SWELLING AND PERMEABILITY BEHAVIOUR OF GRANULATED BENTONITE PERMEATED WITH DIFFERENT PORE FLUIDS

A dissertation submitted in

partial fulfilment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY

In

CIVIL ENGINEERING

(With specialization in Geotechnical Engineering)

Under

ASSAM SCIENCE AND TECHNOLOGY UNIVERSITY

SESSION: 2023-2025

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DECLARATION

I hereby declare that the work presented in this report entitled " **SWELLING AND PERMEABILITY BEHAVIOUR OF GRANULATED BENTONITE PERMEATED WITH DIFFERENT PORE FLUIDS** " in partial fulfilment of the requirement for the award of the degree of Master of Technology in Civil Engineering with specialization in Geotechnical engineering submitted to the Department of Civil Engineering, Assam Engineering College, Jalukbari, Guwahati-13 under Assam Science and Technology University, is an authentic record of my own work carried out in the said college for six months under the supervision and guidance of Dr. Binu Sharma, Professor, Department of Civil Engineering, Assam Engineering College, Jalukbari, Guwahati- 13, Assam.

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ACKNOWLEDGEMENT

I would like to extend my sincere appreciation to Dr. (Mrs.) Binu Sharma, Professor in the Department of Civil Engineering at Assam Engineering College, for her extensive support and encouragement throughout the project. Her guidance, constant supervision and provision of necessary information were invaluable to me. Working under her was an inspiring and great experience, and I am highly indebted to her.

This project would not have been possible without the help of my senior, Bhaskar Jyoti Medhi Sir; laboratory assistants and staffs, for their guidance in various ways. Without their guidance and support it would not have been possible for me to prepare and complete this study.

I am also grateful to Dr. Jayanta Pathak, Professor and Head of the Department of Civil Engineering at Assam Engineering College as well as the entire community of the Department of Civil Engineering at Assam Engineering College for providing us with the necessary infrastructure and comfort throughout the course, particularly during my project.

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ABSTRACT

Granulated Bentonite, a type of swelling clay, is the primary material used in Geosynthetic clay liners because it can expand when it comes into contact with water, forming an impermeable barrier. It is increasingly chosen as an efficient hydraulic barrier for the disposal of hazardous municipal wastes in landfills. There is a growing attention nowadays, on how granulated bentonite reacts after being exposed to landfill leachates.

In this research work Free Swell Index test, Permeability test and Liquid Limit test are carried out on granulated bentonite to study its behavior when organic pore fluids viz. ethanol and methanol mixed with different proportions of distilled water is allowed to saturate the sample. The proportions of the pore fluids consist of 100% distilled water, 20% ethanol/methanol – 80% distilled water, 40% ethanol/methanol – 60% distilled water, 60% ethanol/methanol – 40% distilled water and 80% ethanol/methanol – 20% distilled water.

From the free swell test, the swelling of granulated bentonite is maximum for 100% distilled water. As organic pore fluid concentration increased, the swelling percentage of granulated bentonite decreases. Additionally, the time at maximum swelling for different concentrations, known as break time is recorded and visual pictures of the same is also taken. Further, pore fluid content (PFC) in percentage is also determined from the test. The falling head permeability test is carried out to record the average time at which the soil sample reaches a limiting permeation rate of 10^{-7} cm/s. It has been observed that as the organic pore fluid content increases, the average time also increases. Again, in the Casagrande's liquid limit test, without any organic fluid mixed with distilled water showed maximum value and as the organic content increases, liquid limit values drop.

The reason behind this is when distilled water is poured over the granulated bentonite sample, diffused double layers (DDLs) form around the bentonite particles. This leads to the breakdown of the granules, which in turn reduces the hydraulic conductivity. Consequently, the sample reaches the limiting penetration rate (10^{-7} cm/s) in a shorter amount of time. Additional time is required to reach a permeation rate of 10^{-7} cm/s as the organic content in the pore fluid increases.

The study further, aims to predict relationship between the break time and the average time and also between the conventionally determined liquid limit and the PFC. Multiple linear regression analysis is carried out for predicting the relations.

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CHAPTER 1
INTRODUCTION

1.1 General

Geosynthetic Clay Liners (GCLs) are advanced composite materials widely used in environmental and civil engineering applications to provide effective hydraulic barriers. These materials are composed of a thin layer of bentonite clay encapsulated between two geotextiles or adhered to a geomembrane. The bentonite, a naturally occurring clay with high swelling and low permeability properties, acts as the core component of GCLs, delivering exceptional sealing performance. When hydrated, the bentonite layer expands, forming a dense, cohesive barrier capable of restricting fluid migration. The geotextiles or geomembranes surrounding the clay serve to protect, reinforce, and ensure the durability of the liner during installation and operation.

GCLs have gained prominence due to their numerous advantages over conventional compacted clay liners. These advantages include ease of installation, cost-effectiveness, and superior hydraulic performance in thin sections. They require significantly less material volume compared to traditional liners, making them suitable for projects with spatial constraints or challenging site conditions. Additionally, GCLs offer enhanced chemical resistance and compatibility with a wide range of leachates, making them an ideal choice for applications such as landfill liners, mining waste containment, and water resource management.

GCLs are nearly impervious and can be used as an alternative to conventional compacted clay liners. They offer equivalent or lower rates of release of fluids and chemicals than Compacted Clay Liners (CCLs). GCLs contribute to long-term performance, compatibility with other geosynthetics, and reduced environmental impact, making them a versatile solution for diverse engineering projects.

1.2 Granulated Bentonite

Granulated bentonite is one of the primary components of Geosynthetic Clay Liners (GCLs) that are extensively used for their excellent swelling and sealing properties. It is derived mainly from sodium montmorillonite, with a high-water absorption capacity and ability to swell and form a low-permeability barrier. The swelling properties of bentonite depend on the nature of the pore fluid in contact with the bentonite. Sodium bentonite swells maximally if hydrated with deionized or distilled water, but interference from the presence of ions can significantly reduce its swelling potential. Dissolved salts, organic compounds, and other contaminants within pore fluids could significantly alter swelling potential. Higher salinity and multivalent cations, including calcium and magnesium, can enhance ion exchange in the bentonite structure and thus reduce swelling with increased permeability. Similarly, organic liquids may reduce the hydration rate through the reduction of water availability. The interaction of granulated bentonite with different pore fluids is a matter of interest and crucial for understanding the performance of GCLs under various environmental conditions, including those in landfills or containment systems exposed to leachates. Bentonites used in geo synthetic clay liners typically have montmorillonite contents ranging from 65 to 90% (Shackelfordet al. 2000). In case of waste disposal liner systems, 15%-100% bentonites are used to reduce leakage of pollutants to the sub soil and ground water table (Pusch, 2015). Bentonite is primarily composed of montmorillonite mineral, having high specific surface area, high cation exchange capacity (CEC), high charge density and ability to interlayer swelling.

1.3 Pore Fluids

The pore fluid chemistry plays a very important role on behavior of soil. Various past studies showed that the factors like pore fluid concentration, viscosity, dielectric constant etc. influence the behavior of soil. The granulated bentonite behavior when permeated with organic pore fluids were studied using the pore-fluids; distilled water, ethanol, methanol and their mixtures at different proportions. The ethanol and methanol were combined at increments of 20% by volume with distilled water to prepare organic pore fluid of different proportions. The organic pore fluids reduce the thickness of diffused double layer (DDL) as it reduces the swollen bentonite, flow path opens and permeability enhances. The organic pore fluids mixed in different proportion are 100% distilled water, 20% ethanol/methanol-80% distilled water, 40% ethanol/methanol-60% distilled water, 60% ethanol/methanol-40% distilled water and 80% ethanol/methanol -20% distilled water.

1.4 Objective of the study

The purpose of this study is to assess how swelling behavior in granulated bentonite, which is a key component of Geosynthetic Clay Liners, is affected by different pore fluids. In this study, an attempt is made to understand interactions between bentonite and different fluid compositions, such as distilled water and organic fluids (ethanol and methanol), found in real applications like landfill liners and containment systems. The results are intended to provide insight into the compatibility of bentonite with diverse fluid conditions, optimize the design of GCLs for specific environmental challenges, and enhance predictions of their long-term stability and effectiveness in preventing fluid migration.

The main objective is to study and analyze how granulated bentonite, a core component of Geosynthetic Clay Liners (GCLs), responds when exposed to various pore fluids. This investigation aims to:

- Assess the impact of different pore fluids (e.g., water, organic solvents) on the swelling capacity of granulated bentonite.
- Examine the relationship between swelling characteristics and the permeability of the GCL when different fluids are introduced.

CHAPTER 2
Background and Literature review

2.1 General

The swelling behavior of granulated bentonite when exposed to various pore fluids has been extensively researched to gain insights into its performance in different environmental and engineering contexts. Bentonite, known for its high expansiveness, undergoes considerable volume changes depending on the fluid it interacts with, which affects its utility in applications like liners, barriers, and sealing systems. The nature of the pore fluid is critical in influencing the swelling potential, as elements such as ionic concentration, pH, and fluid composition can alter the expansion of bentonite particles at the interlayer level. Research indicates that water and low-salinity fluids promote maximum swelling, whereas high-salinity or organic fluids can greatly inhibit expansion due to ion exchange and osmotic effects. Grasping these swelling characteristics is vital for enhancing the performance of bentonite-based materials in containment systems, geotechnical projects, and waste management. Current studies are aimed at improving the properties of bentonite or integrating it with additives to boost its swelling capacity and stability across various environmental conditions.

2.2 Literature Review

Arasan (2010) examined various studies on the geotechnical properties of clay liners, focusing on aspects such as consistency limits, hydraulic conductivity, shear strength, swelling, and compressibility when exposed to organic and inorganic chemicals acting as leachate. The author noted that clay liners, due to their low permeability, are the primary material used in solid waste disposal landfills, and their properties can be influenced by a range of chemical, biological, and physical factors stemming from leachate. After reviewing multiple papers, the author concluded that the behavior of low plasticity clays (CL and kaolinite) differs from that of high plasticity clays (CH and bentonite). Specifically, it was found that for high plasticity clay, both the liquid limit and swelling decrease as chemical concentration increases, while for low plasticity clay, these properties increase with higher chemical concentrations. Additionally, the hydraulic conductivity of high plasticity clay rises with increasing chemical concentration, whereas it decreases for low plasticity clay. The author also identified a lack of information regarding the shear strength of clay and clay liners in relation to chemicals but concluded that shear strength tends to increase with higher chemical concentrations. The effects of chemicals on geotechnical properties were explained through Diffuse Double Layer (DDL). These theories suggest that chemical solutions can reduce the thickness of the DDL and cause clay particles to flocculate, leading to a decrease in liquid limit, a reduction in swelling, and an increase in hydraulic conductivity for high plasticity clays. Conversely, for low plasticity clays, chemical solutions tend to increase the thickness of the DDL and disperse the clay particles, resulting in an increase in liquid limit, swelling, and a decrease in hydraulic conductivity.

