

**ENGINEERING GEOLOGICAL EVALUATION OF MFENSI AND AFARI  
CLAY DEPOSITS FOR LINER APPLICATIONS IN MUNICIPAL SOLID  
WASTE CONTAINMENT SYSTEMS**

**By**

**ENDENE CHE EMMANUEL, B.Sc. (Hons) Geology**

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## DECLARATION

I hereby declare that this submission is my own work towards the MPhil and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

**Endene Che Emmanuel**

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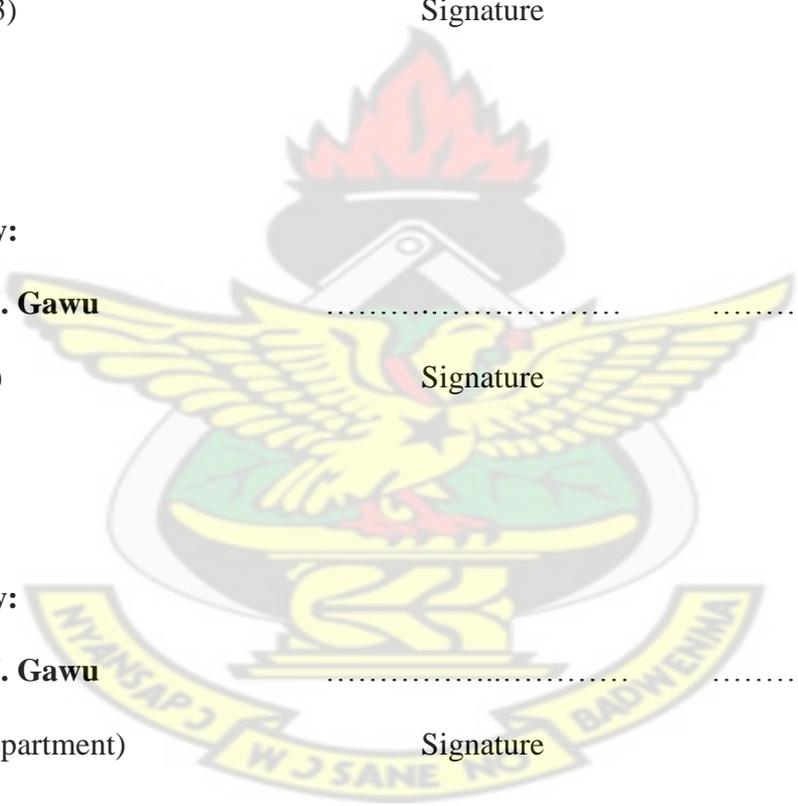
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Date

**Certified by:**

**Prof. S.K.Y. Gawu**

(Supervisor)



.....  
Signature

.....

Date

**Certified by:**

**Prof. S.K.Y. Gawu**

(Head of Department)

.....  
Signature

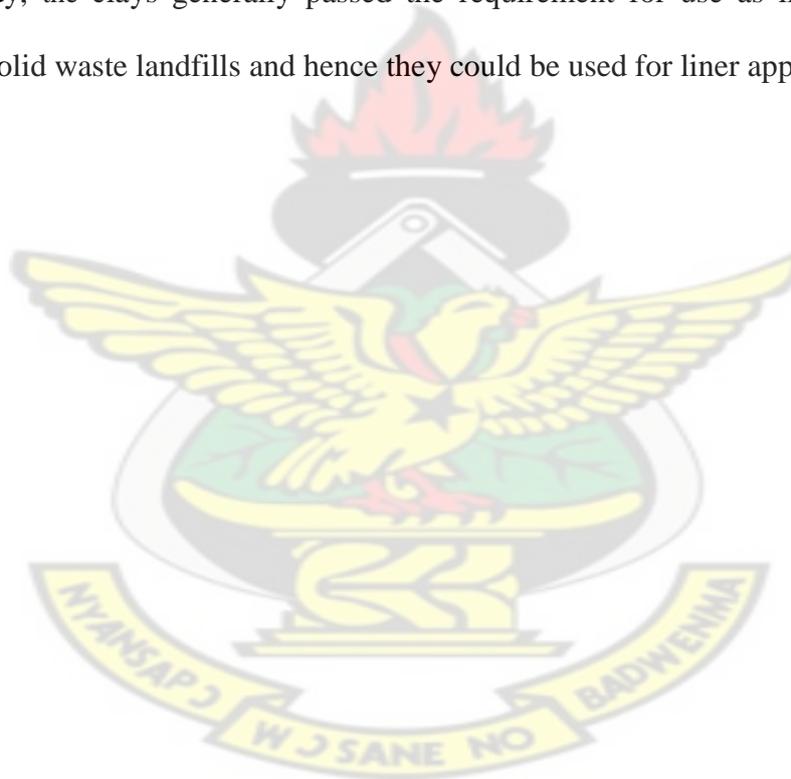
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## ABSTRACT

Mfensi and Afari clay deposits in the Ashanti region of Ghana, have been the subject of considerable research works mainly for pottery, brick and tile, pozzolana, refractory productions, etc, but very little is known about their application as liner materials. This study therefore sought to evaluate the suitability of the two clay deposits as liner materials in municipal waste containment systems. Samples were collected from the sites and subjected to physical, chemical, physico-chemical, mineralogical, geotechnical as well as thermal analyses. Results of the study reveal that; physically, both clays were soft and had high water contents. Afari clay was yellowish in colour while Mfensi clay was greenish-grey in colour. The chemical compositions of the clays were analogous although their concentrations varied. The oxides of silicon, aluminum and iron together constitute about 90% and 80% in Mfensi and Afari clay respectively. The mineralogical compositions of both clays were similar and made up of quartz, kaolinite and magnetite. The cation exchange capacities of the clays were 32.33 meq/100g for Afari clay and 7.79 meq/100g for Mfensi clay. The clays were fine grained, with fines contents of approximately 64% and 88% for Afari and Mfensi clays respectively. Texturally, both clays classify as clay loam. The Atterberg limit tests gave the liquid limits and plasticity indices of both clays to be 64.78% and 40.52% for Afari clay and 42.85% and 22.43% for Mfensi clay respectively. The unconfined compressive strength of the Afari clay was 244.53KPa and that of Mfensi clay was 331.73KPa. The hydraulic conductivities of the clays were found to be of the order  $\times 10^{-7} cm/s$ . The average thermal conductivities of the clays were 0.025W/m°C for Afari clay and 0.215W/m°C for Mfensi clay. The use of leachate led to an increase in the plasticity indices and liquid limits of both clays with a reduction in the plastic limits. Reductions in the permeability's of both clays were also observed when permeated with leachate. From the modeling, Afari clay had a higher flow rate and a

lower breakthrough time relative to Mfensi clay. It is concluded that, Mfensi clay has a better anti-leakage behavior, higher breakthrough time and lower flow rate relative to Afari clay. Based on parametric analyses from the simulation with varying leachate head, leachate density and liner thickness, it was found that, the breakthrough times of both clays did not change when varying the leachate head while the flow rate changed with varying leachate head. Also, the breakthrough times and flow rates of the clays changed with varying liner thickness. Finally, the variation in leachate density resulted to a change in the breakthrough times for both clays and had no effect on the flow rates. From the overall study, the clays generally passed the requirement for use as liner materials in municipal solid waste landfills and hence they could be used for liner applications.



## TABLE OF CONTENTS

<b>DECLARATION.....</b>	<b>ii</b>
<b>ABSTRACT.....</b>	<b>iii</b>
<b>TABLE OF CONTENTS .....</b>	<b>v</b>
<b>LIST OF TABLES .....</b>	<b>ix</b>
<b>LIST OF FIGURES .....</b>	<b>x</b>
<b>LIST OF PLATES .....</b>	<b>xii</b>
<b>ACKNOWLEDGEMENTS .....</b>	<b>xiii</b>
<b>CHAPTER ONE: INTRODUCTION .....</b>	<b>1</b>
1.1 Background to the Study .....	1
1.2 Problem Statement .....	2
1.3 Objectives of the Research.....	4
1.4 Significance of the Study .....	5
1.5 Scope of the Work.....	5
<b>CHAPTER TWO: LITERATURE REVIEW.....</b>	<b>6</b>
2.1 Introduction .....	6
2.2 Formation of clays.....	6
2.3 Types of Clays and their Applications .....	7
2.4 Clay Deposits in Ghana.....	9
2.5 Review of studies on Mfensi and Afari clays .....	12
2.5.1 Chemical and Mineralogical Composition of Mfensi and Afari clays.....	12
2.6 Physical characteristics of Mfensi and Afari clays .....	14
2.6.1 Plasticity characteristics of Mfensi and Afari Clay .....	15
2.7 Industrial applications of Mfensi and Afari clays .....	15
2.8 Clays in Landfills .....	16

2.9 Leachate Generation in Landfills .....	17
2.10 Chemical Composition of Landfill Leachate .....	20
2.11 Chemicals (leachate) transport through liner materials.....	22
2.12 Effects of chemicals and leachate on the geotechnical properties of clays.....	24
Introduction.....	24
2.12.1 Effects of chemicals on the consistency limits.....	24
2.12.2 Effect of chemicals on the Hydraulic Conductivity of clays.....	28
2.12.3 Effect of chemicals on Shear Strength of clays.....	29
2.12.4 Effects of Leachate on the Hydraulic Conductivity of clays.....	30
2.13 Heat generation and its effects on clay liners.....	31
2.14 Compacted Clay Liners.....	34
2.14.1 Components of Clay Liner .....	34
2.14.2 Requirements of compacted clay liner materials.....	36
2.14.3 Thickness, strength, thermal and hydraulic conductivities recommendations for compacted clay liners .....	38
<b>CHAPTER THREE: EXPERIMENTAL .....</b>	<b>40</b>
3.1 Materials.....	40
3.1.1 The Clays.....	40
3.1.2 The Leachate.....	43
3.2 Laboratory Studies .....	44
3.2.1 Sample Preparation.....	44
3.2.2 Sample Testing .....	44
<b>CHAPTER FOUR: RESULTS AND DISCUSSION .....</b>	<b>49</b>
4.1 Nature and Characteristics of the clays .....	49
4.1.1 Chemical Composition of Afari and Mfensi Clays .....	49

4.1.2 Mineralogical Composition of the Clays.....	51
4.1.3 Physico – chemical characteristics of the clays.....	53
4.2 Geotechnical Characteristics of the studied clays .....	55
4.2.1 Specific Gravity and Natural Moisture Content .....	56
4.2.2 Particle Size Distribution and Textural Classification .....	56
4.2.3 Atterberg Limits and Plasticity Characteristics .....	59
4.2.4 Colloidal activity of the clays .....	60
4.2.5 Linear Shrinkages of the clays.....	61
4.2.6 Strength Characteristics of the clays .....	62
4.2.7 Saturated Hydraulic Conductivity of the clays.....	64
4.3 Thermal Conductivities of the Clays.....	66
4.4 Physico-chemical composition of the leachate .....	68
<b>CHAPTER FIVE: SATURATED–UNSATURATED FINITE DIFFERENCE</b>	
<b>SIMULATION OF SEEPAGE THROUGH THE CLAYS .....</b>	<b>69</b>
5.1 Background .....	69
5.1.1 Description of the Physical Problem and Significance of Modeling.....	70
5.1.2 Simulation Structure .....	72
5.2 Methodology .....	73
5.2.1 Model Types .....	73
5.2.2 Numerical Simulation of Steady State Flow through the clays (Saturated case).....	73
5.2.3 Numerical Simulation of Transient State flow through the clays (unsaturated case) .....	76
5.2.4 Determination of the Pore water pressure .....	79
5.2.5 Determination of the Flow Rate .....	79

