

# **Effect of dry density and salt solution on swelling pressure of compacted bentonite**

*A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of*

*Master of Technology*

*In*

*Civil Engineering*

*(Geotechnical Engineering)*



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**NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA**

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***CERTIFICATE***

This is to certify that the project entitled “*Effect of dry density and salt solution on swelling pressure of compacted bentonite*” submitted by Mr. Rajesh Sarkar (Roll No. 213CE1051) in partial fulfillment of the requirements for the award of Master of Technology Degree in Civil Engineering at NIT Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in this report has not been submitted to any other university/institute for the award of any degree or diploma.

Place: Rourkela

Date:

Prof. Ramakrishna Bag  
Department of Civil Engineering  
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## **Abstract**

In many underground nuclear waste disposal facilities, bentonite has been referred as buffer and backfilling materials due to its high swelling capability, high water holding ability and low permeability. Since bentonite gets limited space for occupying itself around the underground nuclear waste containers and in case of water intrusion to the nuclear waste disposal repository, it exerts swelling pressure, therefore, the determination of swelling pressures of compacted bentonites is a significant aspect for such kind of bentonite-built barrier systems. Many of the waste repositories are commissioned in locations where the ground water either contains significant amount of salts or the repositories are anticipated to receive saline water from sea. Hence in this current research, an effort has been made to find out the swelling pressure of compacted bentonites under the influence of dry density and salt solution. Constant volume swelling pressure tests were carried out with compacted bentonite specimens of targeted dry densities varying between 1.2 to 1.8 Mg/m<sup>3</sup> using distilled water and solutions of NaCl (0.5 and 1.0 M) as the hydrating fluids.

It was found that the swelling pressure of compacted bentonite specimens increased with increase in dry density. In all the cases, the equilibrium swelling pressures were found to reach within about 7 days for all cases irrespective of the dry density and the bulk solution. However, the influence of saline solutions was found to decrease the swelling pressure of the bentonite.

## INTRODUCTION

In present situation, environment conservation has become a very important issue of our society. With the rapid growth in exercising nuclear technology, the stockpiling of hazardous nuclear waste from nuclear power stations has also increased. So these radioactive wastes, mainly grouped as high-level and low-level radioactive wastes, have nowadays created a greater threat to the environment. So to separate them from human life and environment, it has become an essential requirement to install waste repositories for their proper disposal in many countries. The present idea which has been found appropriate by most countries is to keep the radioactive waste inside some containers which are better known as canister and bury them below ground to some depth where those canisters can reach a hard geological formation. These canisters are also sealed and surrounded by the safety barriers.

The materials used in the safety barriers act mainly as buffer and backfilling material. Normally, the material which remains next to the surroundings of the waste container is known as the buffer material and the material which is used to seal the passageway i.e., the access tunnel after placing the waste containers is recognized as the backfilling material. The placement of radioactive waste and bentonite barrier system is shown in Figure 1.1.

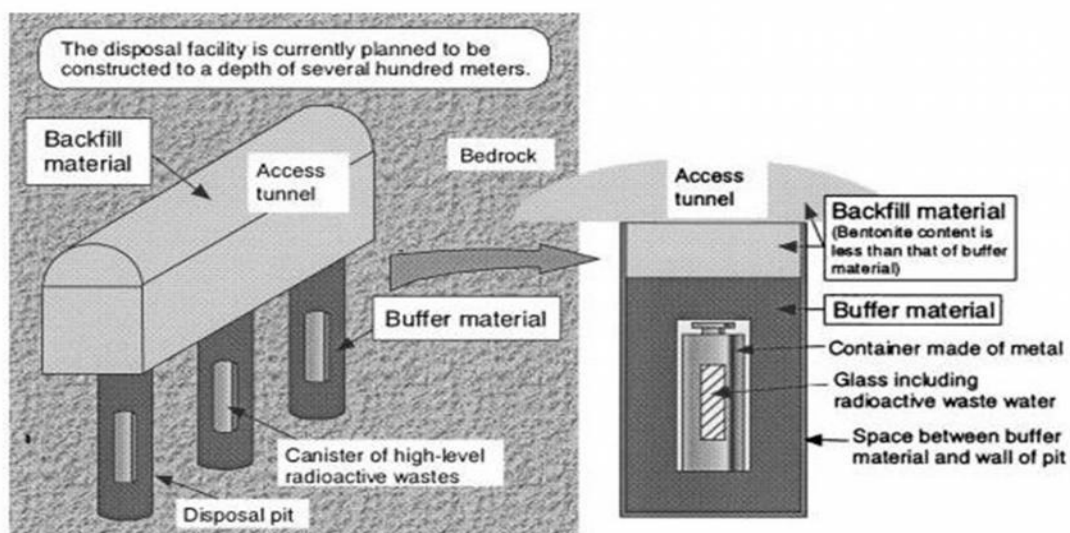


Figure 1.1: Example of nuclear waste disposal facility in Japan (after Ogata et al. 1999).

The three elementary functions of a barrier material are as follows:

1. To support the nuclear waste containers structurally so that they can remain firmly in their places and stop crash down of the excavation.
2. To form a waterproof zone around the containers so that water cannot enter into the waste containers and high-level radioactive waste cannot migrate into the geosphere.
3. To translocate the heat produced inside the waste containers to the host rock (Tripathy et al. 2004; Komine and Ogata 2004).

The basic operation of a backfill material is to build a water-resistant and sealed zone in the excavated tunnel of a disposal facility (Komine and Ogata 2004).

In the past years, compacted bentonites and bentonite-sand mixtures have been recommended as proper barrier and backfilling materials for repository sites of high-level nuclear waste disposal facility. This is because of some advantageous properties of bentonite. Bentonite shows low permeability and has good swelling ability. It also shows good thermal conductivity and low ion diffusivity, i.e., high radionuclide adsorption capacity (Agus and Schanz 2008).

It has been found that the utilization of bentonite-sand mixtures as backfilling material is more advantageous rather than other natural clays. This is because of the fact that they shrink very less on drying. During the process of drying, the void ratio of bentonite decreases which brings the sand particles present in the sand-bentonite mixture into contact. This phenomenon reduces the decrease in the void ratio giving an overall mechanical stability and also reduces further shrinkage. During freezing, ice growth is equally distributed everywhere in the mixture providing a very little change in the macrostructure. However, once liquated and saturated, the bentonite swells to fill voids and as an effect of which bentonite sand mixture shows very low hydraulic conductivity (Studds et al. 1998).

Bentonite may come in contact with other liquids from the surrounding medium when used as barrier material in deep underground repositories. Upon absorbing water or electrolytes, compacted bentonites exhibits considerable volume change. If the volume change is restricted, the clay applies pressure (i.e., swelling pressure) on the nearby surroundings. Therefore, the study of swelling pressure is an important topic when it comes in the context of picking it as buffer and sealing material for such kind of an application. This is a very important characteristic while designing and constructing a nuclear waste disposal facility (Agus and Schanz 2008).

## LITERATURE REVIEW

### 2.1 Mineralogy of bentonite:

Bentonite is an industrial name given to those natural clays which are formed by weathering of volcanic ash or tuff and contains montmorillonite clay as the chief constituent. The basic desirable characteristic of bentonite clays is that they possess a high water soaking capability which allows them to swell highly. However the characteristics of different bentonites depend on the mineralogical composition of the materials. This is because of the different geological history of their sources. Bentonite is primarily made up of montmorillonite which belongs to smectite family, a class of expansive clay minerals with a large variety of chemical compositions. Besides, except montmorillonite, bentonites may have some other accessory minerals as well. Bentonites may contain clay minerals like kaolin, illite, mica etc. in minor quantities and some non-clay minerals like quartz, feldspar, gypsum calcite etc. depending on the geological conditions through which the bentonite is formed.

Bentonite is 2:1 clay with 1 aluminum oxide sheet surrounded by 2 silicon oxide sheets. The internal aluminum sheet and external silicon oxide sheets share oxygen atoms. Such an arrangement would be electrically neutral, but the silicon ion and the aluminum ion frequently undergo substitution by some lower valence metals, such as iron and magnesium, but without a significant change in the crystal structure and resulting in net negative charge.

### 2.1.1 Structure of Montmorillonite:

Montmorillonite consists of the unit layers made up of an aluminium octahedral sheet packed in between two silica tetrahedral sheets. The tetrahedral sheet or silica sheet consists of silica tetrahedron units each of which contains four oxygen atoms occupying the four corners of a tetrahedron with one silicon atom at the centre of the tetrahedron. Three of the four oxygen atoms rest on a triangular face of the tetrahedron, each of which share themselves with another one tetrahedron to form a hexagonal net. The aluminium octahedral sheet consists of aluminium octahedron units made up of six oxygen or hydroxyl groups at six corners of an octahedron and aluminium atom at the centre. The two silica sheets and the aluminium sheet of each unit layer combine together in such a way that tips of the tetrahedron of each silica sheet and one hydroxyl layer of the aluminium sheet form a common layer. The silica-gibbsite-silica layers continue in 'a' and 'b' direction and stack together one above another in 'c' direction. However while stacking oxygen layer on the faces of each unit layer comes close the other oxygen layer of nearby units causing a weak bond between negatively charged faces. Since there are negative and positive charges on the edge, the charge is compensated because the cations are adsorbed from the edge layer to the sheet face.

Water and other polar molecules can enter among the unit layers, causing expansion in lattice to 'c' direction. Hence a montmorillonite structure expands along the 'c' direction depending on the polar molecules present between the silica layers and 'c' axis. The thickness of water layer depends on the nature of exchangeable cations. A typical structure of montmorillonite is shown in figure 2.1.

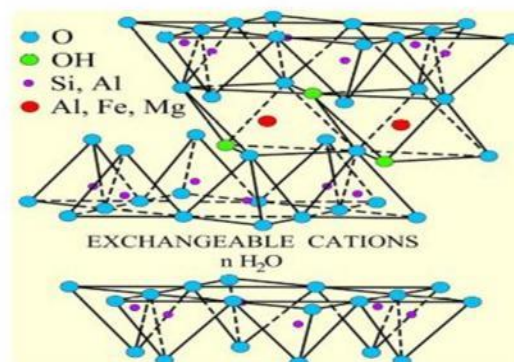


Figure 2.1: Typical structure of montmorillonite.