Bharat et al. (2019) investigated the movement of chemicals through compacted clays and its impact on the materials' porosity. They found that different methods for determining chemical diffusion produce varying concentration data. When comparing effective diffusion coefficients in both reactive and non-reactive conditions for the same type of clay, the results can be misleading. The available porous space is essential for calculating the effective diffusion coefficient in reactive conditions. The selection of a laboratory diffusion technique is influenced by the specific model parameters needed. No single technique can completely substitute for another. For example, while the half-cell technique is effective for estimating porous space, it does not accurately measure the effective diffusion coefficient. Conversely, In-Diffusion and through-Diffusion methods are beneficial for independently measuring effective and apparent diffusion coefficients.

Bouazza (2002) conducted a study on Geosynthetic Clay Liners (GCLs), which have gained widespread acceptance as alternatives to compacted clay liners in various applications, including cover systems, composite bottom liners, and environmental barriers. These liners are utilized in transportation facilities, storage tanks, canals, ponds, and impoundments. The study examined the hydraulic and diffusion properties, chemical compatibility, mechanical behavior, durability, and gas migration of GCLs. The paper reviews key findings, highlighting important factors that influence the service life of GCLs. This work aims to provide a thorough understanding of the design considerations for systems that incorporate GCLs.

Chen et al. (2018) investigated the hydraulic conductivity of geosynthetic clay liners (GCLs) made with granular sodium bentonite when exposed to leachates from coal combustion products (CCPs). They chose five synthetic leachates based on a comprehensive survey of CCP disposal facilities across the country. The study utilized common GCLs from two American manufacturers and discovered that the hydraulic conductivity of the GCLs varied depending on the type of leachate. GCLs that were directly permeated with trona leachate exhibited high conductivity, while others showed moderate to high conductivity with various CCP leachates at a pressure of 20 kPa. The findings indicated that hydraulic conductivity was associated with the ionic strength of the leachate and was inversely related to the bentonite swell index when hydrated in the leachate. An increase in effective stress from 20 to 450 kPa led to a significant reduction in hydraulic conductivity. Pre-hydration on a subgrade had little effect, but pre-hydration with deionized water before permeating with trona leachate greatly reduced hydraulic conductivity, suggesting possible chemical resistance strategies for dealing with CCP leachates.

Evangeline and John (2010) investigated how leachate affects calcium bentonite and four types of sodium-activated bentonites. They used acetic acid and calcium chloride to simulate the components of leachate. The study focused on changes in properties such as Atterberg's limits, swell index, percentage of swell, and hydraulic conductivity at different chemical concentrations. After performing laboratory tests on various samples, the authors discovered that the liquid limit, plasticity index, free swell, and percentage swelling of all bentonite types decreased due to the influence of acetic acid and calcium chloride solutions. They also found that hydraulic conductivity increased with higher concentrations of acetic acid. Additionally, the variations in liquid limit, plasticity index, free swell, percentage swelling, and hydraulic conductivity were notably greater with calcium chloride compared to acetic acid solutions.

Nath et al. (2023) conducted an insightful study investigating the potential use of locally available Khulna clay soil, amended with varying percentages of sodium bentonite, as a material for landfill liners. The study highlights the importance of enhancing the geotechnical properties of local soils to meet the stringent requirements for liner systems in engineered landfill sites, which are crucial for preventing leachate migration and subsequent groundwater contamination.

The research aimed to identify the optimal bentonite-soil mix that satisfies both hydraulic conductivity (HC) and strength criteria required for landfill liner materials. A range of bentonite proportions (5%, 10%, 15%, and 20%) was mixed with Khulna clay, and a comprehensive suite of geotechnical tests was performed. These tests included compaction, consistency limits, hydraulic conductivity, free swell index, unconfined compressive strength (UCS), and pH assessments. The study focused on quantifying the improvements in the soil's geotechnical properties with increasing bentonite content.

Rahman et al. (2021) The study explores how bentonite-sand mixtures swell when exposed to different percentages of ethanol-water and methanol-water solutions. Tests were conducted to determine the free swell index (FSI), modified free swell index (MFSI), and free swell ratio (FSR) using various pore fluid compositions ranging from 0% to 100% ethanol and methanol. The findings show that swelling diminishes as the concentration of ethanol and methanol increases, with the highest swelling occurring in a mixture of 100% bentonite and distilled water. A strong linear relationship was identified between the dielectric constant of the pore fluids and the swelling behavior of the bentonite-sand mixtures. Among the three methods used, MFSI proved to be the most effective for comparing the free swell of these mixtures. The results underscore the important role that dielectric constants play in swelling characteristics, enabling the calculation of free swell based on the properties of the pore fluid.

Rahman and Sharma (2022) This study investigates how bentonite-sand mixtures swell when exposed to different percentages of ethanol-water and methanol-water solutions as pore fluids in a one-dimensional consolidometer. The findings reveal that both swelling pressure and swell percentage diminish as the concentration of ethanol and methanol increases, demonstrating a strong link to the dielectric constants of the solutions. An increase in bentonite content results in more significant swelling, with the highest swelling occurring in distilled water, while swelling decreases with higher organic content in the pore fluid. The research also identifies linear relationships between swelling pressure, swelling percentage, and dielectric constants, which allows for the prediction of swelling behavior through empirical correlations. Furthermore, swell percentage/time plots indicate that the maximum swelling percentage can be estimated from their slope, and swelling pressure declines as the bentonite content is lowered. These results underscore the impact of dielectric constant and pore fluid composition on the swelling properties of bentonite-sand mixtures, offering important insights for engineering applications where managing swelling is essential.

Scalia et al. (2019) introduced two innovative methods to speed up the swell index (SI) testing of bentonite in geosynthetic clay liners (GCLs), addressing the shortcomings of the standard test method specified in ASTM D5890. These methods, called the Fast Alternative Swell Test (FAST) and the Multiple Alternative Swell Test (MAST), aim to significantly cut down the time needed for SI testing while still providing reliable results for granular bentonite that is coarser than the No. 60 sieve. The study compared the FAST and MAST methods to the standard ASTM D5890 approach using bentonites from seven different sources. Tests were performed with various hydration liquids, including deionized (DI) water and potassium chloride (KCl) and calcium chloride ($CaCl_2$) solutions at concentrations of 5, 10, 50, 100, and 500 mM. The results showed:

i. Both expedited methods produced results similar to the standard test when using DI water and KCl solutions.
ii. A slight underestimation of the SI values was noted in tests with $CaCl_2$ solutions, with a maximum error of 25%, although typical errors were below 15%.

Scalia et al. recommended the FAST method for situations involving one to three tests, highlighting its speed and reliability. For projects that require four or more simultaneous tests, the MAST method was suggested due to its efficiency in batch testing. For finer bentonite particles (those not retained on the No. 60 sieve), the standard ASTM D5890 method is still the preferred choice to ensure accuracy.

Seiphoori et al. (2016) investigates the water retention and swelling behavior of granular bentonites for their application in Geosynthetic Clay Liner (GCL) systems, which are widely used as hydraulic barriers in landfills for hazardous municipal waste containment. Bentonites, known for their high retention, adsorption, and swelling capacities, are key components of GCLs. However, their significant volume change upon wetting can affect the hydraulic performance, particularly at lower suction levels.

The research focuses on characterizing the water retention and swelling responses of two granular bentonites: MX-80 (with optimized grain size distribution) and Volclay GC-50, both widely used in GCL systems. Using a novel methodology, water retention behavior was evaluated under various compaction states, and reconstituted GCL specimens were tested to derive water retention curves. The study found that water retention at higher suction values (>2 MPa) is primarily governed by an adsorption mechanism in bentonite. At lower suction values, the composite structure of the GCL (bentonite and geotextiles) influences water retention, with geotextiles playing a more significant role.

The swelling potential experiments revealed a significant increase in the hydrated void ratio at lower suction levels. This increase is attributed to modifications in smectite particle arrangements, which lead to the emergence of new pore structures within the bentonite matrix. These changes in void ratio are expected to influence the hydraulic conductivity and diffusion properties of GCLs.

Shirazi et al. (2010) carried out an in-depth study to assess the permeability and swelling characteristics of bentonite and bentonite-sand mixtures. These factors are crucial for designing waste disposal systems and applications in geo-environmental engineering. Their significance is especially pronounced when considering buffer materials for radioactive waste disposal, where precise predictions of permeability and swelling behavior are vital for maintaining containment integrity. The study highlighted the role of the void ratio in influencing the permeability of both pure bentonite and bentonite-sand mixtures. Key findings include:

i. The permeability of bentonite decreases significantly as the void ratio decreases, with a sharp decline observed when the void ratio falls below 2.
ii. An increased proportion of bentonite in bentonite-sand mixtures leads to a noticeable reduction in permeability, highlighting the role of bentonite content as a controlling factor in buffer material design.
iii. While permeability varied between different types of bentonites under loading and non-loading conditions, the specimen preparation methods had no significant effect on permeability.

This work provides valuable insights into the permeability and swelling behaviour of bentonite and bentonite-sand mixtures. The study emphasizes the importance of void ratio, bentonite content, and environmental factors such as temperature and loading pressure in controlling these properties. This research serves as a foundation for designing reliable buffer materials for waste containment systems, particularly in radioactive waste disposal applications, where performance and safety are paramount.

Vipulanandan and Leung (1991) investigated how methanol and seepage control affect permeable kaolinite soil. Their research focused on the impact of water and methanol on the behavior of kaolinite clay and a clay-sand mixture. Additionally, they used sodium-based bentonites, Portland cement, and sodium silicates as additives and grouting materials to explore seepage control methods in these mixtures. They conducted sedimentation analysis at various methanol concentrations (0%, 25%, 50%, 75%, and 100%). Significant sedimentation was observed when methanol concentrations exceeded 75%. Pure methanol caused soil particles to flocculate and settle within minutes, potentially influencing hydraulic conductivity. The flocculation was attributed to methanol's low dielectric constant, which diminished the diffuse double layer around clay particles.