5.2.6 Procedures used in the preparation of the computer–assisted numerical analysis and simulation.....	80
5.3 Algorithmic model development and simulation.....	81
5.4 Results.....	82
5.4.1 Pore water pressure distribution through the clays.....	82
5.4.2 Validation of the models.....	83
.....	85
5.5 Parametric Analysis.....	85
5.5.1 Leachate Head.....	86
5.5.2 Liner thickness.....	87
5.5.3 Leachate density.....	87
5.6 Conclusion.....	88
6.1 Conclusion.....	89
6.2 Recommendations.....	90
<b>REFERENCES.....</b>	<b>91</b>
<b>APPENDIX A.....</b>	<b>103</b>
<b>APPENDIX B.....</b>	<b>104</b>

## LIST OF TABLES

Table 2.1a: Clay deposits in the Greater Accra, Brong Ahafo, Upper, Central regions of Ghana (Kesse, 1985).....	10
Table 2.1b: Clay deposits in the Northern, Western, Ashanti and Volta regions of Ghana (Kesse, 1985).....	11
Table 2.2: Major oxide composition of Mfensi and Afari clays.....	12
Table 2.3: Typical compositional properties of leachate in Municipal Solid Waste Landfills .....	21
Table 4.1: Results of the chemical analysis of both Afari and Mfensi clay samples ..	50
Table 4.2: Physico – chemical properties of both clay samples .....	54
Table 4.3: Geotechnical characteristics of the studied clays .....	55
Table 4.4: Grading Characteristics of the study clays .....	58
Table 4.5: Atterberg limits of the clays .....	59
Table 4.6. Strength Characteristics of the clays.....	62
Table 4.7: Physico- chemical composition of the MSW Landfill leachate .....	68
Table 5.1: Variables used for parametric study .....	86
Table 5.2: Breakthrough time and flow rate values with corresponding heads.....	86
Table 5.3: Breakthrough time and flow rate values with liner thickness.....	87
Table 5.4: Breakthrough time and flow rate values with leachate densities.....	88

## LIST OF FIGURES

Figure 2.1: X-ray diffraction pattern of Mfensi clay (Amoanyi, 2012).....	13
Figure 2.2: X-ray diffraction pattern of Afari clay (Amoanyi, 2012).....	14
Figure 2.3: Particle size distribution curve of Afari and Mfensi clays (Amoanyi, 2012) .....	15
Figure 2.4: A generalized pattern of leachate formation (Farquhar, 1989) .....	18
Figure 2.5(a) and (b): (a) represents the concentration profile and (b) a corresponding diagram showing heavy metal cation adsorbed by the soil mass and elsewhere remained in pore water (Tanit <i>et al.</i> , 2009).....	23
Figure 2.6: Effect on salt concentrations on the liquid limit of low plastic clays (Seracettin and Temel, 2008). .....	25
Figure 2.7: Effect on salt concentrations on the plastic limit of low plastic clays (Seracettin and Temel, 2008). .....	26
Figure 2.8: Effect of NH <sub>4</sub> Cl and KCl solutions on the liquid limit of high plastic clay (Seracettin and Temel, 2008). .....	27
Figure 2.9: Effect of CuSO <sub>4</sub> and FeSO <sub>4</sub> solutions on the liquid limit of high plastic clay (Seracettin and Temel, 2008).....	27
Figure 2.10: Heat and Mass fluxes in an unsaturated medium under a geomembrane due to temperature gradient (Zhou and Rowe, 2003).....	32
Figure 2.11: Compacted clay liner and components (Fashiur, 2000) .....	36
Figure 3.1: Geological map of the Ashanti Region indicating sampling locations .....	41
Figure 4.1: X- Ray diffraction pattern of Afari clay sample.....	52
Figure 4.2: X- Ray diffraction pattern of Mfensi clay sample.....	53
Figure 4.3: Particle size distribution curves of the clays .....	57
Figure 4.4: Textural classification of the clays .....	58

Figure 4.5: Plasticity characteristics of both clays.....	60
Figure 4.6: Percentage linear shrinkages of Afari and Mfensi clay.....	61
Figure 4.7: Compaction Characteristics of the clays with water and leachate .....	62
Figure 4.8: UCS against strain for Afari and Mfensi clay samples .....	63
Figure 4.9: Variation of hydraulic conductivity with time on Mfensi clay permeated with water and leachate. ....	64
Figure 4.10: Variation of hydraulic conductivity with time on Afari clay permeated with water and leachate .....	65
Figure 4.11: Cooling curves for the clays.....	67
Figure 5.1: Flow domain for Liner breakthrough (EPA, 1984).....	71
Figure 5.2: Computersimulation procedure flow chart.....	72
Figure 5.3: Discretized partial grid of the flow domain.....	75
Figure 5.4: Flowdomain used for simulation.....	81
Figure 5.5: Pore water pressure distribution for model Afari and Mfensi Clays .....	83
Figure 5.6: Graphical user interface for specifying input and output parameters for simulated steady state flow through Afari and Mfensi clays .....	84
Figure 5.7: Graphical user interface for specifying input and output parameters for simulated transient state flow through Afari and Mfensi clays.....	85

## LIST OF PLATES

Plate 1.1: Ground/ surface water contamination (Ahinsan Community).....	4
Plate 1.2: Cracking of liner material due to the effect of heat .....	4
Plate 2.1: Bricks produced from Mfensi clay .....	16
Plate 3.1: Afari clay samples .....	42
Plate 3.2: Mfensi clay samples.....	43
Plate 3.3: Kumasi landfill aerobic leachate cell.....	43
Plate 3.4: Setup of the Lee's Disc Apparatus .....	47



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## CHAPTER ONE: INTRODUCTION

### 1.1 Background to the Study

Since the dawn of mankind, humans have generated and discarded waste. However, discarding of waste in the past did not pose a significant threat due to the nomadic pattern of settlement. With the advent of stable societies came trash which accumulated in these communities posing serious health and environmental risks. The rate of contamination of soil, ground water and aquifers by these wastes has rapidly increased in recent years due to growth in urbanization and industrialization (Bello and Adegoke, 2013). The quantification and extent of spread of these wastes has primary importance for carrying out a remediation work. A proper system for the management of these wastes poses a difficult and complex challenge for society at present time (Sitaram *et al.*, 2014). However, some common methods of dealing with wastes include; deep well injections, composting, incineration and landfills, to name a few. The most common waste disposal method is the engineered landfill. This is due to its economic advantages such as cost saving, efficiency, simplified technique and large capacity (Feng *et al.*, 2004). However, landfills are also associated with problems such as environmental degradation and ground water contamination caused by the leachate and gas generation. There are some aspects of landfill design and construction that require attention, such as the cover systems, side systems and leachate collection system, etc. One of the major elements that must be addressed also is the placement of a liner material at the bottom of the landfill, between the waste and the natural ground to act as a barrier to chemicals leaching into the ground. Properly designed engineered landfills can greatly minimize the seepage of leachate but cannot completely prevent it as a result of uncertainties such as those involved in civil engineering design, landfill operation, occurrence of geologic hazards near the

landfill sites and damage to liner materials (Ozcoban *et al.*, 2006). As such, an important parameter validating the performance of a liner material is its hydraulic conductivity (Daniel and Wu, 1993). To minimize the impact of the generated heat, the liner material must be an insulator. Therefore, the proper assessments of the engineering geological properties of liner materials are important to ensure their effective performance. This study sought to evaluate the suitability of two clays from Afari and Mfensi towns both in the Ashanti Region of Ghana as liner materials for municipal solid waste (MSW) landfill sites in Ghana.

## **1.2 Problem Statement**

Globally, properly designed and operated landfills are the most cost-effective and environmentally acceptable means of solid waste disposal (ADB, 2002). This is due to their ability to contain waste materials that cannot be recycled or eliminated, with the aim of quarantining potentially harmful substances from the surrounding environment until it decomposes to a less harmful state thus preventing ground/surface water contamination and environmental degradation. Typical contamination of ground/surface water is shown in Plate 1.1. In most landfills, the use of productive soils as liner materials in the form of compacted clay (CC) is common (Kaya and Durukan, 2004). Studies have proven that, these soils in the form of CC undergo large changes in physico-chemical properties when exposed to shrink-swell and or freeze-thaw cycling as a result of wetting and drying (Othman *et al.*, 1994). Moreover, their susceptibility to cracking as a result of high temperature leads to an increase in diffusive transport and high hydraulic conductivity (Nassar *et al.*, 1996). Typical cracks in clay liner are shown in Plate 1.2. These lapses hinder their application as liner materials for municipal solid waste landfill sites.

In recent years (from 1986 to present), geosynthetic clay liners (GCLs) are also being used as liner materials in landfill sites (Ojoawo, 2012). Many studies have proven that GCL's are better liner materials to be used in MSW landfill sites, however they are not preferred because, their hydraulic conductivity can change due to fluctuations in temperature and moisture (Kaya and Durukan, 2004). Their high cost is also a major problem. As at 1994, the cost of an installed GCL ranged from \$0.42 to \$0.60 per square foot (EPA, 2001) and is expected to increase with time. Low shear strength and less attenuation capacity are problems also encountered with GCL's (Ojoawo, 2012). In addition to these, high temperature leads to a decrease in GCLs absorption ability and causes desiccation cracking especially those containing an appreciable amount of bentonite (Arden and Mohammad, 2013). Furthermore, permeation of volatile organic compounds (VOCs) through geomembrane is common (Park *et al.*, 1996). Lastly, poor construction and maintenance of GCL's could ultimately result in the seepage of leachate through the GCL material, causing contamination.

The increase in MSW generation, deficient budgetary resources and problems associated with other liner materials has necessitated the use of locally available materials as liner materials for MSW landfill sites (Patil *et al.*, 2010). There is therefore a need to identify local clay deposits which can be utilized for the development of durable and low cost lining material for municipal landfills. In an attempt to address the above mentioned problems, this project sought to investigate the engineering geological characteristics of Mfensi and Afari clays which are available in commercial quantities for potential application in MSW landfill sites.



**Plate 1.1: Ground/ surface water contamination (Ahinsan Community)**



**Plate 1.2: Cracking of liner material due to the effect of heat**

### **1.3 Objectives of the Research**

The main objective of the study is to assess the potential and/or suitability of Mfensi and Afari clays as liner materials for MSW landfill sites.

The specific objectives were:

- i. To determine the physical, chemical, physico-chemical and mineralogical composition of Afari and Mfensi clays.

- ii. To determine the geotechnical and thermal properties of Mfensi and Afari clays in relation to use in lining of landfills.
- iii. To assess the effects of leachate on the Atterberg limits, compaction, unconfined compressive strength and permeability of the compacted clays.
- iv. To develop mathematical models and simulate flow through the clays in order to predict their breakthrough times and flow rates.

#### **1.4 Significance of the Study**

The significant contributions of the study are:

- i. The Mfensi and Afari clays have been characterized and evaluated for utilization as liner materials for MSW landfill constructions.
- ii. A base line study has been established for future research works and policy making in the area of liner materials for MSW landfill sites.
- iii. Mathematical models and a simulator have been developed for two-dimensional seepage analyses through the clays.