## 2.2 Formation of diffuse double layer and expansion mechanism:

The behavior of the swelling pressure of compacted bentonite can be understood from the following figure shown below.

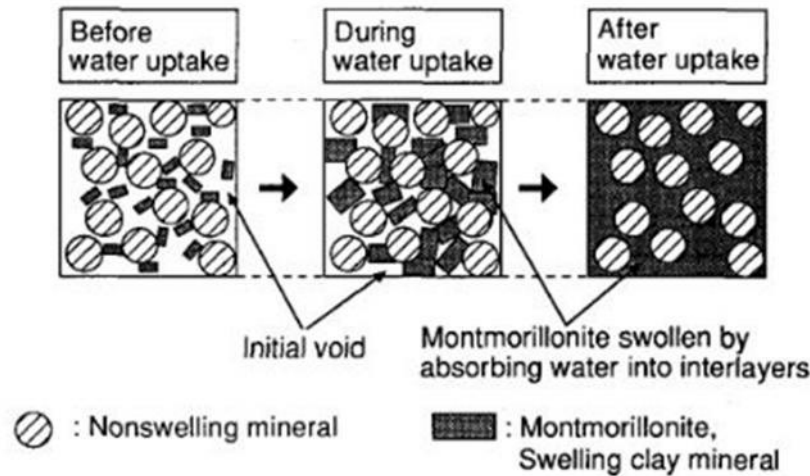


Figure 2.2: Swelling pressure mechanism of compacted bentonite from Komine and Ogata(1996).

In dry condition, compacted bentonite contains montmorillonite, voids and other non-swelling minerals. These voids remain filled with air and free water. During saturation, montmorillonite absorbs water into its interlayers and swells. As a result of which the voids in the bentonite are occupied by these swelled montmorillonites. Therefore, the volume of montmorillonite increases and the swelling pressure occurs. Finally, there remains no void to soak water and hereafter the volume of montmorillonite cannot increase more. At this point, the swelling pressure of compacted bentonite can be measured (González 2013).

The swelling of bentonite occurs mainly due to two mechanisms namely crystalline swelling and osmotic swelling (González 2013). Both mechanisms rely on the extent of hydration and the amount of cations present in the interlayers.

The first mechanism that seems to occur when the montmorillonite imbibes water is the crystalline swelling. This mechanism enlarges the distance between the montmorillonite unit layers. As a result of which the volume of the montmorillonite increases and therefore yields the swelling pressure. The dominant force which acts and controls the crystalline swelling when the clay comes into contact with the water is the hydration of the interlayer cations and the clay surface.



The other force which balances the crystalline swelling is the van der Waals attraction or the Born repulsion. The hydration occurs due to the attraction between water molecules and the polar surface groups and also due to the charge site and exchangeable cations.

In dry condition, the montmorillonite layers remain very close to each other for which the exchangeable cations in between the layers can be found either on the surface of the layers or in the hexagonal holes of the tetrahedral sheets which hold the negatively charged layers together. The van der Waals force is also accountable for the union of the negatively charged layers. When the exchangeable cations come into the contact with water, they arrange themselves midway between two clay layers. It is assumed that at first a layer of water molecules encloses the clay surface fully. Then another molecular layer will get its normal pattern or function disrupted. By this way the insertion of water molecules takes place layer after layer. In sodium montmorillonite, zero to four separate layers of water molecules are inserted between the layers of a montmorillonite particle.

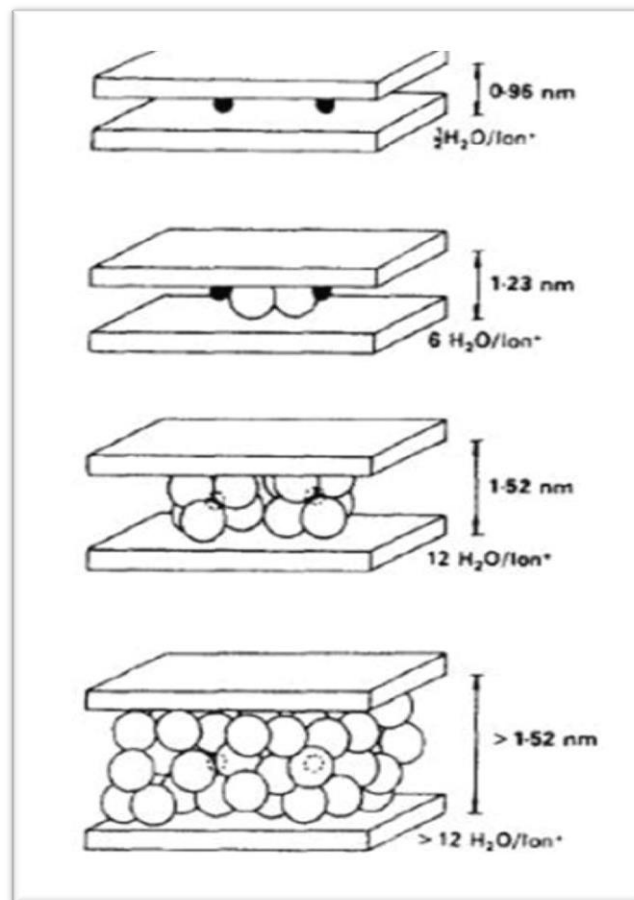


Figure 2.3: Process of water absorption from Madsen and Müller-Vonmoos (1989).

The second mechanism that seems to occur when the montmorillonite imbibes water is the osmotic swelling. This mechanism is responsible for the increase in the distance between the montmorillonite layers. The osmotic swelling occurs due to the concentration variation in the ions adjacent to the surface layers of montmorillonite and in the pore water. The diffuse double layers and the van der Waals attraction influence this mechanism.

Due to the presence of negative charges in clay layers, a repulsion always follows in between them. However, the nearby cations adjacent to the surface of the layer satisfy these negative charges. Since these exchangeable cations are strongly held by the external surfaces, they always show a affinity to diffuse from high concentration regions to low concentration regions in the bulk solution and as an effect of which ions spread out around a clay particle. This is called diffuse double layer.

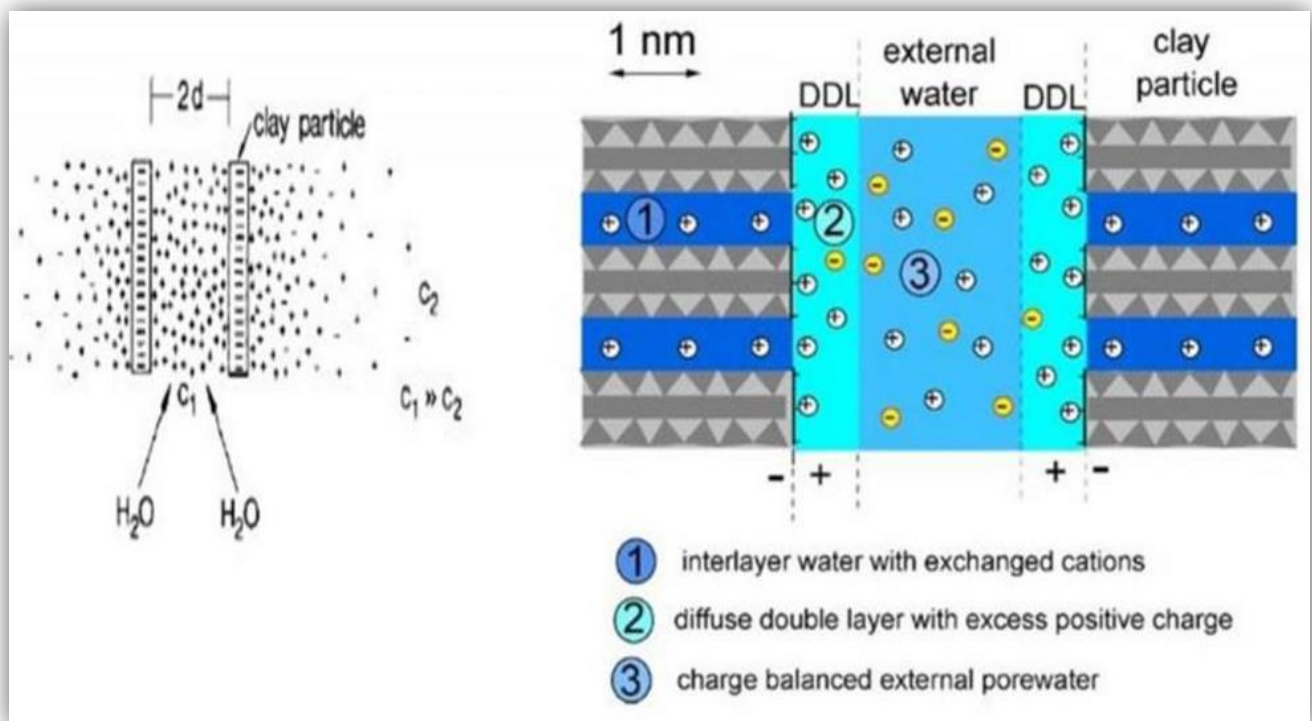


Figure 2.4: Diffuse double layer from Madsen and Müller-Vonmoos (1989).

## **2.3 Different laboratory methods for determining the swelling pressure:**

The most commonly used apparatus for determining swelling pressure of expansive soils is the one-dimensional consolidometer. For a consolidometer test, the swelling pressure represents that pressure which stops allowing the swell of the specimen or that essential pressure which tries to bring a swelled specimen back to its usual position i.e., to its original void ratio, height etc. (ASTM D454-96,1997). However, there is no standard or universally accepted method that has been found out to carry out consolidometer test for getting the swelling pressure. Sridharan et al. (1986) mentioned three different methods for assessing swelling pressure, viz., the free swell test, the swell under load test and constant volume test. Justo et al. (1987) presented four descriptions of swelling pressure with the help of the "loading after soaking" method, "soaking under load" method and "constant volume" method. The procedure for finding swelling pressure by the "soaking under loading" method and "swell under load" method is almost identical but provides two dissimilar values of swelling pressure. It was suggested that a correction is needed to apply to the swelling pressure in order to compensate for soil disturbance through sampling for the constant volume test (Fredlund et al. 1980).