CHAPTER 3
Materials and Methodology

3.1 General

This chapter describes the materials, implementation methods and experiments employed for the research. Different laboratory experiments are discussed one at a time for both index and engineering properties of soil samples (granulated bentonite) as well as the pore fluids (distilled water-ethanol/methanol mixtures) used in this study.

3.2 Materials

3.2.1 Granulated Bentonite

Bentonite has been proposed and utilized as an engineered barrier to improve the effectiveness of landfill liners, the cores of zoned earth dams, and systems for radioactive waste disposal due to its low hydraulic conductivity, high swelling properties, and excellent self-sealing abilities. Granulated bentonite refers to bentonite clay that has been processed into granules. This type of absorbent clay is primarily made up of montmorillonite, a fine-grained mineral. Its unique structure provides it with exceptional absorption and swelling capabilities, making bentonite valuable across various industries for its wide range of properties.

3.2.2 Pore Fluids

Distilled water, ethanol, methanol, and their mixtures in different proportions were utilized as pore fluids to investigate the behavior of granulated bentonite when permeated with organic pore fluids. Ethanol and methanol were combined in increments of 20% by volume with distilled water to create organic pore fluids of varying proportions. The resulting organic pore fluid mixtures included 100% distilled water, 20% ethanol/methanol and 80% distilled water, 40% ethanol/methanol and 60% distilled water, 60% ethanol/methanol and 40% distilled water, and 80% ethanol/methanol and 20% distilled water.

3.3 Testing Methods

3.3.1 Free Swelling Test

Free swelling tests on the soil samples were conducted according to IS 2720 (Part XL):1977. A 10-gm dried soil specimen was placed in two glass graduated cylinders, each with a capacity of 100 ml. One cylinder was filled with pore fluid (distilled water) along with varying concentrations of organic pore fluid for the study, while the other cylinder was filled with kerosene oil up to the 100 ml mark. After gently shaking and stirring with a glass rod to remove any trapped air, the soils were allowed to swell and reach an equilibrium state for a sufficient duration (not less than 24 hours). The final volumes of the soils in each cylinder were recorded for further calculations.

3.3.2 Atterberg Limits

Atterberg limits were determined as per IS 2720 (Part V): 1985. Liquid limits of the different soil samples were determined using Casagrande apparatus. Thread rolling method was used to determine plastic limits.

3.3.3 Permeability Test

3.3.3.1 Falling Head Test

The Falling Head Test is a standard method described in IS 2720 (Part 17):1986 for determining the permeability of soils, including low-permeability materials like Geosynthetic Clay Liners (GCLs). The test is particularly suitable for materials with low hydraulic conductivity, where the constant head method may not be practical.
Hydraulic conductivity (k) is determined using equation

$$k = \frac{2.303\,.\,a\,.\,L}{A.t} \log_{10}(h_1/h_2) \quad \ldots\ldots (3.1)$$

where, a = Cross-sectional area of the standpipe.

L = Length of the specimen.

A = Cross-sectional area of the specimen.

t = Time for water level to fall from h_1 to h_2 (seconds).

h_1, h_2 = Initial and final water heads.

CHAPTER 4
Analysis of Swelling Behaviour of Granulated Bentonite

4.1 General

The swelling behavior of granulated bentonite is a key property that influences its effectiveness as a sealing and hydraulic barrier material in various geotechnical and environmental applications, including Geosynthetic Clay Liners (GCLs). Primarily derived from sodium montmorillonite, bentonite has an impressive capacity to absorb water and expand, forming a low-permeability barrier that effectively limits fluid movement. This distinctive swelling characteristic is affected by factors such as particle size, hydration conditions, and the chemical makeup of the fluid it interacts with. Understanding the swelling behavior of granulated bentonite is essential for assessing its performance under different environmental conditions, such as exposure to saline solutions, leachates, and organic fluids. This analysis offers valuable insights into how well bentonite can work with specific site conditions, aiding in material selection and the design of containment systems. By investigating the mechanisms and degree of swelling, this study seeks to improve the predictive modeling of bentonite's long-term behavior, ensuring its reliability and effectiveness across various applications.

4.2 Analysis of Free swelling behavior of Granulated bentonite

4.2.1 Effect of Granulated bentonite on free swelling

A total of nine samples were prepared in soil (granulated bentonite) by mixing organic pore fluid at different proportions by volume. The proportions involved 100% distilled water, 80% ethanol/methanol-20% distilled water, 60% ethanol/methanol-40% distilled water, 40% ethanol/methanol-60% distilled water and 20% ethanol/methanol-80% distilled water. In order to get pore fluid with varying percentages of ethanol and methanol, the amount of distilled water was gradually added to every test experiment of the solvents in increments of 20 percent by volume. The free swell tests were conducted based on the specifications in IS: 2720 Part (XL)-1977. The measured granulated bentonite soil quantity was 10 grams and this was filled in two 100-ml graduated glasses. Pore fluid to be tested was filled in the first cylinder. Kerosene oil was filled into the second cylinder to a volume of 100 ml. Soils were shaken and stirred using a glass rod to remove any air trapped and left to swell until it attains equilibrium concerning volume for not less than 24 hours. But in this case, the volume of the soils within each of the cylinders were recorded for next 24 hours, i.e. 48 hours.

The free swell index (FSI) was determined as per the equation given in IS: 2720 Part (XL)- 1977.

$FSI = (V_d - V_k)/V_k \times 100$ ……………... (4.1)

Where V_d= Sediment volume of 10 gm soil in a 100 ml cylinder containing pore fluid

V_k= Sediment volume of 10 gm soil in a 100 ml cylinder containing kerosene.

The method based on FSI has a shortcoming in that it gives negative free swell indices for kaolinite rich soils. To counter this problem Sridharan et.al. (1985) proposed a criterion based on modified free swell index (MFSI) The modified free swell index (MFSI) was determined as per the equation proposed by Sridharan et.al. (1985)

$MFSI = V_d/10$ ……………………… (4.2)

Where V_d= Sediment volume of 10 gm soil in a 100 ml cylinder containing pore fluid. It has been observed that the equilibrium sediment volume of kaolinite rich soils in non-polar liquids like carbon tetra chloride and kerosene can be even greater than the equilibrium sediment volume of the same soils in water (Sridharan et.al. 1985). This observation had led Sridharan and Prakash (1999) to propose the free swell ratio (FSR). The free swell ratio (FSR) was also determined as per the equation proposed by Sridharan et.al. (1985).

$FSR = V_d/ V_k$ ………………………... (4.3)

Where V_d= Sediment volume of 10 gm soil in a 100 ml cylinder containing pore fluid.

V_k= Sediment volume of 10 gm soil in a 100 ml cylinder containing kerosene/carbon tetrachloride.

At regular intervals, the sediment volume of soil in each cylinder was measured and noted for use in subsequent computations.

The time at which the bentonite granules are completely broken and maximum swelling occurs, known as break time and denoted by T_f is also recorded. Table 4.2 lists the break time of various concentrations.

Table 4.1: Free Swelling Index of Granulated Bentonite

Pore Fluids	Proportion	FSI	Swell%	Sediment Volume (SV)	MFSI	FSR
		48hr	48hr	48hr		
Ethanol: Distilled Water	0:100	170%	170%	27	2.7	2.7
	20:80	150%	150%	25	2.5	2.5
	40:60	100%	100%	20	2	2
	60:40	50%	50%	15	1.5	1.5
	80:20	30%	30%	13	1.3	1.3

Pore Fluids	Proportion	FSI	Swell%	Sediment Volume (SV)	MFSI	FSR
		48hr	48hr	48hr		
Methanol: Distilled Water	0:100	170%	170%	27	2.7	2.7
	20:80	140%	140%	24	2.4	2.4
	40:60	100%	100%	20	2	2
	60:40	40%	40%	14	1.4	1.4
	80:20	20%	20%	12	1.2	1.2

Table 4.2: Break Time of Granulated Bentonite of different proportions

Pore Fluids	Proportion	Break Time (T_f) (hr)
Ethanol: Distilled Water	0:100	24
	20:80	28
	40:60	36
	60:40	0.333
	80:20	0.01667
Methanol: Distilled Water	0:100	24
	20:80	30
	40:60	32
	60:40	1
	80:20	0.01667

