anil Kumar and Dutta, Jagori (2014). A Study on the Effect of Salt on the Behaviour of Compacted Bentonite, 7th International Congress on Environmental Geotechnics, Melbourne, Australia.
- Jagori Dutta and Anil Kumar Mishra (2014). Influence of Heavy Metals on the Geotechnical Behaviour of Compacted Bentonite, Indian Geotechnical Conference, Kakinada.
- J. Dutta and A.K. Mishra (2014). Effect of Permeant Liquid on the Geotechnical Behaviour of Compacted Bentonite. North East Students Geocongress on Advances in Geotechnical Engineering-2014, IIT Guwahati.