## **2.4 Descriptions of the test methods for laboratory measurement of swelling pressure:**

### **2.4.1 Method-I: Conventional consolidation test/the swell-consolidation/swell load method:**

According to this method, a seating pressure of 6.25 kPa ( $0.0625 \text{ kg/cm}^2$ ) is first applied to the specimen and then permitted to swell fully after saturation. After that only successive loading is allowed to take it back to its normal volume which provides the maximum swelling pressure (Nagaraj et al. 2009). In Figure 6, Curve 1 represents a percentage change in volume against logarithmic plot of pressure for a consolidation test. This curve intersects the horizontal initial state line at point 1. The pressure  $P_1$  analogous to point 1 represents the swelling pressure. This is because, at point 1 the specimen finds its original state after swelling fully at seating load and on complete consolidation (Sridharan et al. 1986). However, it is a time-consuming method but one specimen is enough to find out swelling pressure. The test provides the highest value for the swelling pressure of the soil.

### **2.4.2 Method-II: The method of equilibrium void ratios for different consolidation loads:**

According to this method, three or more identical soil specimens with same initial condition are kept in oedometers at equal seating pressure. The dry specimens are then loaded to different pressures  $P_1$ ,  $P_2$ , and  $P_3$  which are likely to be around the assessed swelling pressure. When the equilibrium is reached due to these loadings, water is supplied to the oedometer cells and the samples are permitted to swell or compress to reach equilibrium void ratios. In Curve 2 of Figure 6 the equilibrium void ratios are symbolized by A, B, C and so on. A straight line can be drawn through these equilibrium points A, B, C and so on, lie on which crosses the horizontal zero volume change line or the line through the starting point at point 2 and the corresponding pressure is  $P_2$ . Thus  $P_2$  denotes the pressure beyond which the specimen would not experience change in volume on saturation which ultimately represent the swelling pressure (Sridharan et al. 1986). However, out of the three methods, this provides the smallest value of the swelling pressure. If this method is applied to a field sample, the probable difficulty one may face is that at least three identical specimens are required which are very problematic to prepare and as well as time consuming (Nagaraj et al. 2009).

### **2.4.3 Method-III: The constant volume method/zero-swell method:**

According to this method, load is applied to the specimen unceasingly so that the change in volume remains practically zero and then water is allowed to enter to the specimen to undergo complete saturation (Nagaraj et al. 2009). It is noteworthy that a slight increment in the loading may compress the sample beyond the initial reading which is not desirable because the initial reading should always be maintained. However, in this method minor variations are not avoidable. When the specimen reaches very near to equilibrium, a slight increase in load compresses the sample to an extent that it crosses the line of the original condition. Pressure  $p_3$  which corresponds the intersection point 3 of curve 3 signifies the swelling pressure. This is a less time consuming method and only one sample is adequate (Sridharan et al. 1986).

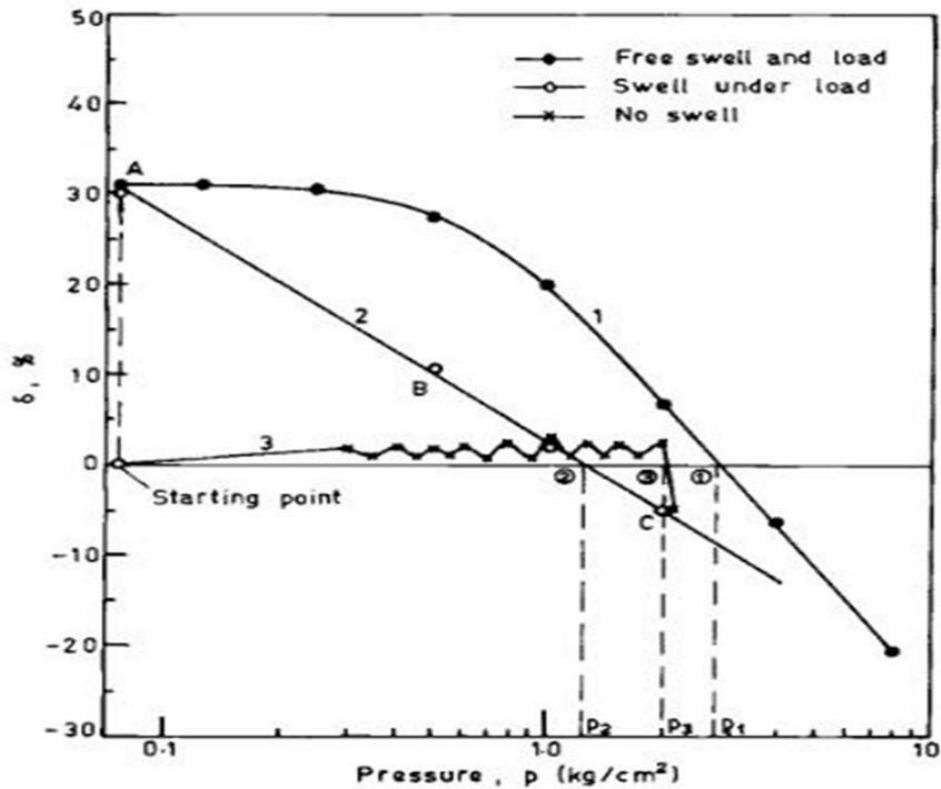


Figure 2.5: Schematic diagram showing the methods of tests to determine swelling pressure (Sridharan et al.1986)

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## 2.5 Influence of salt on swelling pressure of bentonite:

The swelling pressure of bentonite and bentonite-sand mixture is affected by the presence of electrolytes in bulk fluids.

The swelling behavior of a bentonite-sand mixture depends on the concentration of the pore fluid, the applied effective stress and the amount of the clay content. In dilute solutions, at low stresses condition bentonite present in the mixture swells sufficient enough to separate the sand particles and the behavior of the bentonite-sand mixtures is similar to that of the bentonite alone because it reaches a clay-void ratio similar to that achieved by bentonite alone. At high stresses, or in strong solutions, the bentonite has insufficient swelling capacity to force the sand particles apart and swelling is limited by the sand pore volume (Studds et al. 1998).

The swelling behavior of a bentonite-sand mixture in aqueous solutions can be predicted from the swelling properties of the bentonite in the appropriate solution, and the load-deformation properties of the sand (Studds et al. 1998).

The influence of high-pH solutions on the characteristic of swelling pressure decreased concomitantly with increasing initial dry density and higher montmorillonite contents in the bentonite samples. Therefore, samples are apparently less susceptible to the high-alkali solutions according to their montmorillonite contents (Sugiura et al. 2010).

The influence of the high-pH solution on the swelling deformation characteristics did not depend on the montmorillonite content in the bentonite samples and initial dry density. Increasing volume of the bentonite specimen settles at the maximum swelling strain on the effective montmorillonite density of the constant value in solutions of each concentration (Sugiura et al. 2010).

The swelling pressure decreases with the increasing of concentration of pore solution. If the concentrations of injected solution are lower than that used to prepare the sample, the swelling pressures are not always larger than the ones that the concentrations of solutions are same when used to prepare the sample and to inundate the sample. This is due to the fact that while preparing the specimens, the water molecules of the solution penetrate into the clay layers, and some solutions left out around the clay layers. So when the concentration of the flooding or bulk solution, is lower than the original solution to prepare the specimens, the concentrations of the solutions around the clay layers are not necessarily affected by the bulk solutions. So the swelling pressures, in this case, are not always larger than the cases where the concentrations of solutions to prepare and inundate the specimens are equal to each other (Jia and Yang 2010).

## **2.6 Constant volume method:**

In this method, the change in volume is prevented and consequent pressure is measured. Generally, this test is based on the strain-controlled technique, i.e., the most important characteristic of this test is that constant volume is maintained. The apparatus used for constant volume test is Constant-Volume Cell. The Constant-Volume Cell consists mainly of three parts:

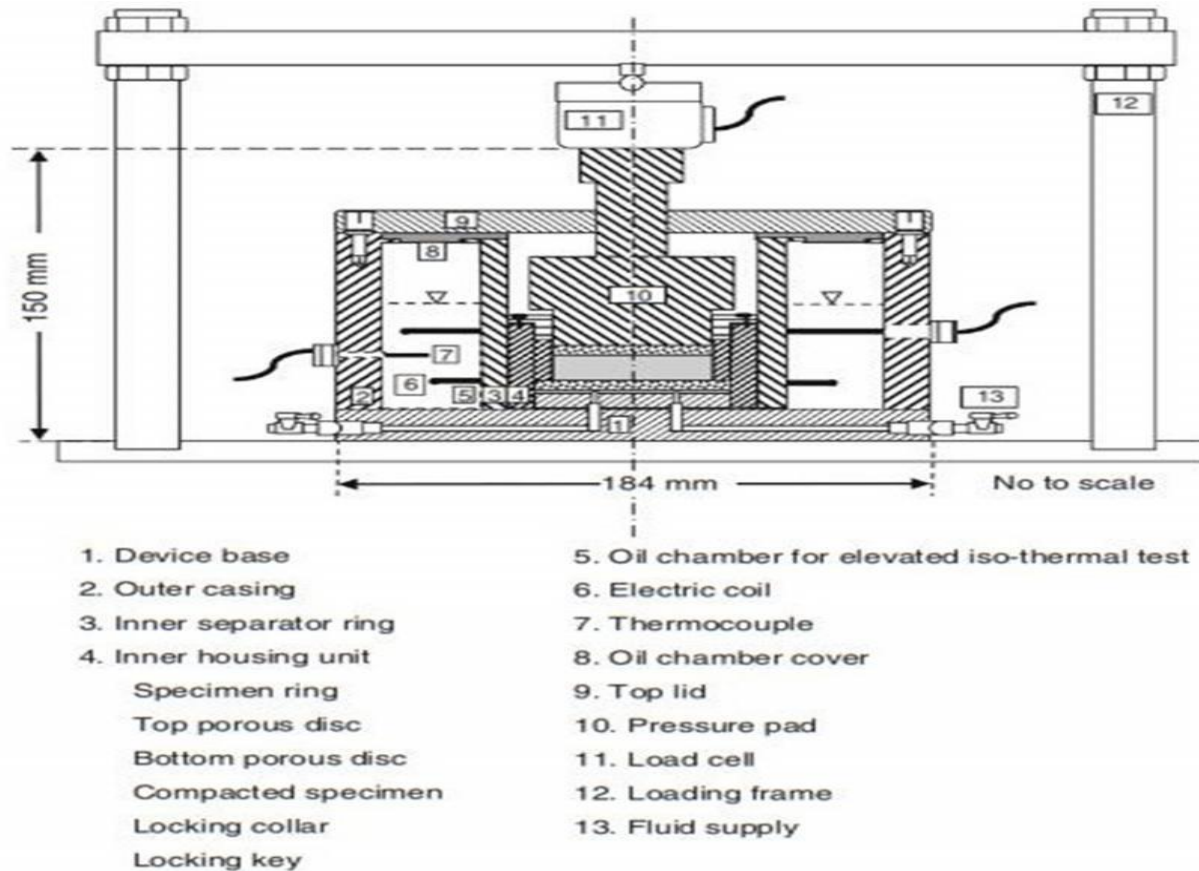


Figure 2.6: Schematic diagram of the constant volume swelling pressure cell (after Tripathy et al. 2014).