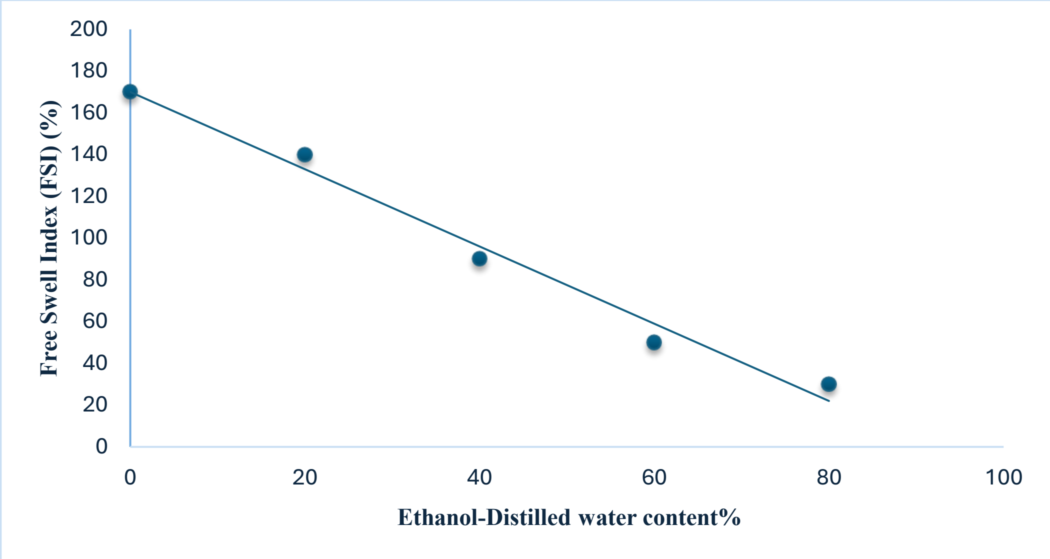

Fig 4.1: Free Swell Index of Ethanol Distilled water content

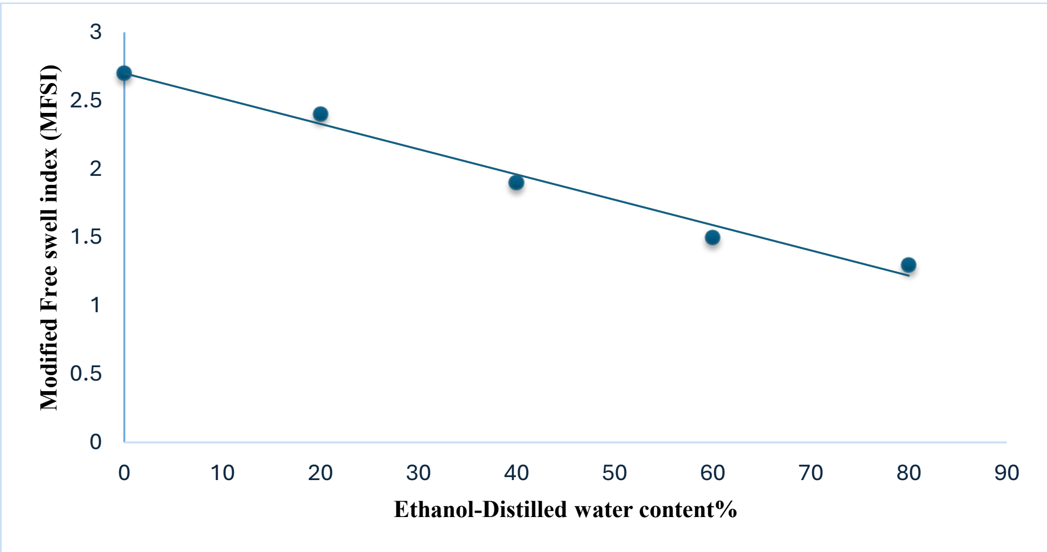

Fig 4.2: Modified Free Swell Index of Ethanol - Distilled water content

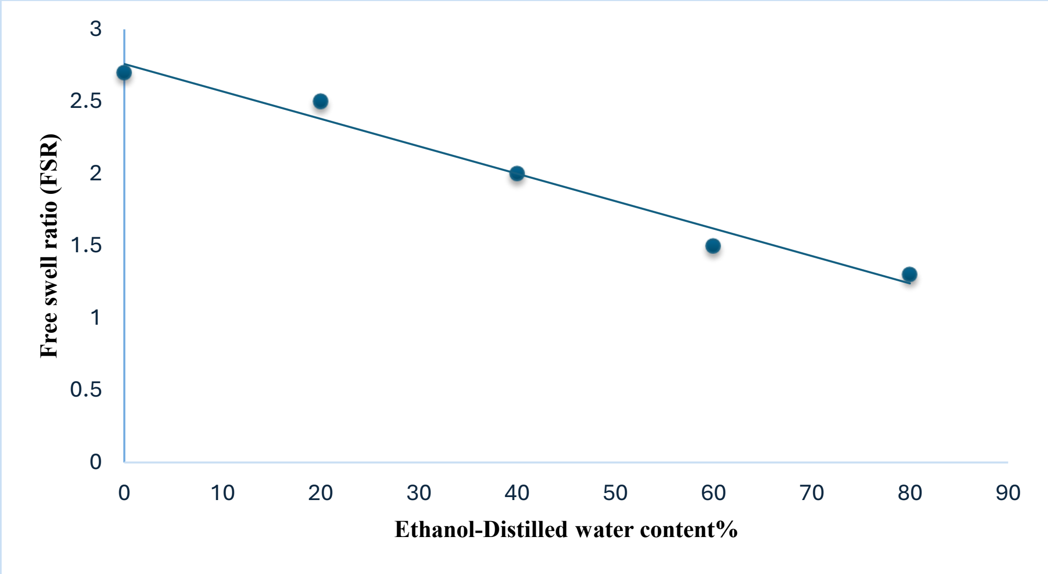

Fig 4.3: Free Swell Ratio of Ethanol - Distilled water content

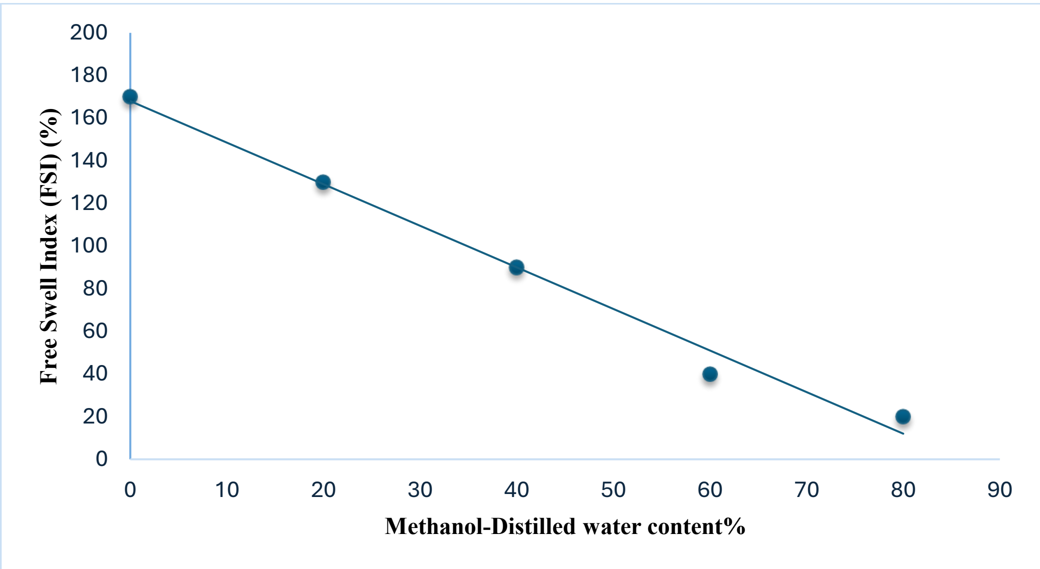

Fig 4.4: Free Swell Index of Methanol - Distilled water content

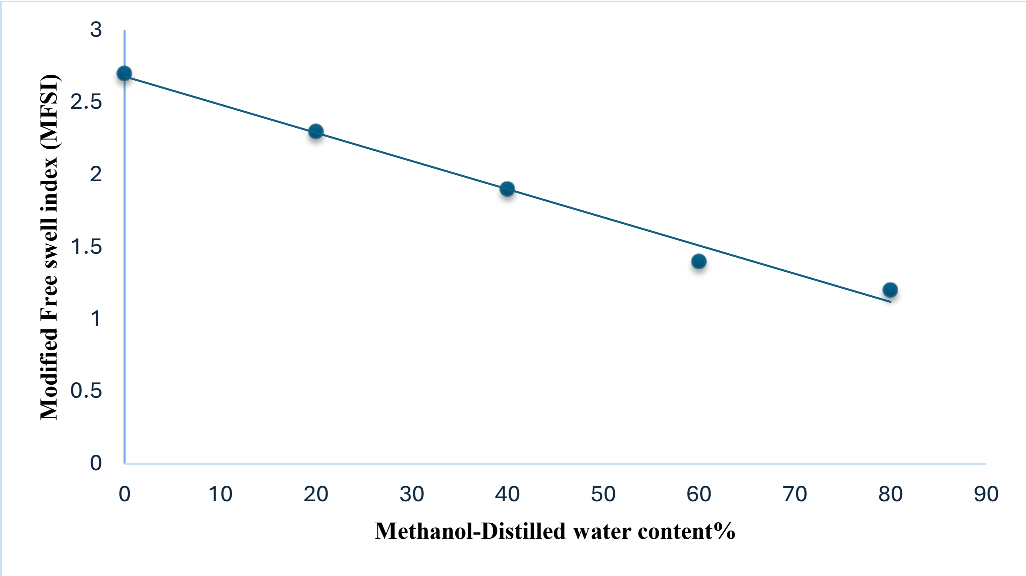

Fig 4.5: Modified Free Swell Index of Methanol Distilled water content

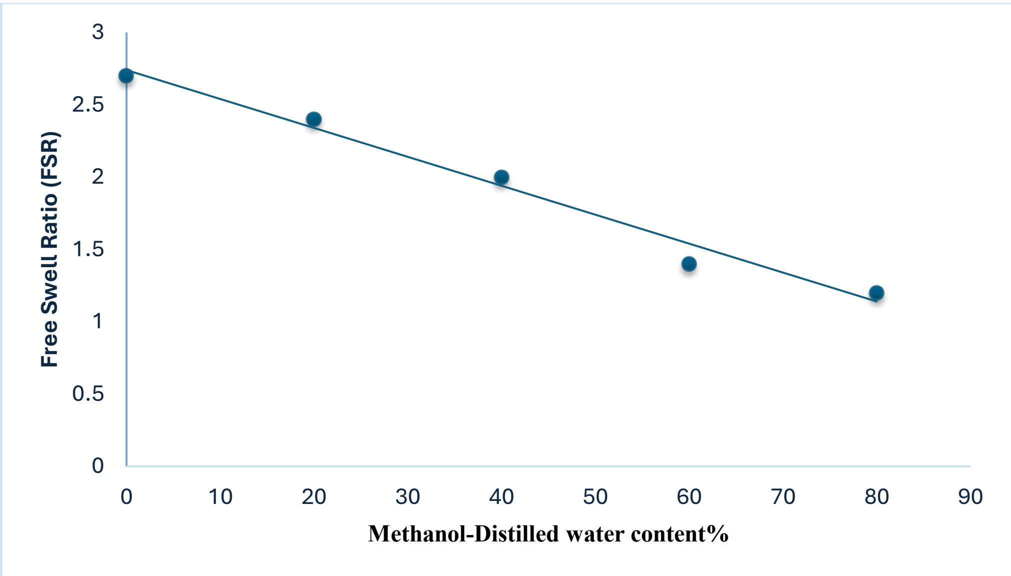

Fig 4.6: Free Swell Ratio of Methanol Distilled water content

In order to analyse the behaviour of granulated bentonite in ethanol-water and methanol-water mixture, the results from performed tests in the laboratory are plotted. The above plots from fig 4.1-4.6 shows free swell index (FSI), modified free swell index (MFSI) and free swell ratio (FSR), it can be seen that swelling is maximum for the pore fluid as distilled water, then with increment of ethanol and methanol content, swelling decreases.

During the Free Swell Index test, photos were captured at different intervals of time. From fig 4.7 to 4.15 shows the sediment volume of granulated bentonite of different concentrations at maximum swelling.