#### **1.5 Scope of the Work**

The study was limited to the use of Mfensi and Afari clays both in the Ashanti Region of Ghana. The engineering geological characteristics evaluated were; physical, chemical, physico-chemical, mineralogical, geotechnical as well as thermal analyses. The study was based on laboratory investigations. Finally, mathematical models were developed and used to simulate flow through the clays, so as to predict their breakthrough times and flow rates for liner applications.

## CHAPTER TWO: LITERATURE REVIEW

### 2.1 Introduction

Clays and clay minerals have been mined for centuries. They are among the most important minerals used by manufacturing and environmental industries. The term 'clay' is applied both to non-metallic inorganic materials having a particle size of less than 2 micrometers and to the family of minerals that have similar chemical composition, consisting mainly of hydrous aluminum silicate and a common crystal structural characteristic (Velda, 1995). Clay is a complex mixture that varies in composition depending on the geological location.

Clay is described as a natural, earthy, fine grained material that consists largely of a group of crystalline hydrous silicate minerals known as clay minerals and which develops plasticity at appropriate water content and becomes hard when dry or fired (Richard, 2006). Clays in their compacted form are commonly used as insulating materials in waste containment facilities. They are generally designed as hydraulic barriers to minimize the effects of seepage or pollution into the ground water.

### 2.2 Formation of clays

Weathering of rock is the primary way by which clay minerals are formed on the Earth. It is the mechanism by which clays are formed as a result of physical breakdown and chemical alteration of rocks that changes the original minerals to clay minerals (Richard, 2006). There are several factors which affect the weathering process such as parent rock, time, climate, topography, etc. Various processes help in the disintegration of rock masses, some alter the physical characteristics of the rocks, such as the particle size, surface area and bulk volume. Others affect the chemical

characteristics such as the transformation of new minerals. As such, there are two major types of weathering of rock masses viz; physical and chemical weathering.

### ***Physical Weathering***

The breakdown of rock masses to sand, silt and finally to clay through physical means without any change in the chemical composition of the rock mass is termed physical weathering. Detailed discussion of physical weathering is reported by Mitchell and Soga (2005).

### ***Chemical Weathering***

Chemical weathering is the chemical break down of rocks; it involves the breakdown of unstable primary minerals and the formation of new minerals. The entering of water, air (CO<sub>2</sub>, O<sub>2</sub>) and organic acids (resulting from the decomposition of humus and organic matter) into rocks, initiates the process of chemical weathering (Gidigasu, 1971). The processes involved in chemical weathering are discussed elsewhere (Mitchell and Soga, 2005).

## **2.3 Types of Clays and their Applications**

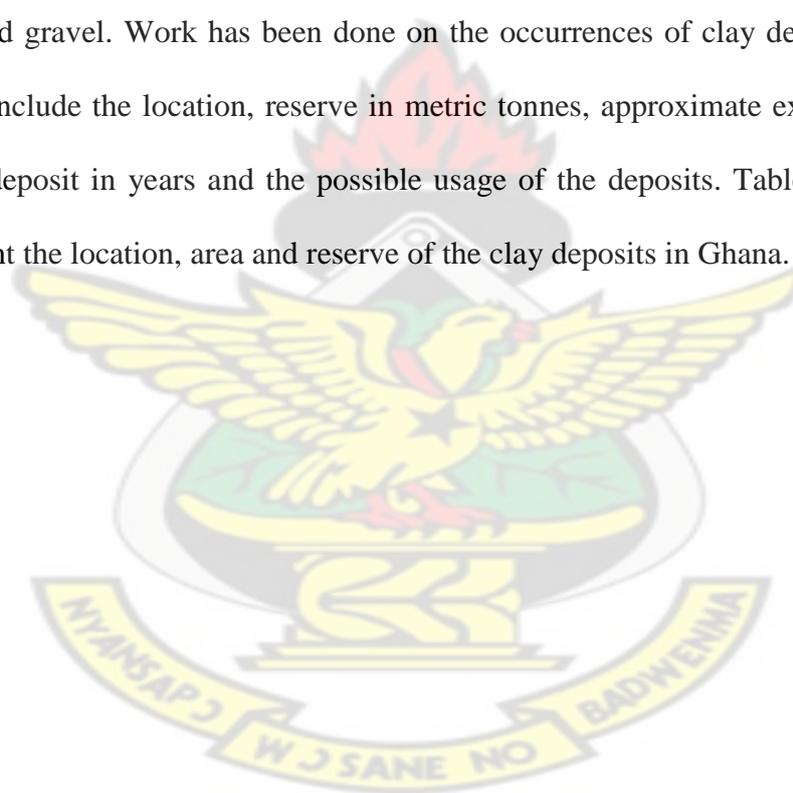
Clays have been grouped into various categories based on the suitability of the clay to meet user's purpose (Bamigbala, 2001). Generally clays are divided into two broad categories; primary and secondary clays, which can be further divided into various sub-groups. Primary clays (residual), are clays formed from the parent rocks which have not been transported by any means, thus remain in the area of their formation. They are mostly white in colour and of low plasticity. On the other hand, secondary clays are those formed from the parent rock and transported mainly by erosion and water from their areas of formation. They are of various colours and of high plasticity (Manukaji, 2013).

According to Ehlers and Blatt (1982), there exists three or four main categories of clays namely; illite, montmorillonite-smectite, kaolinite and chlorite. Chlorites are not always considered as clay sometimes, they are classified as a separate group within the phyllosilicates. There are approximately 30 different types of "pure" clays in these categories, but most "natural" clays are mixtures of these different types, along with other weathered minerals (Ehlers and Blatt, 1982). The U.S Bureau of Mines has categorized clays into the following, namely; ball clay, bentonite, fuller's earth, fire clay, common clay or shale and kaolin clays. These clays have properties which make them differ from one another, such as their mineral composition; for instance, Kaolin is a white clay-like material consisting mainly of kaolinite and other kaolin group minerals and as such, it has a wide variety of applications such as in refractory, rubber, paint, etc. Ball clay is a white- firing plastic clay that is composed primarily of kaolinite and is used mainly for bonding in ceramic ware, primarily dinner ware, floor and wall tiles, etc. (Anonymous, 2001). Kaolinite is the main mineral found in "fire clay" but also it may contain materials such as diaspore, burley, etc. Because of their ability to withstand temperatures of about 1500°C or higher they are mostly used as refractories. The main minerals found in bentonites are smectite minerals, usually montmorillonite. Bentonite is largely used in drilling muds, sealing and in foundry sands, etc. Fuller earth is a type of non-plastic clay which is typically high in magnesia and has specialized decolorizing and purifying properties (Anonymous, 2001). The variation in the mineral contents of these clays such as kaolinite, gibbsite, hydrous iron oxide, etc. contributes to the different colours found in the clays and their various applications. Thus, colour, plasticity, absorption qualities, hardness, cohesion, fineness of grains and refractory characteristics, etc. are a few of the

physical characteristics used to distinguish between the various clay types, (Manukaji, 2013).

#### **2.4 Clay Deposits in Ghana**

Clay deposits are found in all regions of Ghana (Kesse, 1985). These clays are derived from the various rock formations through the processes of weathering, erosion and sedimentation and are mostly alluvial or residual in origin (Kesse, 1985). The clays are generally superficially overlain by humus layers not more than 1.5 meters thick. Intercalations within the clay layers are present in a few cases only and consist of sand and gravel. Work has been done on the occurrences of clay deposits in Ghana, which include the location, reserve in metric tonnes, approximate expected life span of the deposit in years and the possible usage of the deposits. Tables 2.1a and 2.1b represent the location, area and reserve of the clay deposits in Ghana.



*Table 2.1a: Clay deposits in the Greater Accra, Brong Ahafo, Upper, Central regions of Ghana (Kesse, 1985)*

Greater Accra Region					
Area	Location	Reserve (tonnes)	Area	Location	Reserve (tonnes)
Accra	Alajo	48,600	Tema	Afienva East	24,194,681
	Ashiaman	18,677,175		Afienva West	5,514,894
	Prampram A	21,779,929	Ada	Mobole	15,000,000
	Prampram B	74,350		Kasseh/Bedaku	42,661,830
	Prampram C	43,771		Big Ada	51,242,553
	Kpone	10,960,115			
	Oyibi	6,735			
	Kwabanya	2,326,596			
Brong Ahafo Region			Upper Region		
Area	Location	Reserve (tonnes)	Area	Location	Reserve (tonnes)
Sunyani	Sunsan Valley	661,188	Bolgatanga/ Navrongo	Gambibigo	12,419,998
	Tanoso	16,200,200		Sumbrungu	4,020
	Adantia	530,665		Tono	8,477,333
			Sobolo	649,997	
Eastern Region					
Area	Location	Reserve (tonnes)	Area	Location	Reserve (tonnes)
Nkawkaw	Adihima/Asuoya	2,240,099	Asamankese	Asamankese	840,000
	Abepotia	7,614,793		Apinmang	2,801,250
Kibi Anyinam	Framase	41,687	Akim Oda	Akim Swedru	33,173,335
	Tamfoi	1,285,084		Akim Awisa	1,285,553
	Moseaso	444,000	Akim Abonase	Akim Abonase	4,561,000
	Abomосу	4,081,434		Akwapim	1,027,000
		Somanya	Okwenya	34,862,223	
Central Region					
Area	Location	Reserve (tonnes)	Area	Location	Reserve (tonnes)
Cape Coast	Nkuntraw	7,527,168	Winneba	Esuakyir No 2	1,800,000
	Kakum Valley	42,800		Simbrofo	3,100,000
	Atrankwa	12,000,000		Mprumen	35,877
	Ochiso	15,441,702		Kasua/Oduponkpehe	51,702,127
	Ampia Ajumaku	195,000		Nyanyanu	1,107,191
Ajumaku	Esuakyir No 1	6,800,000	Gomoa	Gomoa Brofo	268,968
Dunkwa	Subin Valley	162,000	Komanda	Domenase	3,952,551

*Table 2.1b: Clay deposits in the Northern, Western, Ashanti and Volta regions of Ghana (Kesse, 1985)*

Northern Region					
Area	Location	Reserve (tonnes)	Area	Location	Reserve (tonnes)
Tamale	Koblimahago	9,455,892	Tamale	Kunkuo	234,502
	Kpaliga	259,200		Yapei	38,694
	Nyankpala	48,600			
Western Region					
Area	Location	Reserve (tonnes)	Area	Location	Reserve (tonnes)
Nzima	Alenda Wharf	2,956,522	Sekondi	Inchanban	2,668,600
	Aluku	17,860,944		Shama	7,163,082
	Esiama-Kakam	113,550,239	Takoradi	Dixcove (Mfruma)	9,469,979
	Teleku Bokaso	74,456,122		Wasa	614,249
	Nimzimirim	9,343,117	Amanfi	Wasa Akropong	8,629,200
	Bou-Bamakpolo	31,493,879		Enchi	226,330
	Bokazo	221,600,000		Manso Amanfi	597,780
	Nzima East	241,190,133			
Ashanti Region					
Area	Location	Reserve (tonnes)	Area	Location	Reserve (tonnes)
Kumasi	Womasi	164,570	Obuasi	Asokwa	33,865,955
	Kaasi (Tuantem)	1,086,993	Nkawie	Mfensi	396,548
	Sisai	113,400		Afari	2,055,900
	Kokobriko	21,061		Jankoba	139,999
	Dichemso Valley	81,000		Ahatawsu (Mpasatia)	100,560
	Aboabo	162,017		Awrenfena	268,801
	Dichemso-				
	Aprapong	162,017			
	Satang No 1	32,400			
	Satang No 2	162,017			
Subin Valley	162,900				
Volta Region					
Area	Location	Reserve (tonnes)	Area	Location	Reserve (tonnes)
Ho	Adidome No 1	7,755,319	Bowiri	Kalakpa	501,440
	Adidome No 1	469,800		Tuwotsive	1,944
	Tangidome	7,614		Amanfro/Anyinase	2,000,000
Gbefi-Hoeme	Nuzeme	10,083	Dayi	Dayi River Basin	997,900
	Toga	42,163		Ketekrachi	7,027,707
	Kpetoc	29,160	Hohoe	Adankpe	2,273,361
Aveyiboe	27,540	Adutor		35,854,085	
Kudzra	Valexo	16,300		Kadjebi	Kpoglo
	Aklamapata	6,318	Kadjebi		97,742,979
	Have	6,430			
	Agbeditive	12,961			