1. The bottom part consists of a porous stone which remains in contact with the soil specimen and inlet for the circulation of liquid water or solution.
2. The middle cell contains specimen chamber where the cylindrical specimen is established.
3. At the top, a total pressure sensor/load cell/transducer is fixed for monitoring the swelling pressure and put into direct contact with the top surface of the specimen. It is restrained against volume change/swelling.

## **2.7 Density of water and degree of saturation of compacted bentonite:**

It was found by several researchers that the density of adsorbed water during the hydration of compacted bentonites increases or decreases as compared to that of water. Anderson and Low (1957) noted the density of water as  $0.97 \text{ Mg/m}^3$ . Skipper et al. (1995) showed that the density of water in Na-montmorillonite as  $1.14 \text{ Mg/m}^3$ . This is due to change in the structure of water molecules and in their properties while in contact with montmorillonite surfaces. Low (1979) concluded that the hydrogen-bonded structure of water adsorbed by Na-montmorillonite is more extensible and compressible but also less easily fractured than the structure of the bulk liquid water.

The degree of saturation is the ratio of volume of water in voids to the total volume of voids. Therefore, the degree of saturation of the specimens should not exceed 100%. But several researchers have reported that the degree of saturation of bentonite specimens may exceed 100%. Villar and Lloret (2008) noted that for compacted bentonites hydrated with water, the calculated degree of saturations based on the compaction dry densities and final water contents were greater than 100 %. This is due to the variation in the density of water in bentonite-water systems. Villar and Lloret (2008) noted that by keeping the degree of saturation of compacted saturated specimens at 100 %, the density of the pore fluid increased as compared to that of water.

## **2.8 Objective of the study:**

The objectives of the present study are as follows:

- To determine the swelling pressure of bentonite at different dry densities.
- To study the effect of different concentration of NaCl salt solutions on the measured the swelling pressure of bentonite.



## MATERIAL CHARACTERISTICS AND EXPERIMENTAL PROCEDURE

### 3.1 General:

The material used in this study is bentonite which was collected from Bikaner, Rajasthan to find out its swelling pressure under constant volume condition. The experiments conducted for the characterization of bentonite and the results observed are reported as follows.

### 3.2 Method:

#### 3.2.1 Atterberg's Limits:

Atterberg's limit tests were conducted to study the plasticity property of the soils. The liquid limit and plastic limit are the water contents at which the soils exhibit both liquid and plastic property, respectively. The liquid and plastic limits tests were conducted according to IS: 2720-Part 5 and 6 (1985) and the results are presented in the table1. The liquid limit was determined using the fall-cone method and the plastic limit was determined by rolling 3 mm diameter threads of the soils until they began to crumble. The difference between these liquid limit and plastic limit is known as the plasticity index, which is generally used to characterize the plastic nature of soils.

<b>Limits and Indices</b>	<b>Values</b>
Liquid Limit	140 %
Plastic Limit	61 %
Shrinkage Limit	40 %
Plasticity Index	79 %

Table 3.1: Atterberg's limits of Bentonite.

### 3.2.2 Specific Gravity:

Specific gravity is the ratio of density or specific weight of the particles to the density or unit weight of water. The specific gravity of bentonite was determined using pycnometer method as per IS: 2720-Part 3 (1980) and it is found to be **2.67**.

### 3.2.3 Particle Size Distribution:

Particle size distribution of bentonite was determined using hydrometer method in accordance with IS: 2720- part 4 (1975). Bentonite sieved through 75 $\mu$ m sieve size was collected carefully and used for particle size analysis and the analysis was performed using Hydrometer method. Value of  $D_{10}$  (Diameter of particle corresponding to the 10% finer),  $D_{30}$  (Diameter of particle corresponding to the 30% finer) and  $D_{60}$  (Diameter of particle corresponding to the 60% finer) are to be obtained. But since particles are very fine, it is not possible to get those values and the distribution is shown in figure 3.1. Around a 69% of particles are clay sized.

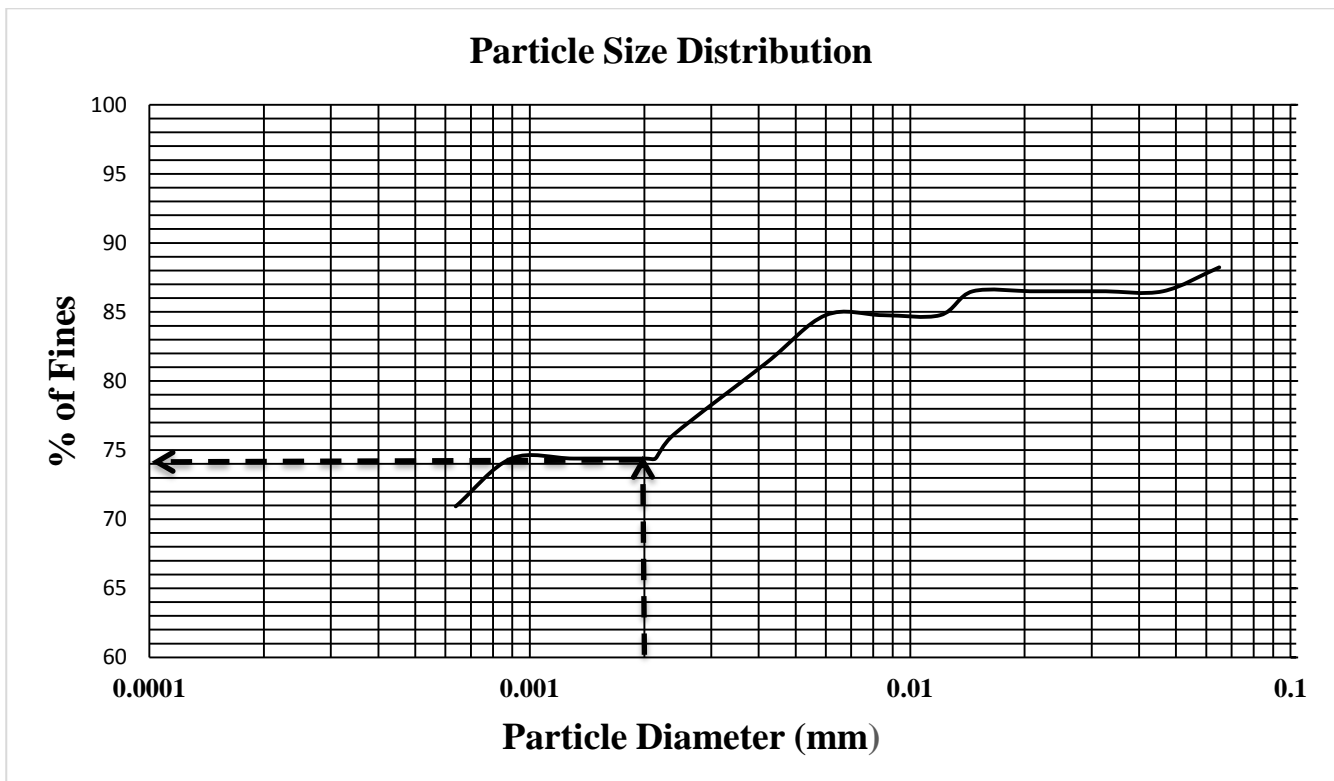


Figure 3.1: Particle Size Distribution curve of Bentonite.

### 3.2.4 X-Ray Diffraction Analysis:

The mineral composition of bentonite was determined by X-ray diffraction method. According to Bragg's law, the XRD identifies the minerals based on the relationship between the angle of incidence of the X-rays,  $\theta$ , to the  $c$ -axis spacing,  $d$ . A Philips automated powder diffractometer was used for XRD analysis in this study.

1.5 g of fine grained sample is kept in oven drying for 2 hours and allowed to cool in room temperature. Then, sample is filled in the sample holder of diffractometer and the XRD pattern is obtained by scanning over angle range of  $20^\circ$  to  $100^\circ$ ,  $2\theta$  at  $0.25^\circ/\text{min}$ . In the step mode, a  $0.05^\circ - 2\theta$  step for 2 s is given. Results are analysed using Xpert High Score software and mineral composition has been found. Quartz, Montmorillonite, Muscovite and Calcite are the minerals found. Result is shown in figure 3.2.