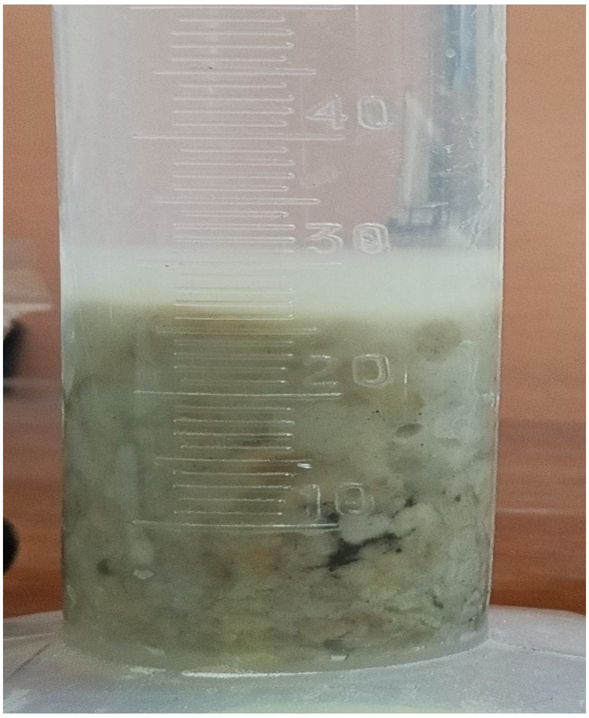

Fig 4.7:100% DW, SV=27, T_f = 24hr

Fig 4.8:(20%E+80%DW), SV=24, T_f = 28hr

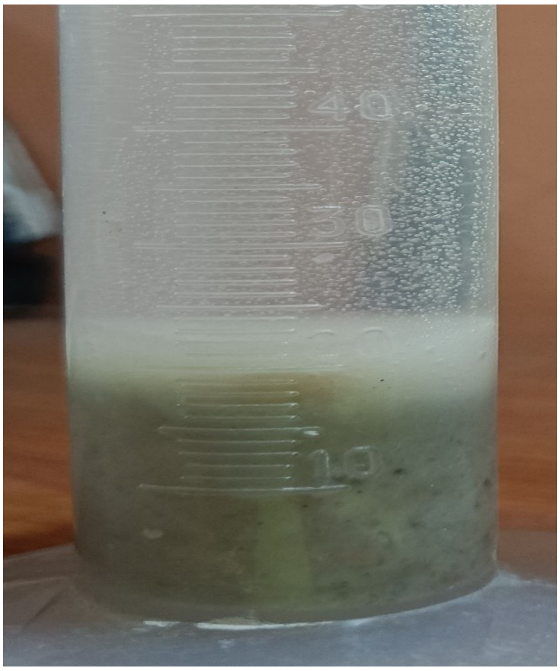

Fig 4.9:(40%E+60%DW), SV=20, T_f = 36hr

Fig 4.10:(60%E+40%DW), SV=15, T_f = 20min

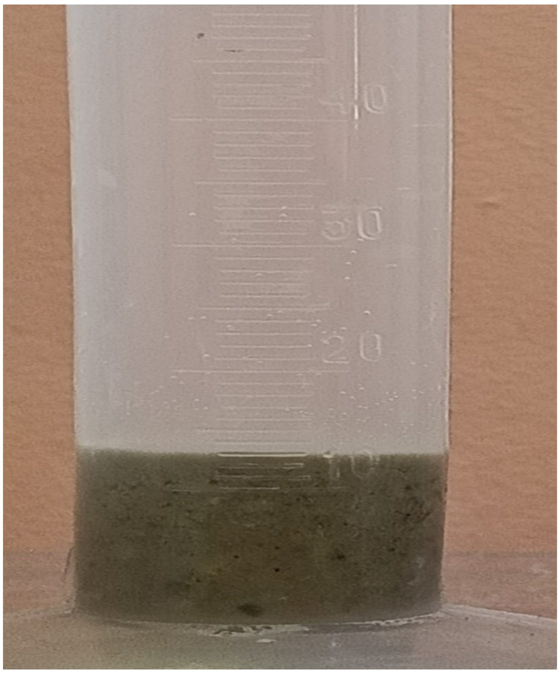

Fig 4.11:(80%E+20%DW), SV=13, T_f = 1min

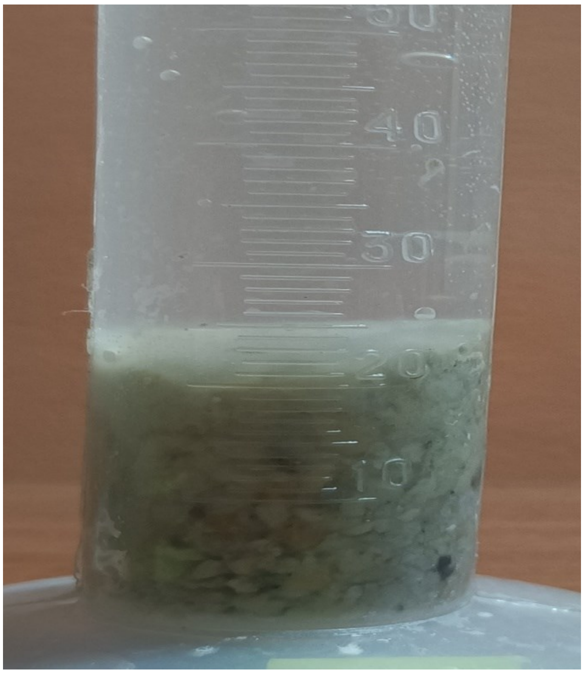

Fig 4.12:(20%M+80%DW), SV=24, T_f = 30hr

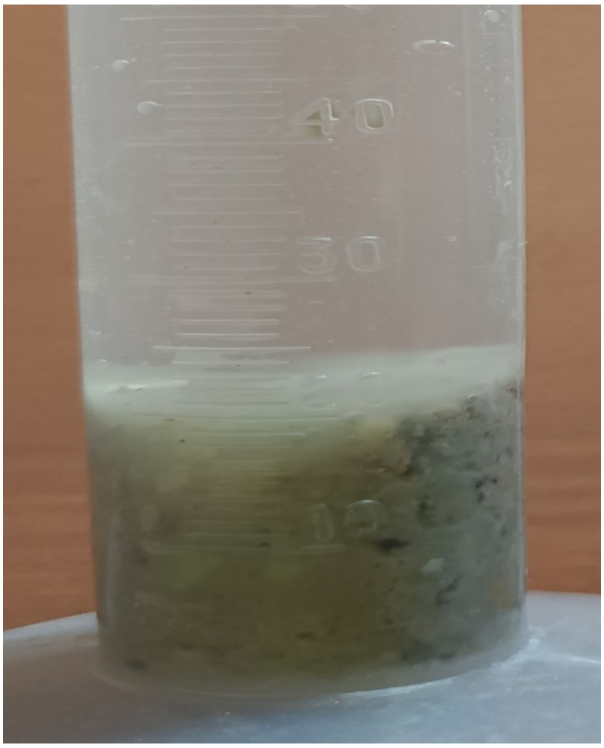

Fig 4.13:(40%M+60%DW), SV=20, T_f = 32hr

Fig 4.14:(60%M+40%DW), SV=14, T_f = 1hr

Fig 4.15:(80%M+20%DW), SV=12, T_f = 1min

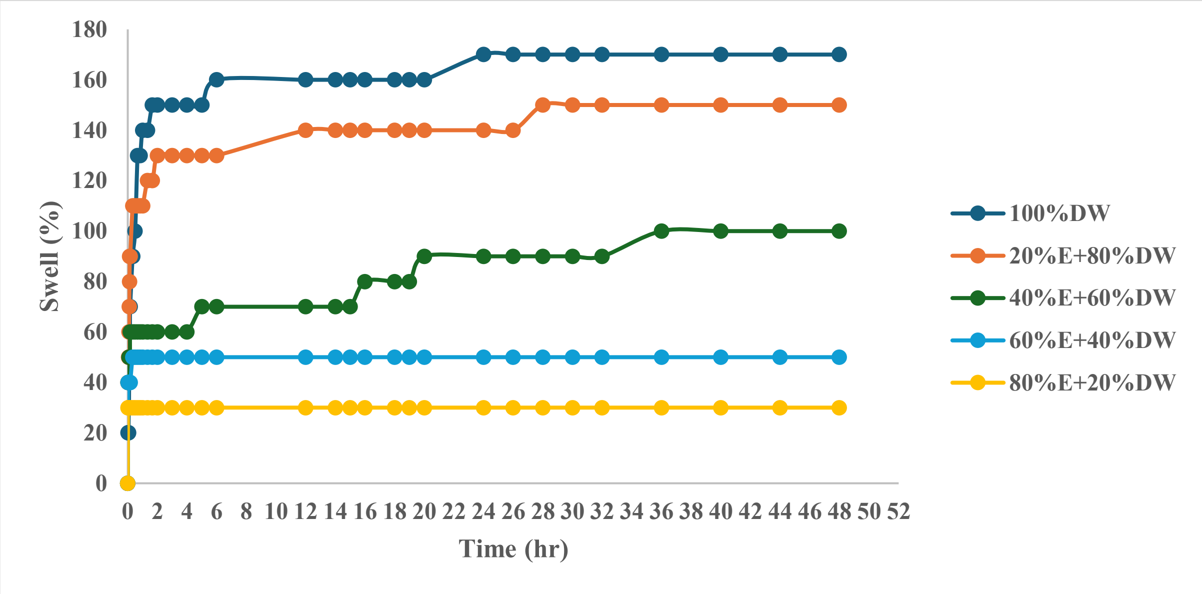

Fig 4.16: Time vs Swell % (100% Distilled Water and Ethanol Proportions)

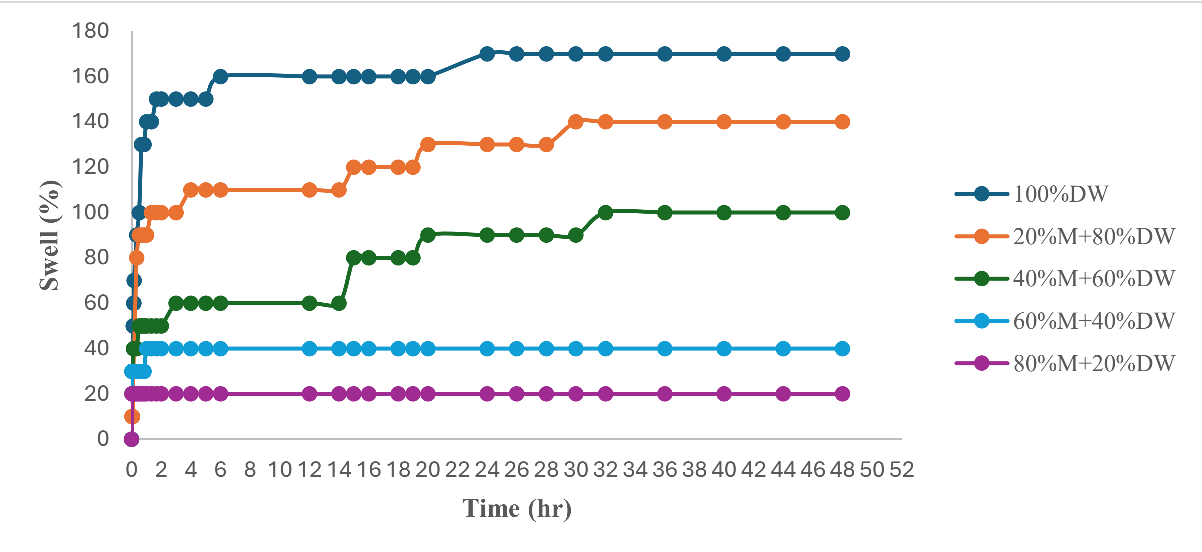

Fig 4.17: Time vs Swell % (100% Distilled Water and Methanol Proportions)