## 2.5 Review of studies on Mfensi and Afari clays

### 2.5.1 Chemical and Mineralogical Composition of Mfensi and Afari clays

#### *Chemical Composition of the clays*

Results of chemical analysis of Mfensi and Afari clays indicate that they are composed mainly of oxides of silicon, aluminum, iron and very little amount of magnesium, potassium and sodium, and some minor quantities of other oxides like calcium, manganese and titanium, as reported in Table 2.2. The sum of the oxides of silicon, aluminum and iron are greater than 70% for all two clays (Andrews *et al.*, 2014). The chemical compositions of both clays vary in accordance with the impurities present, such as Fe<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>, K<sub>2</sub>O and Na<sub>2</sub>O, and thus, reduce the grade of the clay.

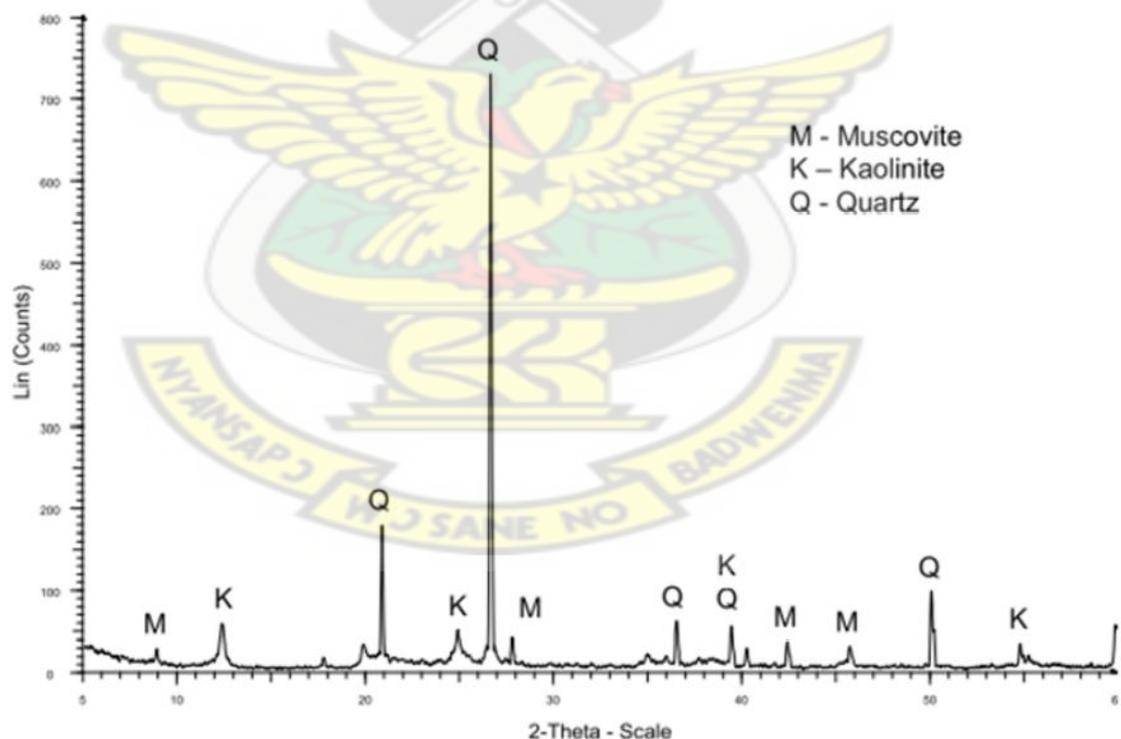
**Table 2.2: Major oxide composition of Mfensi and Afari clays**

OXIDES	Composition (wt %)				
	Afari clay <sup>1</sup>	Mfensi clay <sup>1</sup>	Mfensi clay <sup>2</sup>	Mfensi Clay <sup>3</sup>	Afari clay <sup>2</sup>
SiO <sub>2</sub>	48.88	58.56	65.6	58.6	48.9
Al <sub>2</sub> O <sub>3</sub>	26.56	23.44	19.5	23.4	26.6
Fe <sub>2</sub> O <sub>3</sub>	6.66	3.63	0.8	3.63	6.7
CaO	0.24	0.14	0.2	0.1	0.2
MnO	0.01	0.02	0.2	0.0	0.0
MgO	1.61	1.41	0.4	1.4	1.6
Na <sub>2</sub> O	1.73	2.06	0.9	2.1	1.7
K <sub>2</sub> O	0.13	1.28	0.9	1.3	0.1
TiO <sub>2</sub>	0.79	0.9	0.6	0.9	0.8
P <sub>2</sub> O <sub>5</sub>	0.06	0.13	-	-	-
SO <sub>3</sub>	0.17	0.18	-	-	-
LOI	12	8	10.9	8.0	12

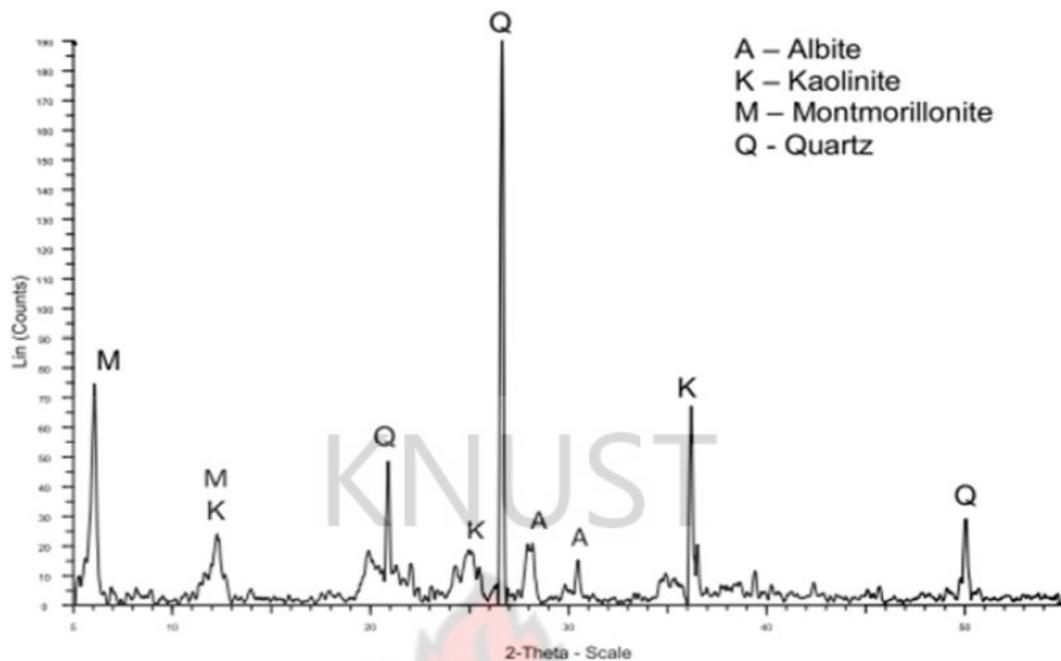
<sup>1</sup>Alorti *et al.*, (2011). <sup>2</sup>Andrews *et al.*, (2013). <sup>3</sup>Andrews *et al.*, (2014).

### ***Mineralogical Composition of the Clays***

The Afari clay has quartz, montmorillonite, kaolinite and albite as the main clay minerals, while Mfensi clay has quartz, kaolinite and muscovite as the main clay minerals (Amoanyi, 2012). Andrews *et al.*, (2014) have however, reported that the main mineral constituents of both clays are quartz and kaolinite in different concentrations. Figures 2.1 and 2.2 show typical X-ray Diffractograms of Mfensi and Afari clay respectively. It was noted that, each mineral had different concentrations as reflected from the intensity of the XRD peaks. The highest peak detected in both diffractograms corresponds to quartz. The dominant phases present in both patterns also correspond to quartz. The minor phases for the Mfensi clay are kaolinite and muscovite while that for the Afari clay corresponds to kaolinite and albite.



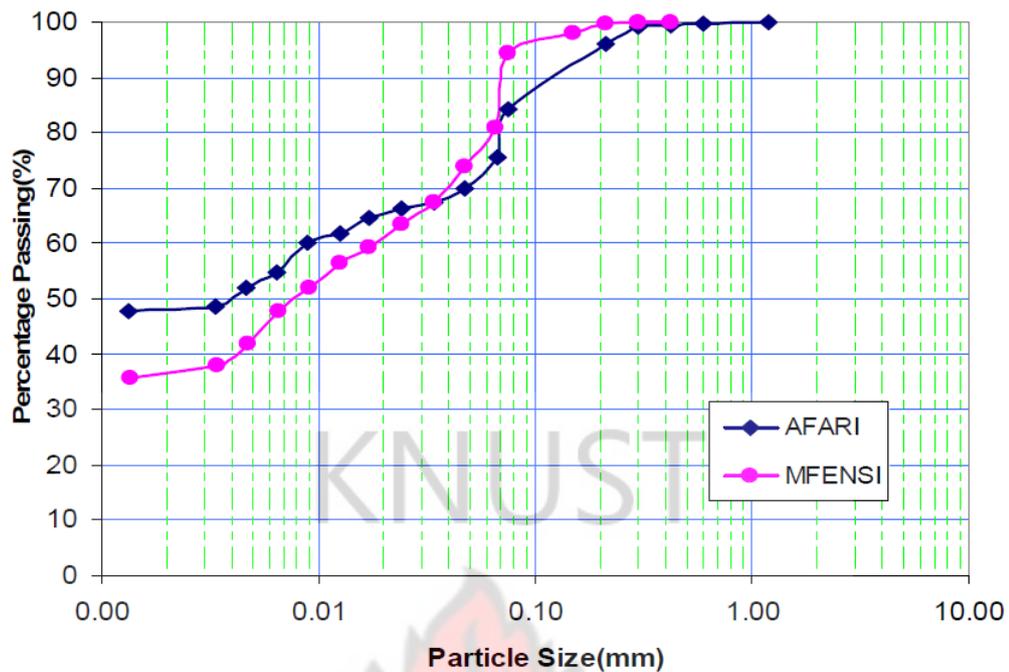
**Figure 2.1: X-ray diffraction pattern of Mfensi clay (Amoanyi, 2012)**



**Figure 2.2: X-ray diffraction pattern of Afari clay (Amoanyi, 2012)**

## 2.6 Physical characteristics of Mfensi and Afari clays

The physical properties of clays vary from colour, texture and particle size, etc. Afari clay is yellowish in colour while the Mfensi clay is greenish–grey in colour (Amoanyi, 2012). The yellowish colour of the Afari clay can be attributed to its high concentration of aluminium oxides (Appiah, 1998). Usually the term clay has a wide range of particle size from 10's of angstroms to millimeters (an angstrom is a unit of measure of the scale of atom). Both clays carry the implication of small particle size, though the particle size of Afari clay are relatively smaller than those of Mfensi clay (Amoanyi, 2012). Figure 2.3 show the particle size distribution curves for Afari and Mfensi clay.