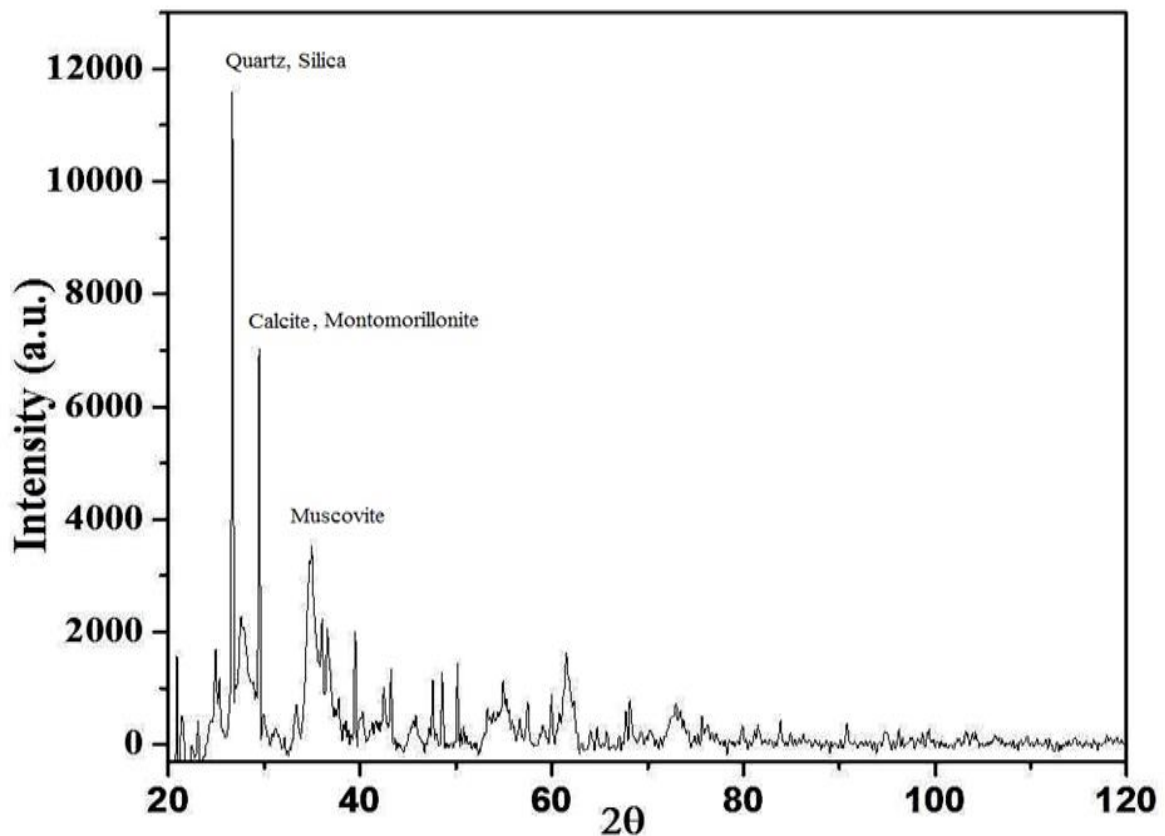


Figure 3.2: XRD analysis of Bentonite.

### 3.2.5 BET Analysis:

Specific surface area being the significant physical parameter has a great impact on the quality and utility of solid phase samples. Gas adsorption analysis is the widely used method for measurement of specific surface area. This method involves exposure of gas to the solid sample under various environmental conditions thereby measuring volume of sample. The Brunauer, Emmett and Teller (BET) technique is commonly employed tool to determine the surface area of powder sample. Here, nitrogen gas is used as probe that is exposed on the solid material under standard conditions. Thus, surface area of the sample can be measured from the monolayer adsorbed using the prior knowledge of cross sectional area of probe being used. Activation of sample must be done to ensure that no air or gas has been adsorbed on the solid particle before evaluation which may affect the sample quality. Activation can be done by heating the sample under vacuum conditions. Specific Surface Area has been determined by BET analyser and value is found to be 79.23 m<sup>2</sup>/g.

### 3.2.6 Cation Exchange Capacity (CEC):

Cation Exchange Capacity (CEC) is defined as the amount of exchangeable ions that a soil can hold at a given pH value. The Cation Exchange Capacity (CEC) of the soil sample and soil lime mixture was found as per ASTM D7503 – 10 method. The Nitrogen concentration was determined by spectrophotometer as per modified Parsons et al. (1984). The nitrogen concentration was determined by the graph obtained by the absorbance of the standard solution of known concentration. After Nitrogen Concentration is known, the CEC of the sample is calculated by the equation

$$CEC \left( \frac{cmol}{kg} \right) = \frac{N \times 1 \times 0.25}{140 \times \text{mass of soil taken}} \times 1000$$

where N = nitrogen concentration in mg/L and the CEC value of bentonite is calculated as **54.71 meq/100 g**.

### 3.3 Experimental procedure:

Bentonite has been considered as the buffer material around the nuclear waste containers in several projects associated with the underground disposal of nuclear waste. Since bentonite gets limited space for swelling below the ground whose swelling pressure measurement is important for design purpose so in this study measurement of swelling pressure is done with the help of constant volume method.

The apparatus used in this study is the conventional Consolidometer (Oedometer) cell with floating type ring. It consists of a base with drain tube, a bottom porous stone disc, a specimen ring to accommodate a compacted bentonite specimen and is provided with a collar which rests securely on the specimen ring, a top porous stone disc, a pressure pad and a locking collar with locking keys to hold the specimen ring in place.



Figure 3.3: Components of a conventional oedometer.

### 3.3.1 Compaction:

- Firstly, based on assumed targeted dry density and initial moisture content, calculated amount of bentonite powder is statically compacted within thick-walled oedometer ring which is first lubricated with technical grade silicon grease to minimize the side friction. A high capacity compression testing machine is used for preparing the compacted specimen.
- After compaction the height of the specimen is measured to find the actual dry density of the specimen. The consolidation specimen ring with the specimen in then placed in between two porous stones providing filter paper between the specimen and the each porous stone. A pressure pad is then placed on top of the top porous stone and the arrangement is kept fixed with the help of locking collar and screws.



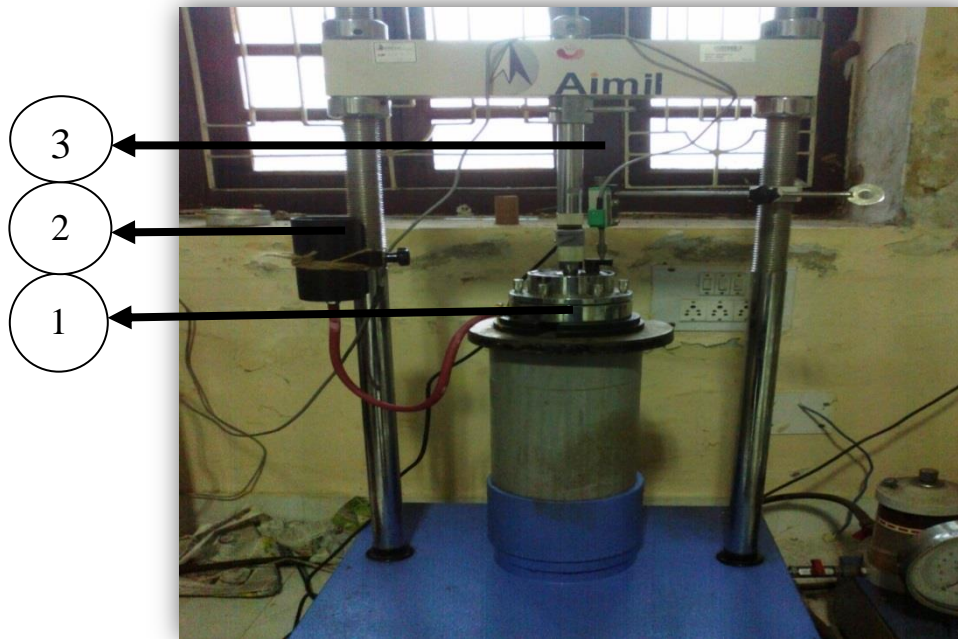
Figure 3.4: Compaction of bentonite powder within thick-walled oedometer rings.



Figure 3.5: Compacted bentonite specimen.

### 3.3.2 Swelling pressure measurement:

- Then the assembly is placed on the platen of the loading unit. A transducer/load cell with a precision of 0.01 kN is attached on the pressure pad with the help of a pressure ball. The function of the load transducer is to monitor the transient vertical thrusts exerted by the specimens during the swelling pressure test. Initially a seating pressure is applied to the pressure pad and the initial reading of the load cell is noted. Then the distilled water is supplied from the bottom and the soil is allowed to swell.
- The readings are taken till equilibrium is reached. This is ensured by making a plot of swelling pressure reading versus time whose plot becomes asymptotic with abscissa (time scale) the equilibrium swelling is normally reached in a period of 6 to 7 days in general for all expansive soil.
- During the test procedure, the volume change is considered to be negligible.



1. Consolidometer with specimen.
2. Water tank.
3. Transducer

Figure 3.6: Constant volume swelling pressure test set up.

SL No.	Targeted Dry density (Mg/m <sup>3</sup> )	Initial water content (%)	Bulk fluid used
1	1.2	11.6	Distilled water
2	1.3		
3	1.4		
4	1.5		
5	1.6		
6	1.7		
7	1.8		
8	1.3		0.5 M NaCl solution
9	1.5		
10	1.8		
11	1.3		1.0 M NaCl solution
12	1.5		
13	1.8		

Table 3.2: Initial details for conducting each swelling pressure test.



## RESULTS AND DISCUSSION

### 4.1 Introduction:

Based on the targeted dry density and initial moisture content swelling pressure test is conducted by adopting constant volume method as discussed earlier to find out the swelling behavior of the bentonite. The results are shown in following section.

Table 4.1 presents the loads applied during preparing the compacted specimens, the dry densities of the specimens after removal of the compaction loads, the measured swelling pressures, and the measured water contents of the specimens after the swelling pressure test.

SL No.	Applied static load(kN)	Targeted dry density (Mg/m <sup>3</sup> )	Dry density after release of static load (Mg/m <sup>3</sup> )	Bulk fluid used	Swelling pressure(kPa)	Water content after swelling pressure test (%)
1	12.64	1.2	1.19	Distilled water	62.0	63.3
2	18.39	1.3	1.26		203.0	56.7
3	33.91	1.4	1.32		207.0	46.1
4	40.23	1.5	1.42		353.0	50.5
5	73.56	1.6	1.51		738.99	47.6
6	112.07	1.7	1.60		903.21	52.6
7	195.3	1.8	1.68		1367.31	48.8

Table 4.1: Swelling pressure test results using distilled water as bulk fluid.