Fig 4.16 and 4.17 illustrates that as the pore fluid transitions from distilled water to ethanol-water and methanol-water mixes, investigations have shown that the sediment volume of the granulated bentonite sample decreases. The result shows that maximal swelling occurs after 24 hours for 100% distilled water whereas for 20% ethanol - 80% distilled water and 40% ethanol - 60% distilled water, maximum swelling are reached after 28 and 36 hours, respectively. Moreover, the maximal swelling occurs after 30 and 32 hours for 20% methanol - 80% distilled water and 40% methanol - 60% distilled water, respectively. Therefore, it may be stated that break time increases when the pore fluid changes from distilled water to ethanol-water and methanol-water mixtures. It is also evident from the visual images that all of the bentonite granules are shattered at this moment during break time. However, soil samples showed insignificant swelling at 60% ethanol-40% distilled water and 80% ethanol-20% distilled water proportions. A similar result is seen when the proportion of 60% methanol - 40% distilled water and 80% methanol - 20% distilled water is used. According to the data, swelling stopped about 0.33 hours (20 minutes) and 0.0167 hours (1 minute) at proportions of 60% ethanol to 40% distilled water and 80% ethanol to 20% distilled water, respectively. Again, maximum swelling is reached after 1 hour and 0.0167 hours for the 60% ethanol-40% distilled water and 80% ethanol-20% distilled water proportions respectively. In addition, visual images demonstrate that the bentonite granules are unbroken.

CHAPTER 5

Prediction of Liquid Limit of Granulated Bentonite by Free Swell Index test

5.1 General

Liquid limit of granulated bentonite is one of the significant characteristics describing its ability to absorb water and change from plastic to liquid condition. Typically exhibiting a high liquid limit, more than 300%, granulated bentonite, because of its major mineral sodium montmorillonite, possesses a very high surface area and considerable attraction for water. A high liquid limit of bentonite means it can hold high water contents and retain its sealing and swelling capabilities, which are useful for applications such as Geosynthetic Clay Liners (GCLs). The concept of liquid limit is basic to the evaluation of bentonite's plasticity, environmental compatibility, and performance.

5.2 Liquid Limit Determination

Liquid limit of granulated bentonite was determined using Casagrande apparatus as per IS: 2720 (Part 5) – 1985. Liquid limit test was done for 100% distilled water, 20% ethanol/methanol + 80% distilled water, 40% ethanol/methanol + 60% distilled water, 60% ethanol/methanol + 40% distilled water and 80% ethanol/methanol + 20% distilled water.

Table 5.1: Liquid limit of granulated bentonite of different proportions of pore fluids

Proportions	Liquid Limit (%)
100% Distilled Water	355
20% Ethanol + 80% Distilled Water	328
40% Ethanol + 60% Distilled Water	274
60% Ethanol + 40% Distilled Water	225
80% Ethanol + 20% Distilled Water	202
20% Methanol + 80% Distilled Water	335
40% Methanol + 60% Distilled Water	310
60% Methanol + 40% Distilled Water	275
80% Methanol + 20% Distilled Water	260

5.3 Pore Fluid Content Determination using Free Swell Test

The pore fluid content at maximum swelling is computed for 100% distilled water, 20% ethanol/methanol + 80% distilled water, 40% ethanol/methanol + 60% distilled water, 60% ethanol/methanol + 40% distilled water and 80% ethanol/methanol + 20% distilled water using the sediment volume (SV), dry weight of the soil sample and its specific gravity (G = 2.75). The pore fluid content, w is determined by the following equation:

$$ƒ_d = (G.\ ƒ_w) / (1+w.G) \Rightarrow w = (ƒ_w / ƒ_d) - (1/G) \quad \ldots\ldots\ldots\ldots \quad (5.1)$$

where, $ƒ_d$ = Dry density (gm/cm^3)

G = Specific gravity = 2.75

$ƒ_w$ = Mass density of the pore fluid (gm/cm^3)

w = Pore fluid content in percentage (PFC) (%)

Mass density of the pore fluids for all the concentrations is listed in Table 5.2

Table 5.2: Mass density of ethanol-distilled water and methanol-distilled water mixtures (Rahman and Sharma, 2022)

Pore Fluids	Proportion	Mass density (gm/cm^3)
Ethanol: Distilled water	0:100	0.997
	20:80	0.966
	40:60	0.931
	60:40	0.887
	80:20	0.839
Methanol: Distilled water	0:100	0.997
	20:80	0.967
	40:60	0.935
	60:40	0.895
	80:20	0.847

Pore fluid content, w expressed in percentage for all the proportions is determined and listed in table 5.3

Table 5.3 Pore Fluid Content of the Ethanol/ Methanol proportion with Distilled water

Proportion	PFC, %
100% DW	232.83
20%E + 80%DW	205.14
40%E + 60%DW	149.84
60%E + 40%DW	96.69
80%E + 20%DW	72.7
20%M + 80%DW	195.72
40%M + 60%DW	150.64
60%M + 40%DW	88.94
80%M + 20%DW	65.28

5.4 Relation between Liquid limit and Pore fluid content of granulated bentonite

The figure 5.1 and 5.2 displays the liquid limits and the pore fluid contents for the concentrations of 100% distilled water, 20% ethanol-80% distilled water, 40% ethanol-60% distilled water, 60% ethanol-40% distilled water, 80% ethanol-20% distilled water, 20% methanol-80% distilled water, 40% methanol-60% distilled water, 60% methanol-40% distilled water, and 80% methanol-20% distilled water, as indicated in tables 5.1 and 5.3 respectively.

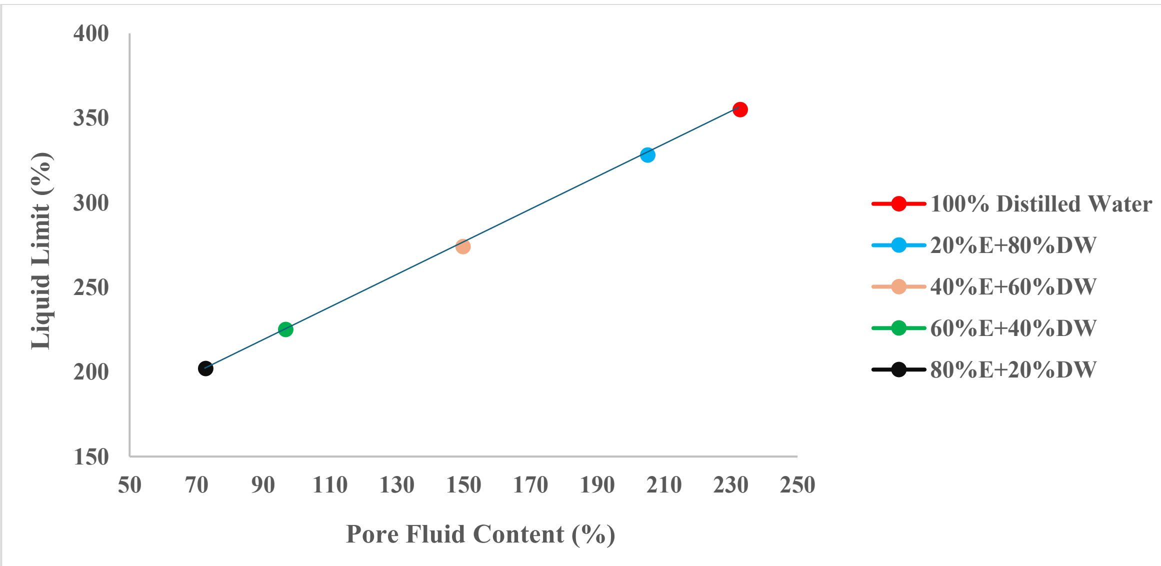

Fig 5.1: Pore fluid content vs Liquid limit of 100% distilled water, 20% ethanol, 40% ethanol, 60% ethanol and 80% ethanol at full swelling

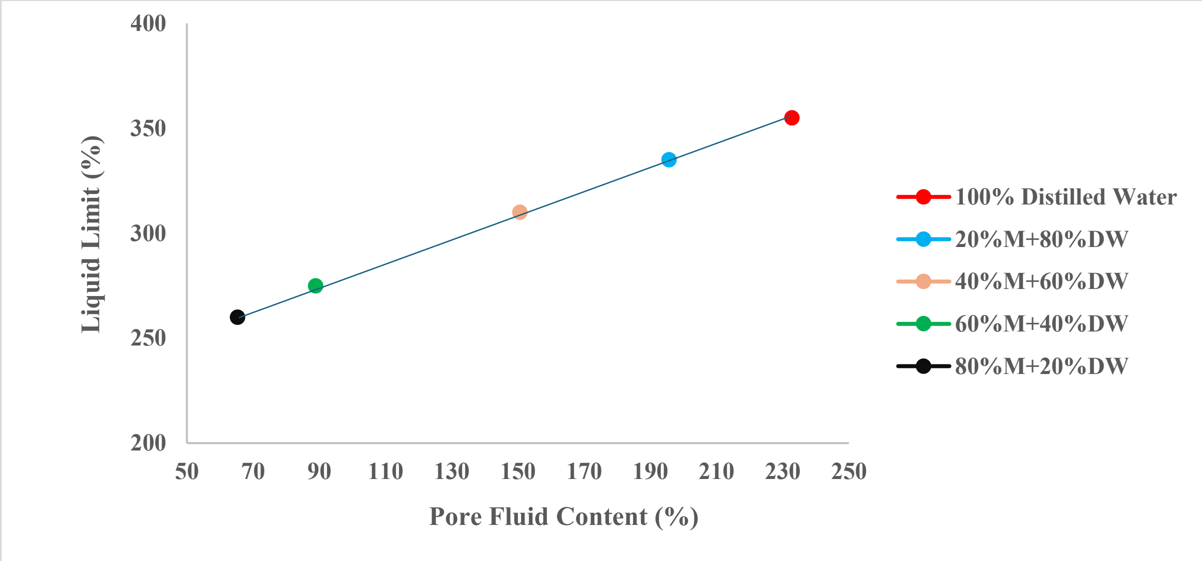

Fig 5.2: Pore fluid content vs Liquid limit of 100% distilled water, 20% methanol, 40% methanol, 60% methanol and 80% methanol at full swelling

Fig 5.1 and 5.2 shows that pore fluid content of granulated bentonite versus the conventionally determined liquid limit. It is observed that when the pore fluid is 100% distilled water PFC is maximum and then with the increment of ethanol and methanol content, pore fluid content decreases. Based on the pore fluid content, % obtained from the free swell test, and the various ethanol and methanol contents, an empirical correlation has been established to determine the liquid limit. Multiple linear regressions were used to analyze data on liquid limit, pore fluid content and various ethanol and methanol concentrations based on the experimental results. The following empirical association was therefore established.