**Figure 2.3: Particle size distribution curves of Afari and Mfensi clays (Amoanyi, 2012)**

### **2.6.1 Plasticity characteristics of Mfensi and Afari Clay**

Work carried out by Amoanyi (2012) indicated that, the liquid limit (LL) of Afari clay was 73.40% while that of Mfensi clay was 43.34%. The plastic limits of both clays were below 30%, with Afari clay having a plastic limit of 26.92% and that of Mfensi clay being 20.80%. The plasticity index (PI) of Afari clay was found to be higher than that of Mfensi clay with a value of 46.58% and 22.54% respectively.

### **2.7 Industrial applications of Mfensi and Afari clays**

Millions of tons of clays are utilized annually in a large variety of applications. Many and varied products are made from it due to their low electrical and thermal conductivities, chemical inertness over a relatively wide range of pH, soft and non-abrasive nature, good plasticity characteristics and cost effective than most competing materials (Appiah, 1998).

Based on their properties (physical, mineralogical and chemical) the Mfensi and Afari clays have been found to be suitable for industrial and academic purposes. The availability of these clays in commercial quantities caused indigenes to establish small scale pottery industries, producing wares such as grinding bowls, palm wine pots, water coolers, burnt bricks, building materials, etc. (Amoanyi *et al.*, 2012). Typical burnt bricks produced from Mfensi clays are shown in Plate 2.1.



**Plate 2.1: Bricks produced from Mfensi clay**

## **2.8 Clays in Landfills**

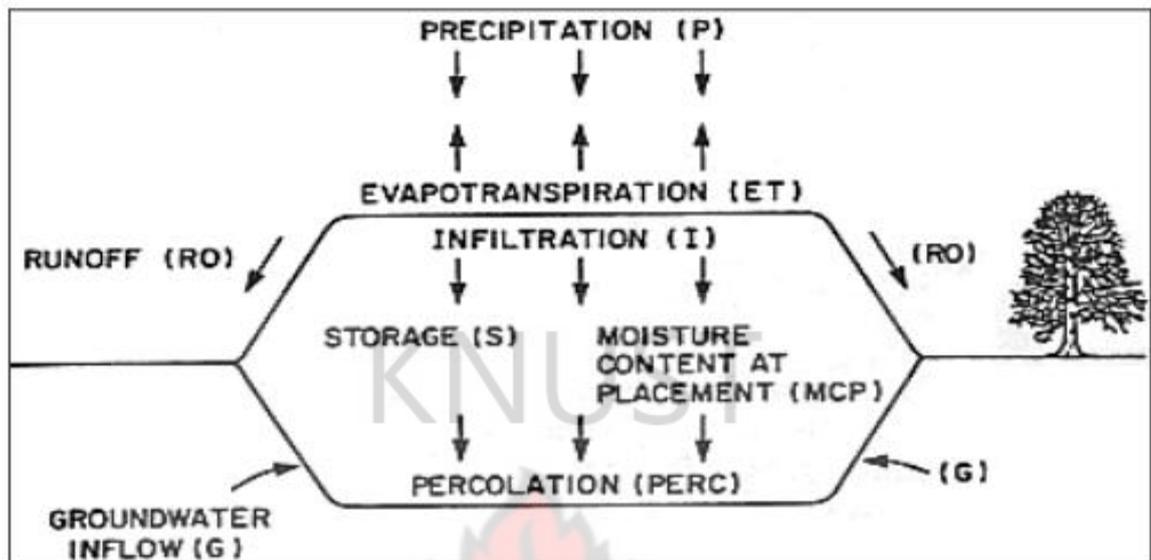
Clays are generally used as liners and capping materials for landfill sites. In each case, they isolate potentially polluting wastes from the surrounding environment, such that the environmental impacts attributed to landfills are minimized (Arch, 1998). Clays serving as barrier systems are usually compacted in their natural state and are used because of their low hydraulic conductivity, high contaminant attenuation and cost effectiveness (Sitaram *et al.*, 2014). If natural clays or clayey soils are not available, commercially available high-swelling clay (bentonite) or clay which is brought from nearby areas can be mixed with local soils (Taha and Kabir, 2005).

## 2.9 Leachate Generation in Landfills

Leachate generation is as a result of the interaction of landfill materials with moisture from rainfall or other forms of precipitation on to the active part of the landfill site and by a series of physical, hydrolytic and fermentative degradation of organic matter, inorganic ions and heavy metals present in the solid waste (Ince *et al.*, 2013). It is noted that, in areas of low precipitation (arid and semi-arid regions) relatively high moisture content of the wastes can play the main role in leachate generation (Safari and Baronian, 2002). The quantity of leachate is usually determined using a simple water balance approach taking into account the amount of water entering the landfill either from external sources or within the waste mass (precipitation, surface water run-off, ground water interflow, waste moisture in excess of moisture holding capacity of the waste and the additional water input such as water in waste-water treatment plant sludge) and the amount leaving (evaporation, evapotranspiration and water consumed in biochemical reactions) (Rhyner *et al.*, 1995).

Keelson (2014a) reported that, the main reason for which this generated leachate needs to be contained in landfills is to minimize the effect of ground water contamination and to ensure stability of the waste. Studies have shown that the use of this method (water balance) to predict the generation of leachate in landfills dated as far back as 1970s (Avhasei, 2012). This water balance procedure for estimating landfill leachate employs the same concept as the mostly used Hydrological Evaluation of Landfill Performance (HELP) model but provides a faster method for analysis compared to HELP due to its minimal site specification input data requirements. Also, the HELP excludes the biochemical reactions and computes the leachate quantity based on detailed metrological and MSW characteristic data (Safari

and Baronian, 2002). An outstanding work by Farquhar (1989) simplifies the various compartments of the water balance and is shown in Figure 2.4.



**Figure 2.4: A generalized pattern of leachate formation (Farquhar, 1989)**

It can be seen from Figure 2.4 that, not all the precipitation falling into the landfill infiltrates, some are lost as runoff. Due to geographical variations, a wide range of temperature exists, as such; some proportions of the non-infiltrated water in the landfill are lost through the process of evaporation. Also, for landfills with the presence of vegetation, some of the precipitation directed into it will be lost in the form of evapotranspiration. Thus, the presence of vegetation in landfills has the capability to deflect rainfall from reaching the ground surface and redirecting it to the atmosphere as water vapour.

After evaporation, evapotranspiration and runoff has occurred, there is a major condition to be met for the infiltrating water to reach the base of the landfill and it is of two folds (Avhasei, 2012). They are:

- i. The final and intermediate barrier covers must reach the maximum (field) capacities to allow drainage to occur.

ii. The wastes content in each cell must reach its field capacity.

After the above folds are met, the percolating water will seep downward and finally, appear as leachate as it interacts and dissolves the solute particles in the waste. The various components (after Farquhar, 1989) of the water balance for the production of leachate in a post closure condition can be expressed by equation (2.1) while that in an active condition can be expressed by equation (2.2). From the equations, the difference or surplus equals percolation which becomes leachate.

$$PC = P - RO - ET - SC + G \quad (2.1)$$

**Where;**

*PC = Percolation, P = Precipitation, RO = Runoff, ET= Evapotranspiration, SC= Storage Capacity, G= Ground water.*

$$PC = P + S - E - WA \quad (2.2)$$

**Where;**

*PC = Percolation, S = Pore squeeze liquid from waste, E = Moisture lost through evaporation, WA = ( $\mathbf{\pounds}_{FC} - \mathbf{\pounds}$ ),  $\mathbf{\pounds}_{FC}$  = Field capacity of the waste,  $\mathbf{\pounds}$  = Initial Moisture content of the waste.*

Avhasei (2012) noted that, equations (2.1) and (2.2) developed by Farquhar (1989) are comprehensive and conceptually correct but has some draw backs with a high degree of uncertainties and/or ambiguities. As a result of this, he proposes more research in this area. Researchers such as Blight and Blight (1993), Blight *et al.*, (1995) and Blight (2006) have carried out studies on the various components of the water balance in landfills, where it was defined in terms of the water input to the

landfill, output and water retained in the refuse body, thus applying the law of conservation of mass.

## **2.10 Chemical Composition of Landfill Leachate**

Any liquid that in the course of passing through solid waste extracts soluble or suspended solids or any other component of the material through which it has passed is termed leachate. Their compositions vary with respect to the type of contaminants from which they are formed. The volume of leachate produced depends on various factors such as; the absorption capacity of the liner, areal extent of landfill, composition of waste, cover material, landfill operation and the amount of recharge water available at any particular site (Chereminsinoff and Gigliello, 1983).

Leachate characteristics vary from one landfill to another and over time, depending on several factors among them includes; age of the landfill, type of waste, site surface hydrology, local climate, state of closure, level of compaction, stage of decomposition, etc. (Kjeldsen *et al.*, 2002). As such the characteristics of leachate are not constant and it is highly possible that, the composition of leachate at any landfill can be unlikely to accurately predict. That notwithstanding, various authors have determined the chemical composition of leachate, as represented in Table. 2.3.  $\text{Cl}^-$  and  $\text{SO}_4^{4-}$  are the most common anions present in the leachate samples with high concentrations while  $\text{NH}_3$  and N are the Nitrogen constituents with least concentrations in the leachate samples as indicated in Table 2.3. It can also be seen from Table 2.3 that, the concentrations of the organic carbon constituents of all the samples are high. The lower the pH of the leachate, the more acidic it is and the greater its effect on the liner materials by dissolving components, thus leading to an increase in the permeability of the liner material.