## 4.2 Loading History of Compacted Specimens Prior to Swelling Pressure Tests:

The maximum applied load at the highest targeted dry density was 195.3 kN whereas the applied loads were less at smaller dry densities. The applied static loads during specimen preparation are plotted against the corresponding targeted dry densities of the specimens before the swelling pressure tests which is shown in figure 4.1.

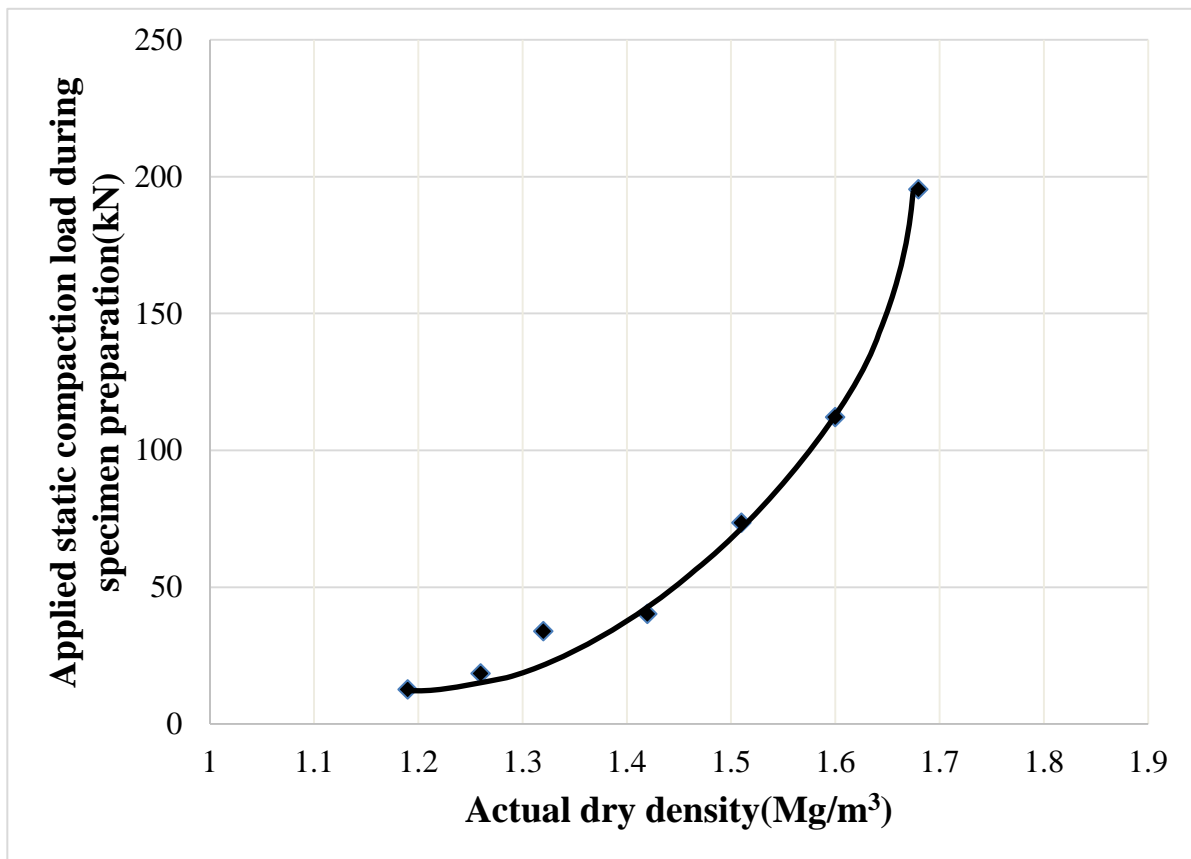


Figure 4.1: Load-deformation curve.

### 4.3 Time-swelling pressure behaviour in distilled water:

The time versus swelling pressure plots for the compacted bentonite specimens hydrated with the distilled water as bulk fluid are shown in Figure 4.2. All the tests were conducted at ambient temperature. The compacted bentonite specimens were tested immediately after completion of the compaction process and further hydrating the specimens using distilled water. The equilibrium swelling pressures were found to reach within about 7 days for all cases irrespective of the dry density and the bulk solution. The time-swelling pressure results in this study showed that interlayer expansion was more dominant than collapse of the bigger voids upon hydration leading to single maxima for all swelling pressure tests.

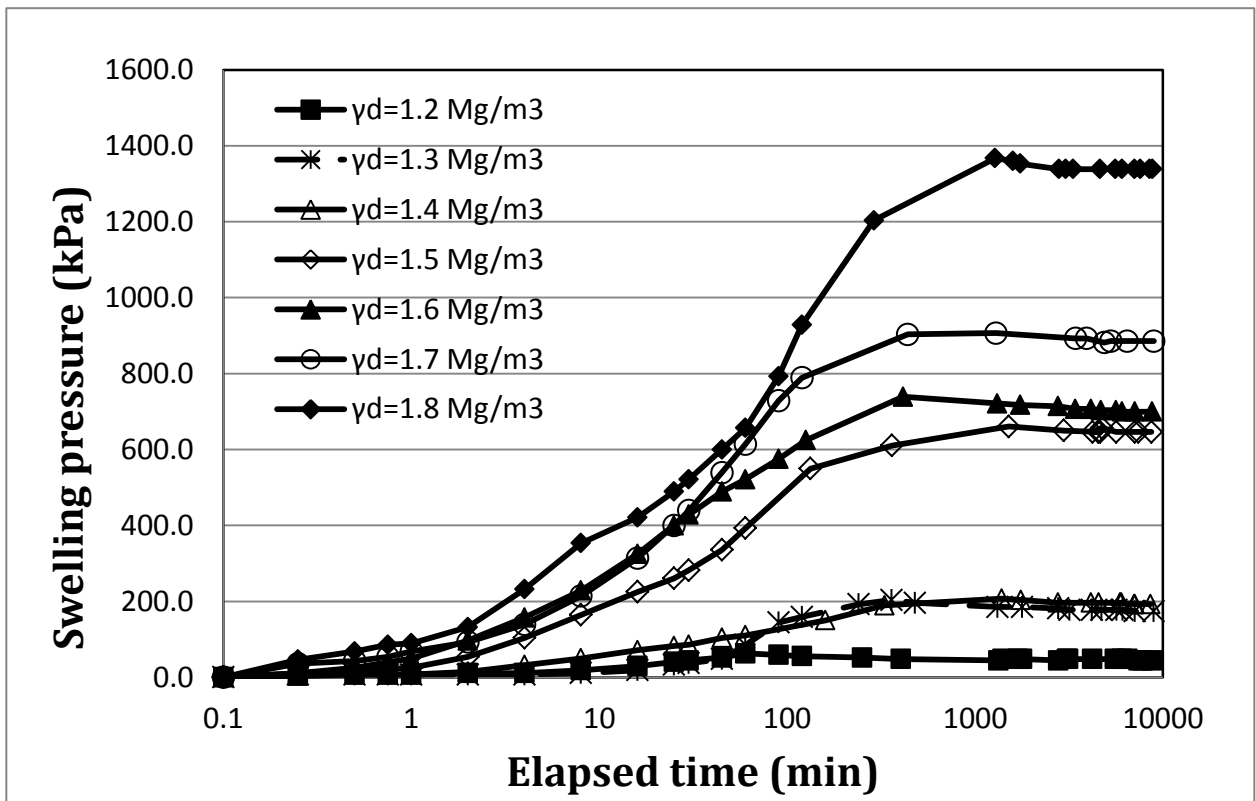


Figure 4.2: Typical time-swelling pressure plots with distilled water as inundating fluid.

#### 4.4 Dry-density swelling pressure plot:

Figure 4.3 shows the dry densities of the bentonite at the end of the tests and the corresponding maximum swelling pressures of the specimens tested in the laboratory. The dry densities of the bentonite at the end of the tests may slightly vary from the dry density to which the sample was initially compacted. This is due to the small deformations allowed by the equipment and to inaccuracies in the application of loads. Compacted bentonite specimens in all the tests were hydrated with distilled water. It has been found that with increase in dry density swelling pressure increases. This behaviour is due to the fact that as the dry density increases which causes a decrease in the interlayer spacing and an increase in the osmotic pressure between the clay platelets and thus the swelling pressure of the clay increases. An increase in the swelling pressure due to an increase in the dry density of swelling clays occurs due to a decrease in the magnitude of suction stress associated with a decrease in suction and development of the interparticle repulsive pressure (i.e., the swelling pressure). The magnitude of interparticle repulsive pressure in saturated bentonites increases with an increase in the dry density.