LL=134.92 + 0.94 PFC (%) - 0.02 Ethanol (%) ……………………………………………… (5.2)

LL=232.30 + 0.53 PFC (%) - 0.07 Methanol (%) …………………………………………... (5.3)

Where, LL = Predicted liquid limit (%)

PFC = Pore fluid content (%)

Equation (5.2) applies to granulated bentonite when permeated with any concentrations of ethanol mixed with distilled water, with a correlation coefficient of $R^2 = 0.99$, whereas, equation (5.3) applies when the organic pore fluid is methanol- distilled water and the correlation coefficient of $R^2 = 0.99$.

CHAPTER 6
Analysis of Permeability Behaviour of Granulated Bentonite

6.1 General

Permeability is regarded as one of the most crucial properties of soil in geotechnical engineering. It is influenced by various factors, including the shape and size of soil grains, the properties of pore fluids, the structural arrangement of soil particles, and the degree of saturation of the soils. The rapid increase in human population has led to a simultaneous rise in municipal solid waste generation. This significant growth in waste production worldwide makes the design and construction of landfills a critical issue today. Clay, particularly bentonite, is recognized as an effective material for constructing landfill liners to prevent the migration of leachate into subsoils, thanks to its excellent adsorption and swelling properties. Typically, landfill liners are designed with water as the pore fluid in mind. However, when water interacts with the organic pollutants found in landfills, it forms fluids with properties that differ from those of water, which can cause the liner materials to behave differently when in contact with these organic fluids. The permeability of the liner is a vital mechanical property that plays a crucial role in the effective operation of the landfill. This chapter discusses the permeability properties of granulated bentonite under different effective stresses in a dry, loose condition by permeating mixtures of ethanol-distilled water and methanol-distilled water. While the initial conditions of the soil can influence permeability behavior to some extent, factors such as void ratio, soil characteristics, soil structure, and the nature of organic pore fluids are primary determinants affecting soil permeability.

6.2 Analysis of Permeability behaviour of granulated bentonite in presence of organic pore fluid

The permeation test was conducted by my senior, Mr. Bhaskar Jyoti Medhi Sir. I want to express my gratitude to him for providing me with his data so I could do my research.

One dimensional consolidometer apparatus is used to examine the permeability behaviour of granulated bentonite. The investigation employed commercially available granulated bentonite. During the course of study, market-sourced methanol and ethanol were also used. To create an organic pore fluid with varying proportions and dielectric constants, distilled water is added to ethanol or methanol at a 20% volumetric increment. In order to perform the permeability test by falling head permeability test, a graduated stand pipe was attached to the consolidometer. The consolidometer cutter measured 20 mm in height and 60 mm in internal diameter. Up to the third-fifth (12 mm) height of the cutter, dry samples of granulated bentonite were positioned at an initial density of 1 gm/cm^3.

After 15 minutes of boiling, porous stones were positioned above and below the filter papers, which were placed at the top and bottom of the samples. The loading hanger was subjected to an initial seating load of 5 kN/m^2 at the beginning of the test. Distilled water and different methanol-distilled water and ethanol-distilled water mixes were applied through the stand pipe to saturate the dry soil samples. At regular time intervals, the head of the permeant pore fluid in the stand pipe was measured and recorded until it reached a constant value.

The permeation rate is measured using the falling head permeability equation given below:

$$k = \frac{2.303 \, . \, a \, . \, L}{A.t} \log_{10}(h_1/h_2) \quad \ldots\ldots (6.1)$$

where, a = Cross-sectional area of the standpipe.

L = Length of the specimen.

A = Cross-sectional area of the specimen.

t = Time for water level to fall from h_1 to h_2 (seconds).

h_1, h_2 = Initial and final water heads.

According to United States Environmental Protection Agency (USEPA) standards, hydraulic conductivity of landfill liners must be less than 10^{-7} cm/sec. The time at which a permeation value reaches a limiting value of 10^{-7} cm/s is thus, recorded from the permeation values measured for each time period and is denoted as T_k. Based on the aforementioned studies, a significant correlation between the time at which the bentonite granules broke during the free swell test, denoted by T_f and the average time at which the permeation value reached 10^{-7} cm/s during the consolidometer test, expressed as T_k is expected. The time it takes for GCLs containing granulated bentonite in the landfill to fully break all of its granules, swell, and seal all of the macro voids resulting in a pore fluid permeation rate of 10^{-7} cm/s across it can thus be ascertained using a basic laboratory swelling test.

The fluid permeation rate of various ethanol and methanol concentrations with distilled water through granulated bentonite is illustrated in figure (6.1). The time it takes for various ethanol and methanol concentrations with distilled water to achieve the limiting permeation value is listed in the table (6.1). When granulated bentonite is permeated with distilled water alone, its permeation rate reaches the limiting value of 10^{-7} cm/s within 72 hours of the test beginning, confirming that granulated bentonite can effectively seal macro-voids when distilled water is present without the application of any stress. When 20% ethanol - 80% distilled water solution and 20% methanol - 80% distilled water solution pass through the granulated bentonite sample, the macro-voids are completely sealed reaching the limiting permeation rate after 96 hours of testing without any external loading. In case of 40% ethanol – 60% distilled water and 40% methanol – 60% distilled water solution too, without any applied stress the macro-voids are fully sealed after 144 hours and 120 hours respectively. Although the permeation rate decreases when the pore fluid is 60% ethanol - 40% distilled water, and 60% methanol - 40% distilled water, external loading of 40 kPa and 20 kPa must be applied in order to reach the limiting permeation rate of 10^{-7} cm/s and this is accomplished after 264 and 216 hours, respectively. Further, external loading of 80 kPa and 40 kPa is required for 80% ethanol- 20% distilled water and 80% methanol-20% distilled water, respectively, to obtain the limiting penetration rate of 10^{-7} cm/s and this is achieved after 312 and 264 hours. Therefore, the test indicates that the time trend to achieve the limiting permeation rate lengthens as the percentage of organic fluids, such as ethanol and methanol mixed with distilled water, increases. Additionally, without applying external loading, the limiting permeation rate of 10^{-7} cm/s cannot be achieved in the proportions following 60% ethanol – 40% distilled water and 60% methanol – 40% distilled water.

This is because when distilled water is poured over the granulated bentonite sample, diffused double layers (DDLs) develop around the bentonite particles. As a result, the granules break down, reducing the hydraulic conductivity. The sample therefore approaches the limiting penetration rate (10^{-7} cm/s) within a shorter time i.e 72 hours. However, the osmotic potential of granulated bentonite is decreased in the presence of organic pore fluids, resulting in the development of a thin double layer that inhibits self-sealing. As a result, the sample needs more time to seal all of the spaces, which means it takes longer time to achieve the limiting permeation rate. The osmotic potential of granulated bentonite further decreases as the content of organic pore fluid grows, making it more difficult to construct the diffuse double layer. Therefore, in order to close all of the gaps and so attain the limiting penetration rate, external loading must be applied. The table 6.1 below makes it evident that more time is needed to achieve the permeation rate of 10^{-7} cm/s as the organic content in the pore fluid rises.

Table 6.1: Time to reach a limiting permeation value of 10^{-7} cm/sec

Pore fluids	Proportion	Average Time, T_k (hr)
Ethanol: Distilled water	0:100	72
	20:80	96
	40:60	144
	60:40	264
	80:20	312
Methanol: Distilled water	0:100	72
	20:80	96
	40:60	120
	60:40	216
	80:20	264

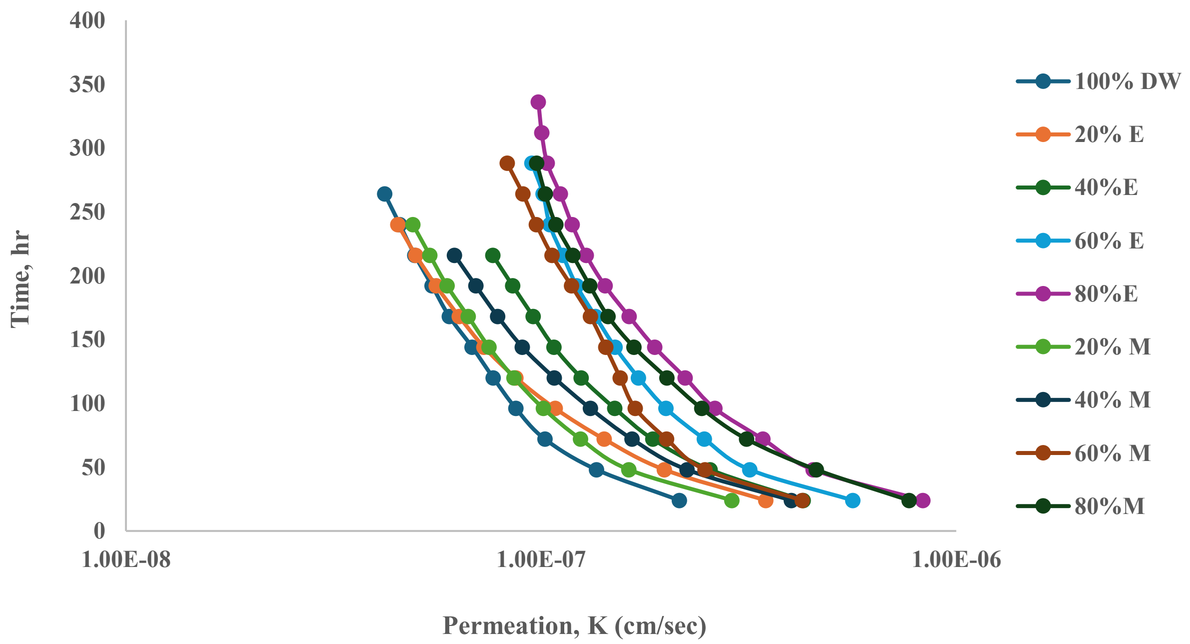

Fig 6.1: Permeation vs Time

The average time to attain the limiting permeation rate of 10^{-7} cm/s is shown in figure 6.2 against the pore fluid contents of 100% distilled water, 20% ethanol-80% distilled water, 40% ethanol-60% distilled water, 60% ethanol-40% distilled water and 80% ethanol-20% distilled water.