**Table 2.3: Typical compositional properties of leachate in Municipal Solid Waste Landfills**

		<b>Robinson and Maris(1979)</b>	<b>Ehrig (1988)</b>	<b>Hohl (1992)</b>	<b>Tchpbanoglouset al. (1993) New landfill (&lt; 2 years)</b>	<b>Tchpbanoglous et al. (1993) Matured landfill (&gt; 10 years)</b>	<b>Kruse (1994)</b>	<b>Timur (1996)</b>	<b>Kjeldsen et al. (2002)</b>
pH		6.2-7.6	4.5-9	4.5-9	4.5-7.5	6.6-7.5	6.2-8.3	7.3-7.8	4.5-9
Concentration (mg/l)									
Organic Carbon Constituent	COD	66-11600	500-60000	500-60000	3000-60000	100-500	460-40000	14900-19980	140-
	BOD	2-8000	20-40000	20-40000	2000-30000	100-200	20-27000	6900-11000	152000
	TOC	21-4400	100-5000	100-5000	1500-2000	80-160	150-1200	4550-6000	20-57000 30-29000
Nitrogen Constituent	Org. N	0.9-160 5-730	- 30-3000	- 30-3000	10-800 10-800	80-120 20-40	- -	- 1120-2580	14-2500 50-2200
	NH <sub>3</sub> -N								
Anions	Cl <sup>-</sup>	43-2800	100-5000	-	200-3000	100-400	315-12400	5620-6330	150-4500
	PO <sub>4</sub> <sup>2-</sup>	0.02-4.4	-	-	5-100	5-10	-	-	0.1-23
	SO <sub>4</sub> <sup>4-</sup>	55-460	10-1750	10-1750	50-1000	20-50	20-2500	142-352	8-7750
Metals	Na	43-2500	50-4000	-	200-2500	100-200	1-6800	-	70-7700
	Mg	12-480	40-1150	-	50-1500	50-200	25-600	363.8-640	30-15000
	K	20-650	10-2500	-	200-1000	100-200	170-1750	-	50-3700
	Ca	130-1200	10-2500	10-2500	200-3000	100-400	49-2300	97-787.5	
Heavy Metals	Mn	0.19-26	0.03-60	-	-	-	-	0.11-5.3	10-7200
	Fe	0.09-380	3-2100	3-2100	50-1200	50-1200	2-500	14.2-44	0.03-1400
	Cr	0.005-0.14	0.13-1.6	30-1600	-	-	0.002-0.53	0.02-0.78	3-5550
	Ni	0.02-0.16	0.02-2.05	20-2050	-	-	0.01-1	0.32-0.45	0.02-1.5
	Cu	0.004-0.15	0.04-1.4	4-1400	-	-	0.005-0.56	0.02-0.13	0.015-10
	Zn	0.02-0.95	0.03-120	0.03-120	-	-	0.05-16	0.38-1.06	0.03-1000
	Cd	0.002-0.13	0.0005-0.14	0.5-140	-	-	0.0007-0.525	0.01	0.0001-0.4
	Pb	0.003-0.22	0008-1.02	8-1020	-	-	0.008-0.4	0.04	0.001-5

## 2.11 Chemicals (leachate) transport through liner materials

There are three main processes by which landfill leachate and contaminants percolate through liner materials, namely: physical, chemical and biological processes. Advection and diffusion constitute the physical process while chemical sorption, dissolution and volatilization constitute the chemical processes, whereas the main biological process is microbial degradation (Tanit *et al.*, 2009). Advection is the most common transfer mechanism which depends on the hydraulic conductivity of the liner while diffusion prevails in conditions of low hydraulic conductivity. The transient transport of a chemical having an initial influent concentration of  $C_0$  can be governed by one-dimensional advection–diffusion transport equation (2.3) that accounts for the

chemical sorption, and can be expressed as; 
$$\frac{\delta C}{\delta t} = \frac{D}{R} \frac{\delta^2 C}{\delta z^2} - \frac{V_s}{R} \frac{\delta C}{\delta z} \quad (2.3)$$

*Where;*  $C$  is the concentration of the chemical,  $z$  the direction of transport,  $V_s$  is the seepage velocity,  $t$  the time of transport,  $R$  the retardation factor, and  $D$  the dispersion coefficient. During the transient transport process, the adsorption process prevails until the adsorption capacity of the liner material is reached (Tanit *et al.*, 2009). Tanit *et al.*, (2009) reported that, the above transport equation has a unique solution that was suggested by (Ogata and Banks, 1961) which is expressed in terms of absolute concentration, and is defined as a function of the concentration ratio of depth and time to the initial concentration of the soil, and expressed as;

$$\frac{C(z,t)}{C_0} = \frac{1}{2} \left\{ \operatorname{erfc} \left( \frac{1-T_R}{2 \sqrt{\frac{t}{P_L}}} \right) + \exp(\rho_L) \operatorname{erfc} \left( \frac{1-T_R}{2 \sqrt{\frac{t}{P_L}}} \right) \right\} \quad (2.4)$$

**Where;**

$$T_R \text{ (time factor)} = V_{st}/R_z,$$

$z$  = depth

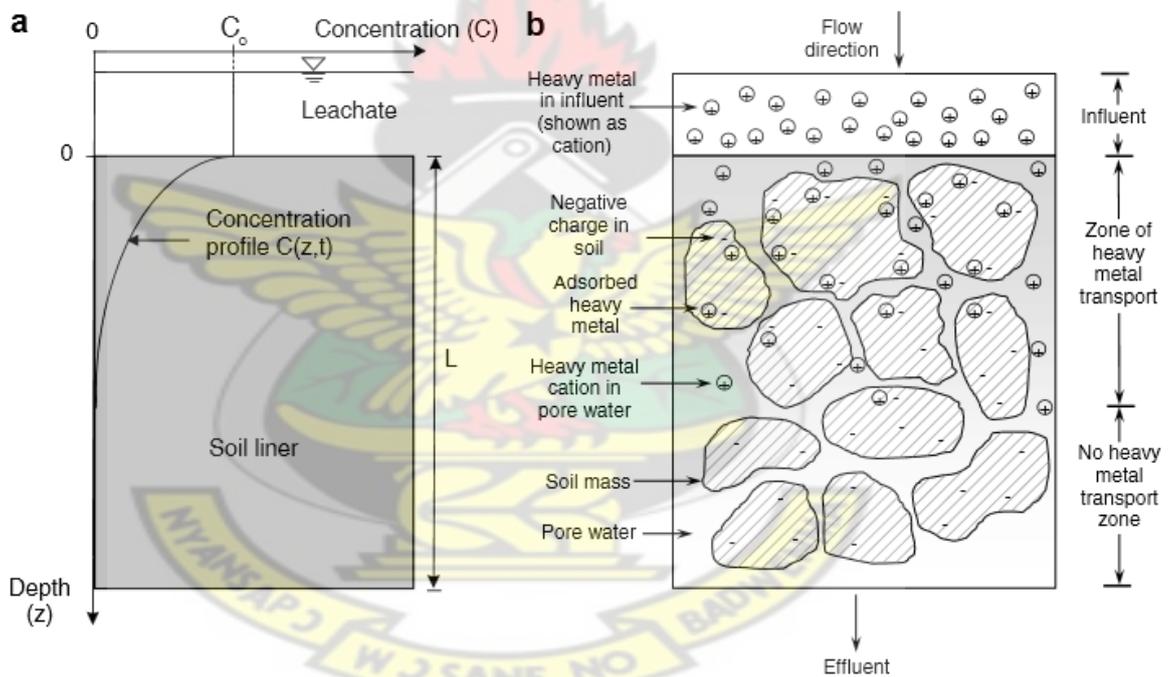
$C_o$  = initial concentration,

$t$  = time of transport

$$P_L \text{ (Peclet number)} = V_s z/D,$$

erfc = error function

Figure 2.5 (a) and (b) represent one-dimensional transient transport of heavy metals in clayey soils.



**Figure 2.5(a) and (b): (a) represents the concentration profile and (b) a corresponding diagram showing heavy metal cation adsorbed by the soil mass and elsewhere remained in pore water (Tanit *et al.*, 2009)**

## 2.12 Effects of chemicals and leachate on the geotechnical properties of clays

### Introduction

The properties of clay liners are affected by chemicals and leachate. It is therefore important to discuss the effects of some chemicals and leachate on the geotechnical characteristics of low plastic and heavy plastic clay liners.

#### 2.12.1 Effects of chemicals on the consistency limits

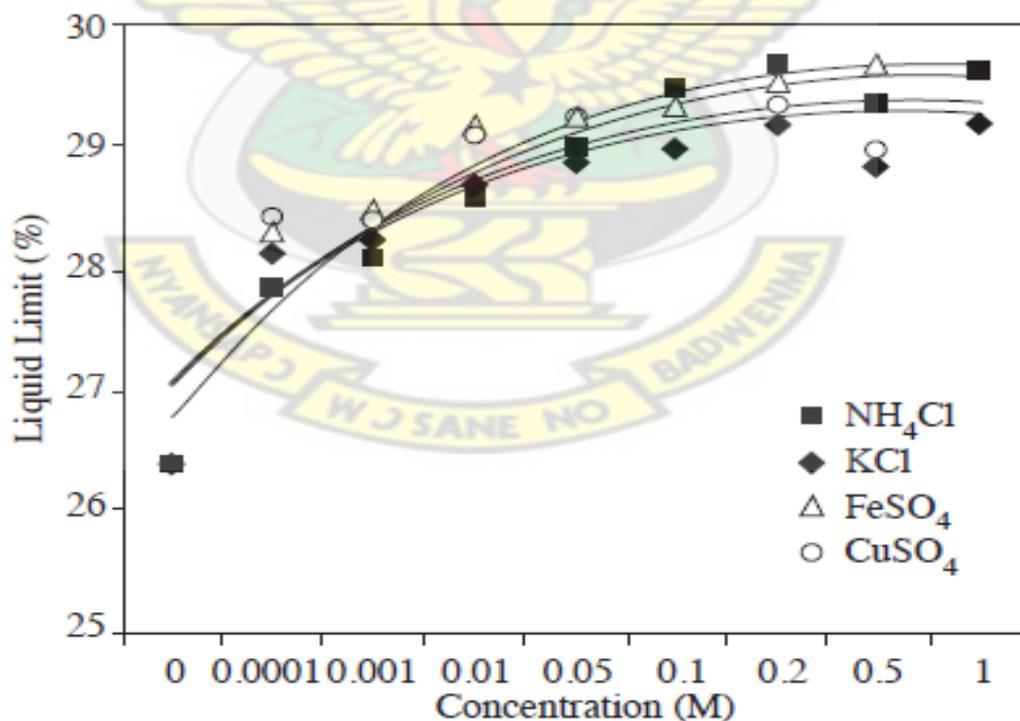
The evaluation of the effects of chemicals on the consistency limits of soils/clays provides some very basic mechanical data about the soil/clays and also a first insight into the chemical reactivity of the clay/soil (Seracettin and Temel, 2008). These effects by chemicals on the consistency limits of both high and low plastic clays have been a general consensus (Seracettin, 2010) and are discussed below.