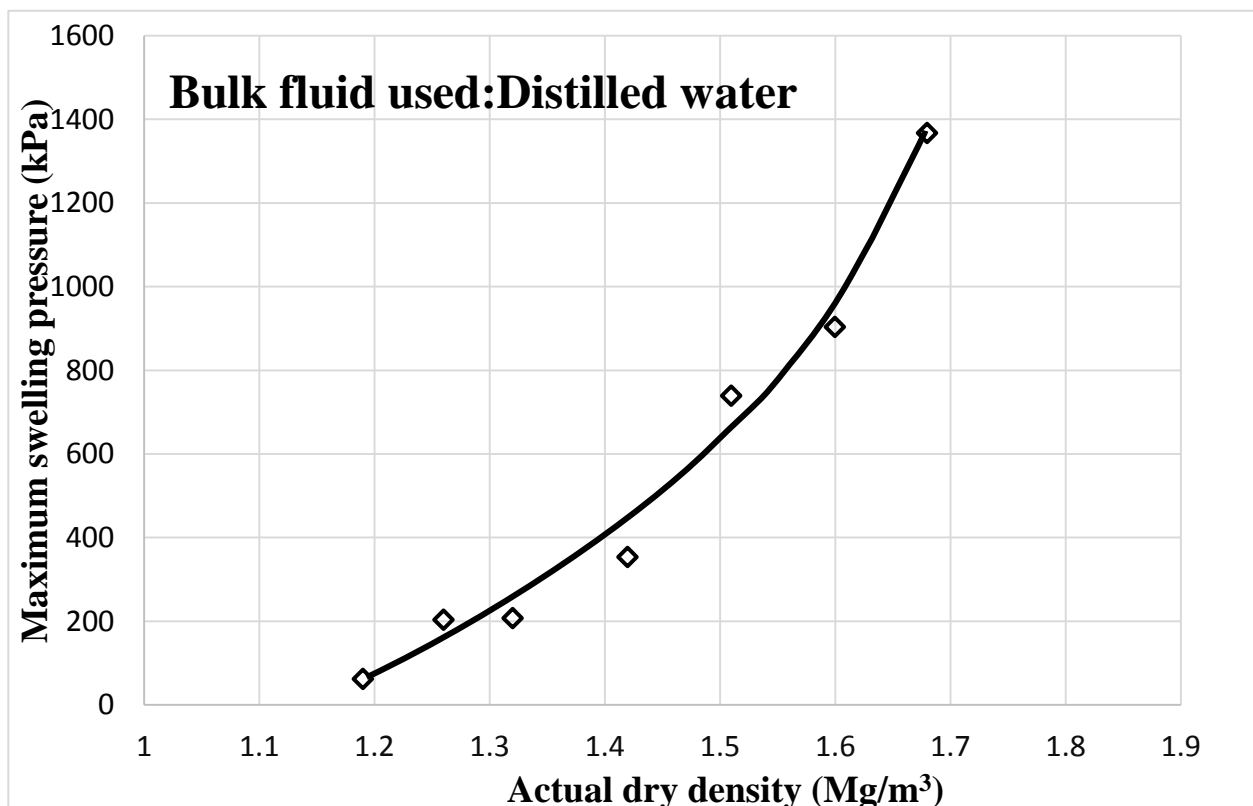


Figure 4.3: Dry density-swelling pressure curve.

### 4.5 Dry density-water content plot:

Figure 4.4 shows the dry density and the corresponding water contents of the specimens after completion of the swelling pressure tests. The water contents remained in between 46% and 64% but almost remained constant for dry densities greater than 1.3 Mg/m<sup>3</sup>.

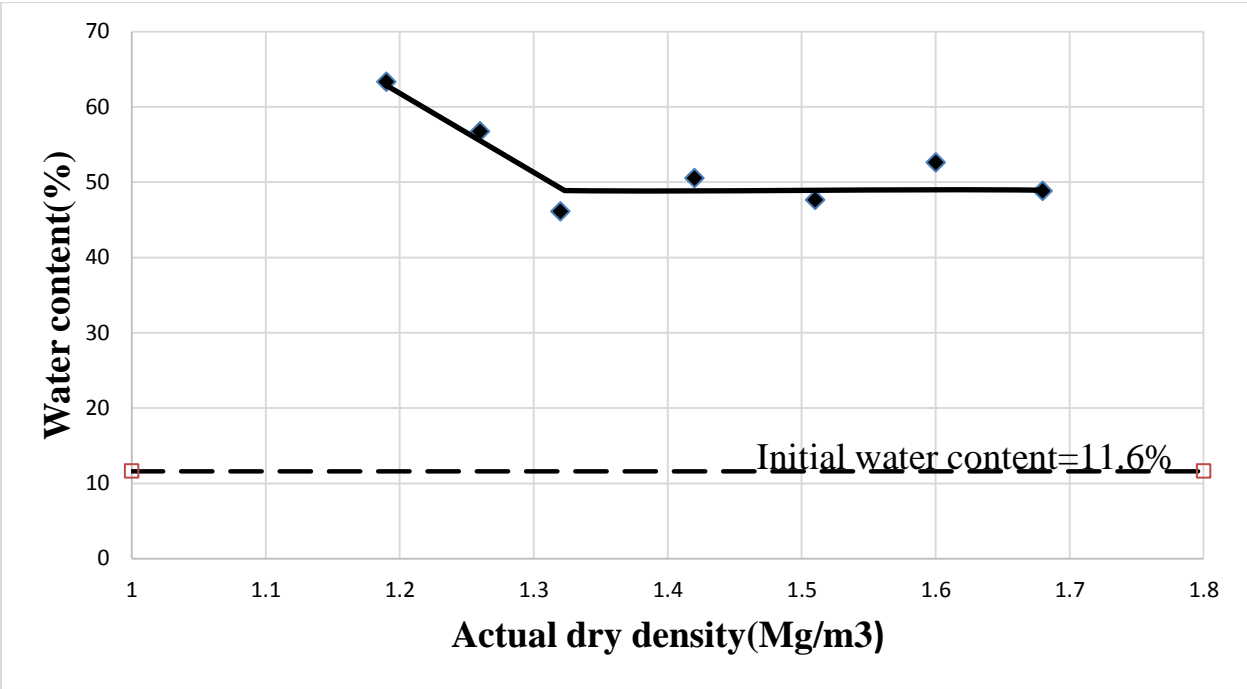


Figure 4.4: Dry density-water content curve.

### 4.6 Time-swelling pressure behaviour of compacted bentonites in salt solutions:

A typical swelling pressure variation with time of compacted bentonite specimens are shown in figure 4.5 and figure 4.6 when saturated with 0.5 M NaCl and 1.0 M NaCl solution. The equilibrium swelling pressures were found to reach within about 7 days for all cases irrespective of the dry density and the bulk solution.

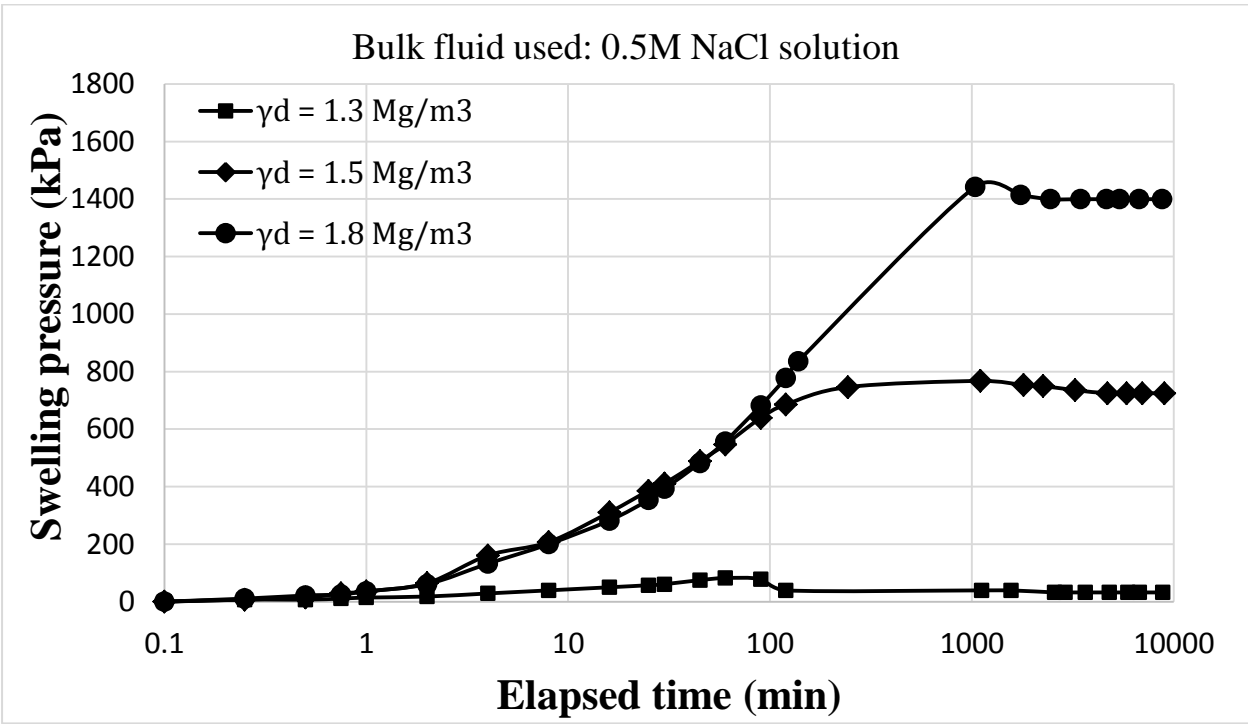


Figure 4.5: Typical time-swelling pressure plot with 0.5 M NaCl solution as inundating fluid.