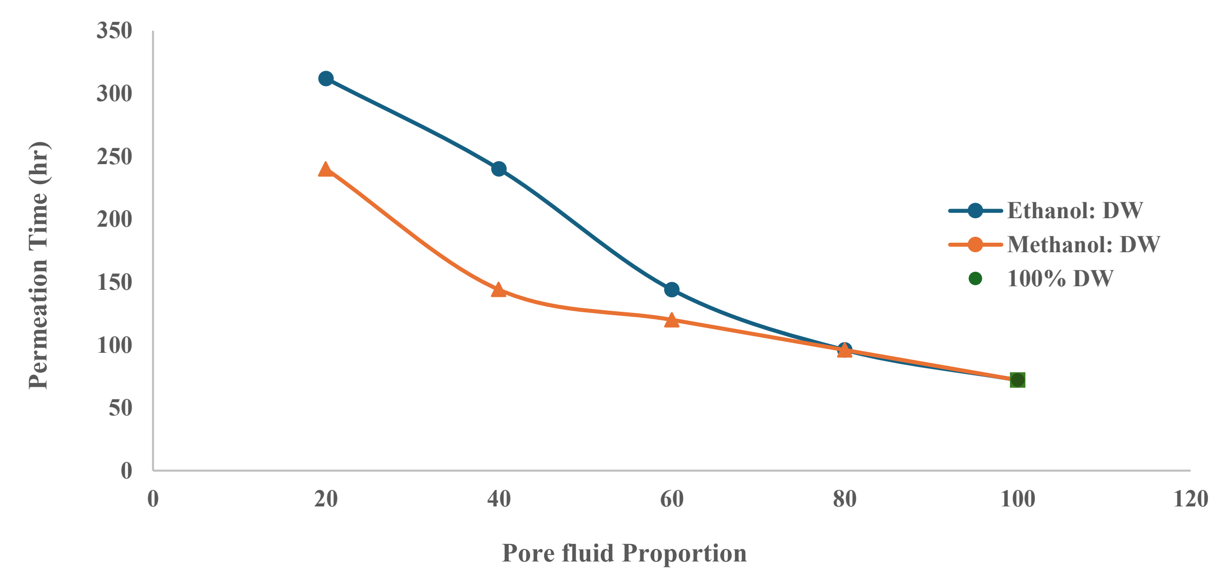

Fig 6.2: Pore fluid Proportion vs Permeation time

The plot shows that the time difference in reaching the permeation value of 10^{-7} cm/s is relatively little when the amount of organic pore fluid is lower. However, the difference in the average duration also grows as the concentration of ethanol and methanol in distilled water rise. In addition, ethanol takes longer than methanol to achieve the limiting permeation value.

6.4 Relation Between Break Time and Average Time to Achieve Limiting Permeation Value of 10^{-7} cm/s

The figure 6.3 displays the break time, T_f and average time to reach the limiting permeation rate of 10^{-7} cm/s, T_k for the proportions of 100% distilled water, 20% ethanol-80% distilled water, 40% ethanol-60% distilled water, 60% ethanol-40% distilled water, 80% ethanol-20% distilled water, 20% methanol-80% distilled water, 40% methanol-60% distilled water, 60% methanol-40% distilled water, and 80% methanol-20% distilled water, as indicated in tables 6.2.

Table 6.2: Break Time and Permeation Time of different proportions

Pore Fluids	Proportion	Break Time (T_f) (hr)	Average Time (T_k) (hr)
Ethanol: Distilled Water	0:100	24	72
	20:80	28	96
	40:60	36	144
	60:40	0.3333	264
	80:20	0.01667	312
Methanol: Distilled Water	0:100	24	72
	20:80	30	96
	40:60	32	120
	60:40	1	216
	80:20	0.01667	264

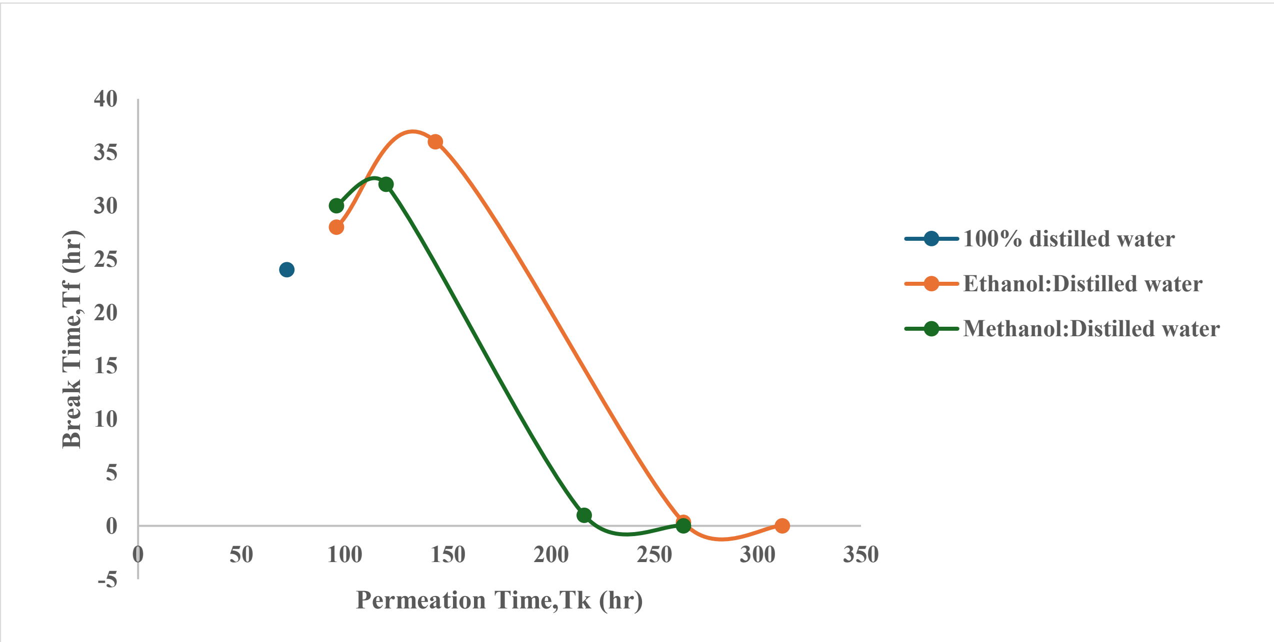

Fig 6.3: Permeation Time vs Break Time

The average duration, denoted as T_k, for granulated bentonite to attain the limiting permeation rate of 10^{-7} cm/s is pivotal in comprehending its behaviour under diverse conditions. Based on the break time, T_f obtained from the free swell test, and the various ethanol and methanol contents, an empirical correlation has been established to determine the average time Tk. This method offers an accurate approach to forecast the average time of granulated bentonite after being permeated by varying quantities of an organic pore fluid. Multiple linear regressions were used to analyze data on average time, break time, and various ethanol and methanol concentrations based on the experimental results. The following empirical association was therefore established.

T_k=116.78 - 2.09 T_f + 2.44 Ethanol (%) …………………………………………………… (6.2)

T_k=120.87 - 2.07 T_f + 1.72 Methanol (%) ………………………………………………..... (6.3)

Where T_k = Predicted permeation time (hr)

T_f = Break time (hr)

Equation (6.2) applies to granulated bentonite when permeated with any concentrations of ethanol mixed with distilled water, with a correlation coefficient of R^2 = 0.996, whereas, equation (6.3) applies when the organic pore fluid is methanol- distilled water and the correlation coefficient of R^2 = 0.996.

Based on the aforementioned studies, a significant correlation between the time at which the bentonite granules broke which is at maximum swelling during the free swell test and the time at which the permeation value reached 10^{-7} cm/s during the consolidometer test is established. The time it takes for GCLs containing granulated bentonite in the landfill to fully break all of its granules, swell, and seal all of the macro voids resulting in a pore fluid permeation rate of 10^{-7} cm/s across it can thus be ascertained using a basic laboratory free swelling index test.

CHAPTER 7
Conclusion

In this work, the swelling and permeability characteristics of nine granulated bentonite sample with different mixture of organic pore fluids and distilled water were studied using Free Swell Index test and Permeation test (Falling Head method).

From this work, following conclusions can be derived:

1. In free swelling index test maximum swelling occurs in granulated bentonite for 100% distilled water and subsequently swelling decreases with the increase of organic pore fluids percentage.
2. The break time increases when the pore fluid changes from distilled water to ethanol-water and methanol-water mixtures.
3. The soil samples showed insignificant swelling at 60% ethanol/methanol - 40% distilled water and 80% ethanol/methanol - 20% distilled water proportions.
4. The liquid limits of different proportions of pore fluids is maximum when the pore fluid is distilled water and decreases with the increase of the concentration of the organic pore fluid.
5. A good linear relationship exists between liquid limit and pore fluid content of the different concentrations of the pore fluid at maximum swelling. We can predict the liquid limit of granulated bentonite treated with different pore fluids concentrations from this linear relationship.
6. The average time recorded while the falling head permeability test performed during the consolidation test to achieve a limiting permeation rate of 10^{-7} cm/s increases with the increase in the organic pore fluid concentration.
7. This study establishes a relationship between the average time (the time to reach a limiting permeation rate of 10^{-7} cm/s) and break time (the time at which bentonite granules are completely broken which is at maximum swelling percentage) of different ethanol and methanol concentrations. With this relationship the average time to reach the permeation rate of 10^{-7} cm/s can be predicted from the free swell index test using the break time of different pore fluid concentrations.

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