##### i. *Consistency limit of Low plastic clays*

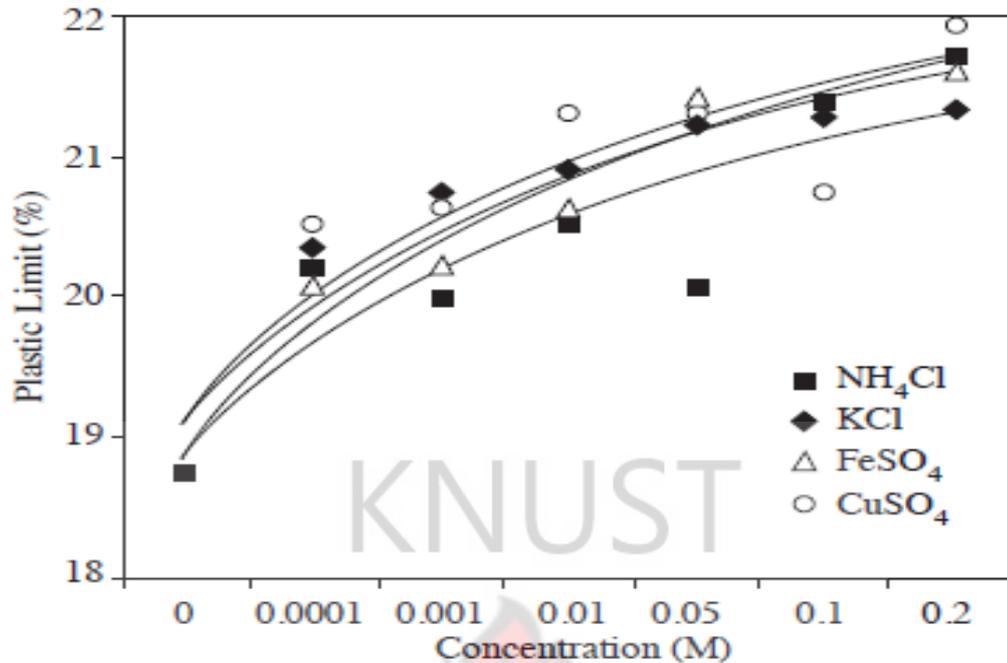
Both the liquid and plastic limit of low plastic clays increases with increase concentration of salt solution, (Arasan and Yetimoglu, 2006). However, Park *et al.*, (2006) reported that,  $\text{CaCl}_2$  solution has no effect on the liquid limit but decreases the plasticity index of kaolinite soils. Furthermore, Sivapullaiah and Manju (2005) reported that, the liquid limit of a soil with low plasticity increases with increase NaOH concentration due to the formation of new swelling compounds. Rao and Mathew (1995) also indicated that, the interaction of clay particles with chemicals leads to dispersion of the clay particles, as such, the geotechnical properties are changed, especially the permeability. Sridharan *et al.*, (2002) reported that, a decrease in the thickness of the double layer and flocculation effect as a result of increase ion concentration can lead to an increase in liquid limit of some clays and also a decrease in liquid limit with increasing ion concentration of others, when he performed a study

on three marine clays and one had an increase in liquid limit with increase ion concentration and the other two a decrease in liquid limit.

The effects of inorganic salt solutions on the consistency limits of two clays have been investigated and report reveals that, the liquid limit of low plastic clays increases with increase salt concentration. This increase in liquid limit is more significant with concentrations approximately 0.2Moles as shown in Figure 2.6. Beyond such concentrations the increase is of less significance (Seracettin and Temel, 2008). Seracettin and Temel (2008) further revealed that, the liquid limit varies slightly with solutions such as;  $\text{NH}_4\text{Cl}$ ,  $\text{FeSO}_4$ ,  $\text{CuSO}_4$  and  $\text{KCl}$ . Moreover, they also reported that, the plastic limit of low plastic clays increases with increasing salt concentrations up to about 0.2Moles as shown in Figure 2.7. At concentrations greater than that, the clay behaves like a non-plastic soil as a result of damaged fabric.



**Figure 2.6: Effect on salt concentrations on the liquid limit of low plastic clays (Seracettin and Temel, 2008).**

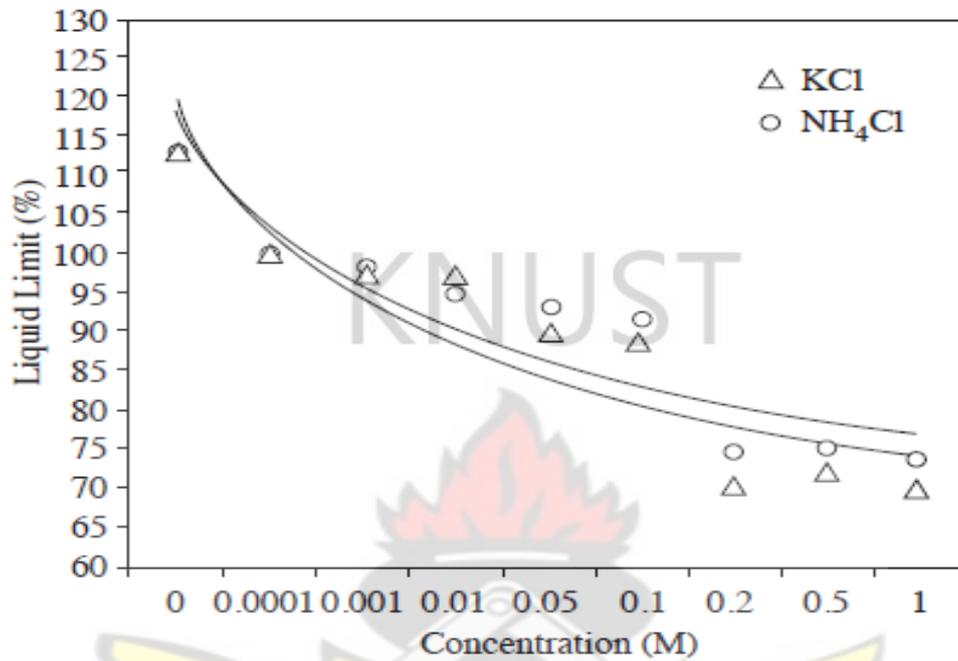


**Figure 2.7: Effect on salt concentrations on the plastic limit of low plastic clays (Seracettin and Temel, 2008).**

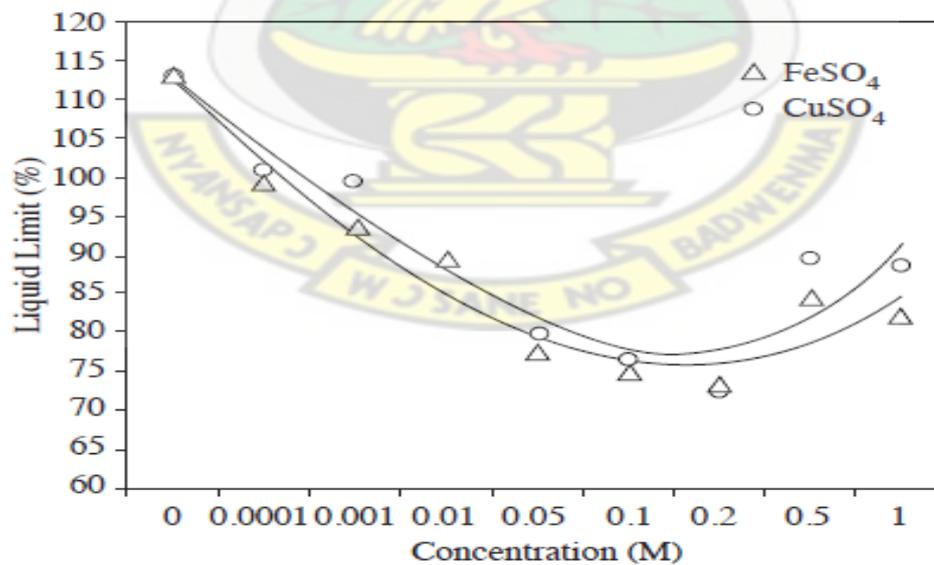
*ii. Consistency limit of high plastic clays*

Kurt *et al.*, (2007) reported that, the liquid limit of high plastic clays decreases with increasing concentration of NaCl and KCl salt solutions. Gleason *et al.*, (1997) also reported that, chemical solutions at low concentrations have minimal effects on the geotechnical properties of high plastic clays than those at higher concentrations. Furthermore, Seracettin and Tamel (2008) reported that, both heavy metal salts and alkali metal salts have different effects on the liquid limit of high plastic clays as shown in Figures 2.8 and 2.9. With alkali metal salts, the liquid limit decreases with increasing concentration of the salt up to 0.2Moles, beyond which it is of less significance. But with heavy metal salts, the liquid limit decreases with increasing salt concentration up to approximately 0.2Moles, beyond this, the liquid limit increases with increase salt concentration. They also reported that, plastic limit decreases with increase salt concentration. The difference in cation valence is the main reason for the

discrepancy in the effect for heavy metal salts and alkali metal salts. Therefore, it can be concluded that, salt solutions tend to reduce the thickness of the diffuse double layer (DDL) and flocculate high plastic clays resulting in reduction in liquid limit.



**Figure 2.8: Effect of NH<sub>4</sub>Cl and KCl solutions on the liquid limit of high plastic clay (Seracettin and Temel, 2008).**



**Figure 2.9: Effect of CuSO<sub>4</sub> and FeSO<sub>4</sub> solutions on the liquid limit of high plastic clay (Seracettin and Temel, 2008)**

### ***2.12.2 Effect of chemicals on the Hydraulic Conductivity of clays***

Hydraulic conductivity is an important property of materials used as clay liner. Such clays should possess the required permeability. In view of this, some work has been done on experimental studies dealing with the effects of chemicals on the permeability of clays. Some of the studies focus on inorganic liquids while others address organic liquids and leachate components (Seracettin, 2010). The effects of Inorganic chemicals can be divided into acid, bases and salts and are discussed below.

#### ***i. Hydraulic properties of high plastic clays***

##### ***Acids***

Gordon and Forrest (1981) reported appreciable changes in the hydraulic conductivity of high plastic compacted clays when permeated with sulphuric acid ( $H_2SO_4$ ) with pH of 1.5. D'Appolonia (1980) identified an increase in hydraulic conductivity when bentonite soil was permeated with 5% solution of hydrochloric acid (HCl) which resulted to the dissolution of the clay minerals. Simons *et al.*, (1984) reported an increase in the hydraulic conductivity of compacted natural clays in a rigid wall permeameter using 5% solution of sulphuric acid ( $H_2SO_4$ ), nitric acid ( $HNO_3$ ) and hydrochloric acid (HCl) after 120 days of exposure.

##### ***Bases***

Clays with high amount of active clay minerals and fine particles generally have low permeability; because they increase the thickness of the DDL when permeated with inorganic bases (Seracettin, 2010). The thickness of the DDL is an important factor controlling the structural development, hydraulic conductivity and other physico-chemical and mechanical properties of soils (Mitchell, 1993). Lentz *et al.*, (1985) reported a decrease in hydraulic conductivity of different soil types by factor of 2.5 to 13 when permeated with sodium hydroxide (NaOH). They further concluded that, the

most observed decrease was in magnesium montmorillonite which could be as a result of ion exchange, where a divalent magnesium ion is replaced by a monovalent sodium ion, thus causing an increase in the double layer thickness.

### ***Salts***

Clay minerals undergo large inter-layer shrinkage when in contact with certain salts, which is then followed by potential cracking and increase in hydraulic conductivity values (Quigley, 1993). Increase permeability and flocculation were observed in soil structure when permeated with aqueous salt solution (Alther *et al.*, 1985). Rao and Sridharan (1987) indicated an increase in hydraulic conductivity when compacted clay was permeated with high pore salt concentration which retards full mobilization of the DDL thickness thus increasing the effective void space and increase the permeability.

#### ***ii. Hydraulic properties of low plastic clays***

The hydraulic conductivity of low plastic clays decreases with increased concentration of salt solution (Yilmaz *et al.*, 2008a). Experimental tests on some low plastic kaolinite clay samples indicated a decrease in the permeability when permeated with solutions such as acetone, benzene, phenol, etc. (Seracettin, 2010). It can be concluded that, the decrease in hydraulic conductivity with increasing concentration of salt solutions can be attributed to the decrease in the thickness of the DDL, resulting in flocculation of the clay particles due to contraction (Seracettin, 2010).