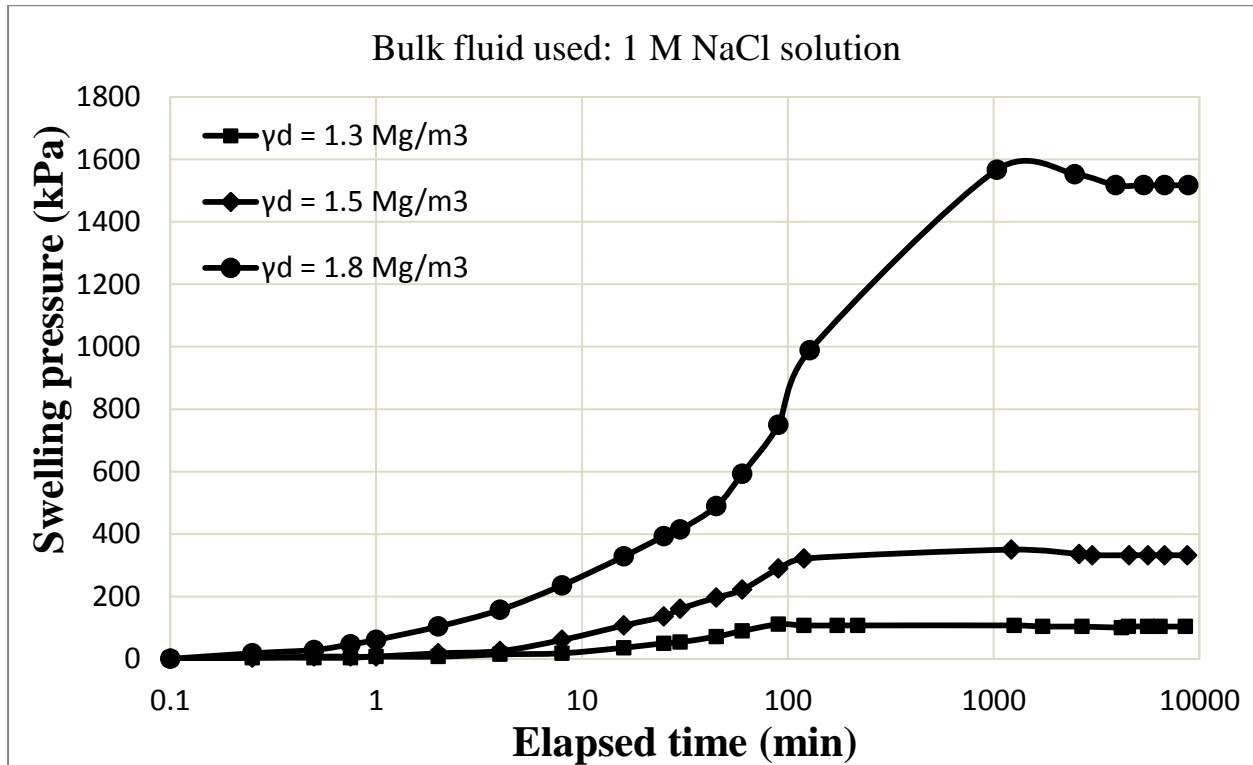


Figure 4.6: Typical time-swelling pressure plot with 1.0 M NaCl solution as inundating fluid.

#### 4.7 Dry-density swelling pressure plot for salt solution:

Figure 4.7 shows the relationship between the maximum swelling pressure and the initial targeted dry density of compacted bentonite material. The figures portray the influence actual dry density immediate after compaction maximum swelling pressure in distilled water and each concentration salt solution.

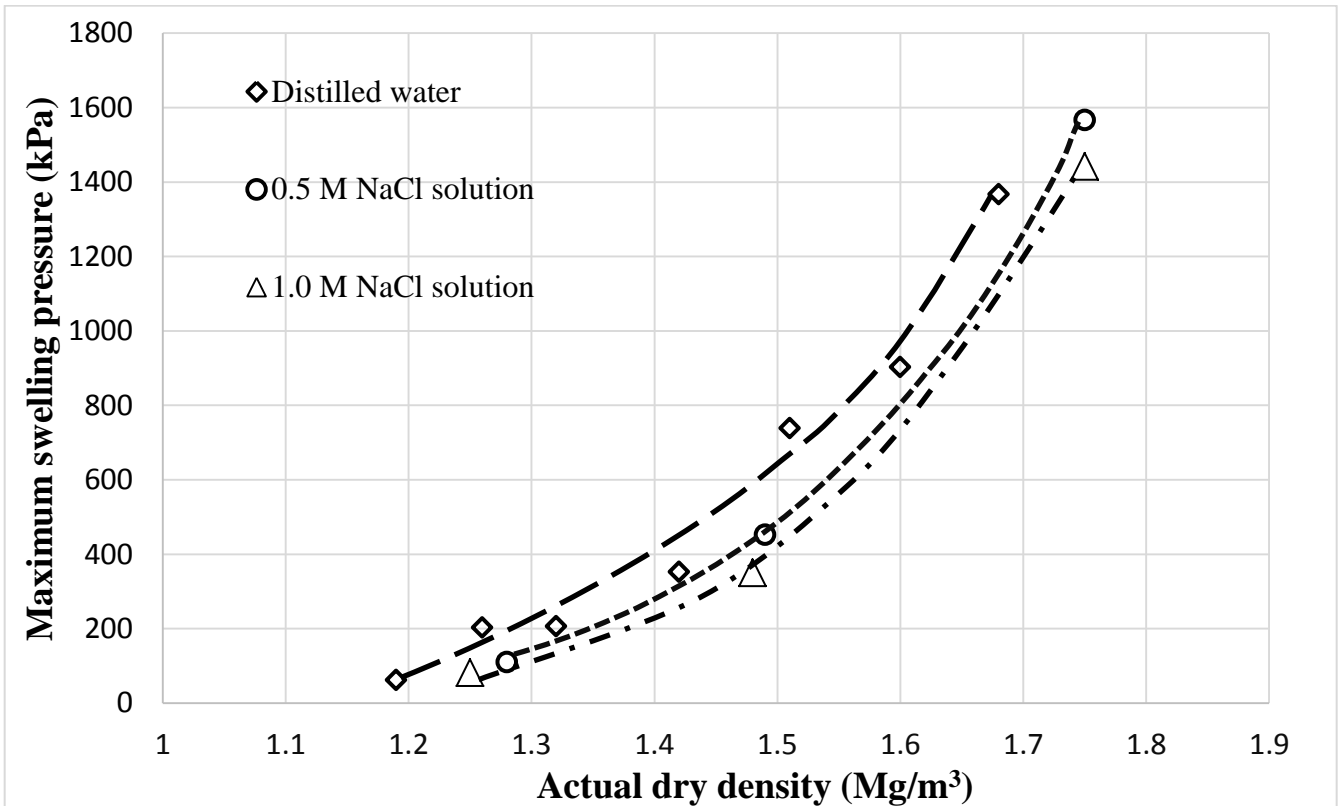


Figure 4.7: Dry density-swelling pressure curve for NaCl solution.

#### 4.8 Dry density-water content plot for salt solution:

Figure 4.8 shows the dry density and the corresponding water contents of the specimens after completion of the swelling pressure tests. When the compacted bentonite specimens are hydrated with distilled water, water contents remained in between 46% and 64% but almost remained constant for dry densities greater than 1.3 Mg/m<sup>3</sup>. In case of salt solutions, the water contents of the specimens after swelling pressure tests was found to decrease with an increase in the targeted dry density for all the tests.



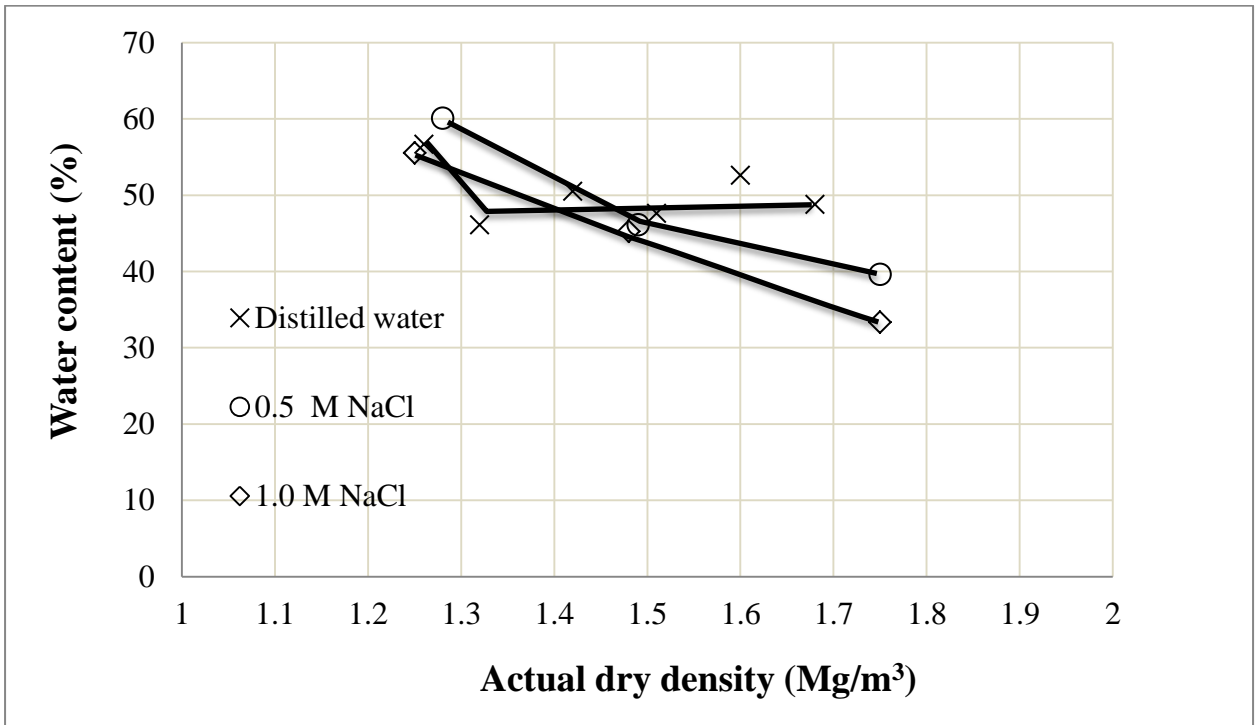


Figure 4.8: Dry density-water content curve for NaCl solution.

## CONCLUSIONS

The effect of dry density and electrolytic solution on swelling pressure of bentonite are brought out in this chapter. The measured water contents of specimens after swelling pressure tests are shown in the experimental results. Based on above experimental results the following concluding remarks can be drawn.

Higher load required for compaction of bentonite at higher dry density. The equilibrium swelling pressures were found to reach within about 7 days for all cases irrespective of the dry density and the bulk solution. With increase in dry density swelling pressure increases. Water uptake capacity was found to be decreased at lower dry densities, whereas, beyond targeted dry density of  $1.4 \text{ Mg/m}^3$  it was remain constant when swelling pressure tests of bentonite specimens were conducted with distilled water as a bulk fluid. When swelling pressure tests of bentonite specimens were carried out with different concentrations of NaCl solution, water contents of specimens after swelling pressure tests were found to be decreased with the increase in dry densities. The influence of higher NaCl concentration in the bulk fluid was found to reduce the swelling pressures of compacted bentonite specimens.

### 5.1 Future scope of the work:

Base on the current investigation following future research works are suggested

- Theoretical swelling pressure - dry density relationship can be found out using diffuse double layer and stern layer theory.
- Carry out test at higher temperature.
- Swelling pressure tests to be carried out with sand-bentonite mixture specimens.

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