#### ***2.12.3 Effect of chemicals on Shear Strength of clays***

Limited information is available on the effects of chemicals on the shear strength of liner materials (Seracettin, 2010). Notwithstanding, several researchers have

investigated the effects of chemicals on the shear strength of liner materials and have presented the following results. Ayininuola *et al.*, (2000) reported that, an initial increment in soil angle of friction and cohesion was observed when a sub soil was saturated with  $\text{CaSO}_4$  at different concentrations to investigate its shear strength. Also, Sivapullaiah and Manju (2005) investigated the utilization of kaolinitic soils blended with bentonite and lime, as liner material and reported that, the peak stresses of the liner saturated with HCl and NaCl were lower than those of NaOH and water. It was further postulated that, the low strength of the soil with NaCl solutions was as a result of the reduction in soil cohesion caused by reduced water absorption capacity due to the reduction in the thickness of the DDL. It can therefore be concluded that, the increase in shear strength is as a result of increase concentration of solutions which can be attributed to the changes in the thickness of the DDL of clays.

#### ***2.12.4 Effects of Leachate on the Hydraulic Conductivity of clays***

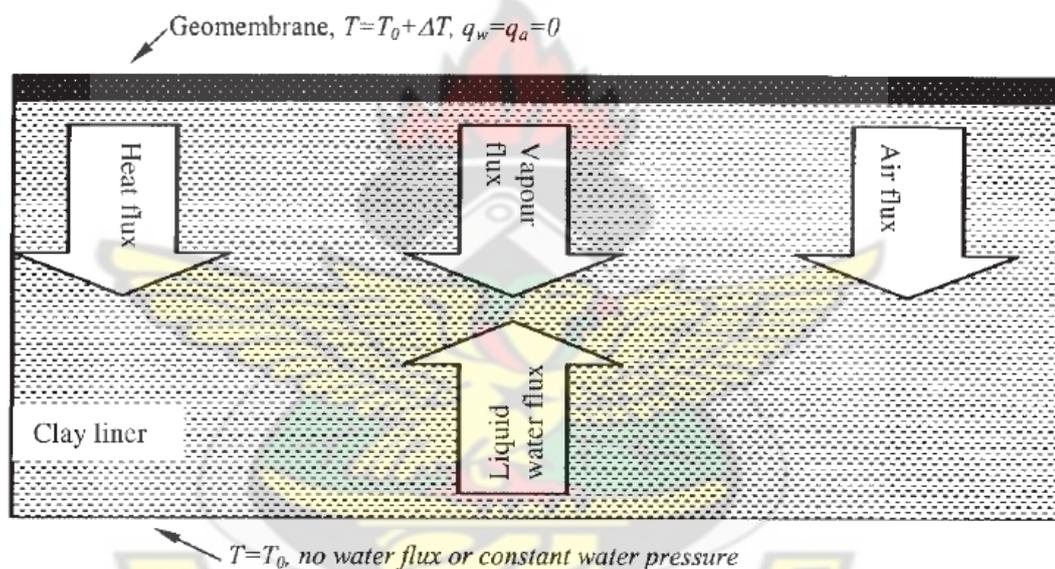
The permeability of clays can also be influenced by the leachate they come in contact with when used as liner materials. Leachate can influence the hydraulic conductivity of liners in two main ways; through the dissolution of the soil minerals or changes in clay structure (Mitchell, 1993). Soil minerals can be dissolved or reduced during the interaction of the liner materials with leachate, thus increasing the hydraulic conductivity, for instance, aluminum and iron in the liner material can be dissolved by acid; and silica in the liner by bases. Moreover, cations can be created as a result of the interaction of the leachate with liner materials thus leading to a change in the clay or liner structure, and as such, influencing the hydraulic conductivity of the liner material. Sharma and Lewis (1994) reported that, leachate permeating underlying clay liners have the ability of changing various factors that can influence the thickness of the diffuse double layer and hence the permeability of the compacted clay.

Despite the increasing hydraulic conductivity of compacted clays when permeated with leachate, several authors have reported a reduction and an unchanged hydraulic conductivity of the compacted clays when permeated with the same leachate. Daniel *et al.*, (1984) reported a decrease in the hydraulic conductivity of a soil after permeation with domestic waste leachate. Fang and Evans (1988) reported an unchanged hydraulic conductivity of silty clay soil when it was permeated with landfill leachate. Fernandez (1989) also reported a reduction in the hydraulic conductivity due to an increase in the amount of Na<sup>+</sup> adsorption during leachate permeation which could lead to an expansion in the double layer. Leachate may affect the hydraulic conductivity of clay liners depending on the clay mineralogy and leachate constituents (Fashiur, 2000).

### **2.13 Heat generation and its effects on clay liners**

Even though temperature has significant effects on various landfill components, limited information exist on temperature within wastes liner system (Yesiller and Hanson, 2003). An important factor influencing the long-term performance of a liner material is the liner temperature (Rowe, 2005). Both aerobic and anaerobic biological decomposition of organic matter involves an exothermic reaction that leads to heat generation and consequently increased temperature within the waste mass (Southern *et al.*, 2002). Also, hydration of incineration ash within the landfill is a main source of heat generation within the waste mass (Southern and Rowe, 2005). The generated heat leads to the development of a temperature gradient through the liner material; as such it gives an opportunity for the transfer of heat (Appiah, 2010). Temperature gradient and capillary pressure are two driving mechanisms for moisture transport in clay liner systems under non-isothermal conditions (Zhou and Rowe, 2003). When a temperature gradient is applied to an unsaturated liner material, changes in water and

air pressure are observed in the medium as shown in Figure 2.10. In such situations liquid water moves from higher capillary pressure towards lower capillary pressure, vapour water moves from higher temperature areas towards lower temperature areas due to vapour diffusion and air moves from higher air pressure to lower air pressure in the media (Zhou and Rowe, 2003). All these combined effects (air, water and vapour) are a redistribution of water in the liner system, thus, this redistribution has the potential to cause desiccation of the liner material in the area of higher temperature (Zhou and Rowe, 2003).



**Figure 2.10: Heat and Mass fluxes in an unsaturated medium under a geomembrane due to temperature gradient (Zhou and Rowe, 2003)**

The effects of desiccation are: reduction in void ratio, deformation, volume change and crack initiation (Abu-Hejleh and Znidarcic, 1995). Liner temperature can be affected by factors such as: the nature of waste, rate of land filling and the availability of moisture (Rowe and Hoor, 2009). An increase in waste water content due to leachate mounding or purposeful introduction of moisture to accelerate waste stabilization amplifies the level of temperature (Rowe, 1998). Under certain

conditions, the temperature of the landfill may increase from 50°C to 70°C (Koerner, 2001). These elevated temperatures are likely to persist as long as organic matter remains in the waste (Southen and Rowe, 2005). As decomposition proceeds, it elevates the temperature within the waste mass. An increase in temperature can lead to an increase in the hydraulic conductivity and diffusion coefficient of the liner materials as a result of the generated cracks (Zhou and Rowe, 2003).

Several studies on temperature and heat generated at the base of landfills under waste covered conditions have been reported. For example, Rowe (1998) reported that, temperatures approximately 20°C to 50°C were recorded at the base of landfills in Japan. Liner temperatures of 10° to 30°C and 20° to 30°C were reported for landfills in California and Florida respectively (Rowe, 1998).

The effects of increased temperatures and heat to liner materials are many, and can be in the form of cracking due to freeze-thaw cycles (Othman *et al.*, 1994), desiccation (Daniel, 1987), and in addition to the potential changes in shear strength, settlement and hydraulic conductivity of liner soils (Yesiller and Hanson, 2003). The above mentioned problems of increase temperature and heat generation within the fills and its effects on liner materials can be controlled to some extent, for instance, by the use of tire shreds as an insulator for the liner materials, but this increases the thickness of the liner materials and definitely reduces the amount of waste that can be accommodated by the landfill. The question arises whether liner materials cannot act as an insulator themselves to control the heat (temperature) generated, if the temperature is expected to approach unacceptable levels in terms of the liner service-life. As such, it is adequate to determine the thermal properties of materials for use as a liner material.

## **2.14 Compacted Clay Liners**

The United States Environmental Protection Agency (USEPA, 1993) has specified that, compacted clay (CC) may be used as an effective barrier for the containment of landfill leachate. Compacted clay liners (CCL) are materials which are constructed of cohesive soils that have been compacted to increase bulk density and homogeneity with the aim to minimize seepage through them. A CCL can serve as a single liner, composite liner or double liner. More often, CCLs are composed of natural soils or bentonite-soil blends and compacted in layers called lifts. These liner materials can be used effectively as hydraulic barriers and to ensure effective maximization of their potentials, certain quality control measures need to be implemented, for example; selection of the liner materials, methods of compaction, placement and protection of the liner, etc.

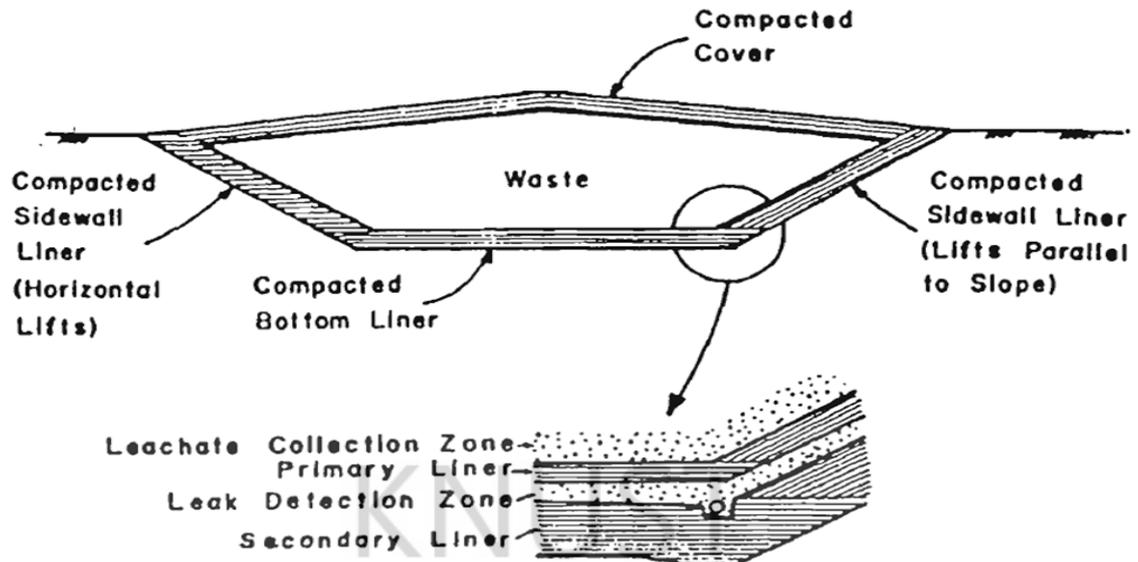
CCLs used in landfills have received the most prominent attention in recent times (Fashiur, 2000). The main reason for their use is their low hydraulic conductivity and their ability to maintain this characteristic in the long term under chemical, biological and moisture conditions at the base of the landfill. Moreover, their abundance in nature, cost effectiveness, high sorption potential for ion exchange, has made clay materials most suitable adsorbents (Preeti and Singh, 2007).

### ***2.14.1 Components of Clay Liner***

For centuries, clay has been used as liner material both in municipal and hazardous solid waste sites such as canal linings (Holtz, 1953), sewerage lagoons, landfills and surface impoundments (Daniel and Wu, 1993), mine tailings, chemical liquid storage ponds and evaporation ponds (Daniel, 1984b). Liner materials do have various components which assist in their function as insulating materials. These components could be partitioned as base liners, side liners and cover liners (Fashiur, 2000). The

basic component and function of a typical compacted clay liner in a landfill is shown in Figure 2.11 and are discussed.

- **Base Liners:** A landfill base liner material is a low permeable barrier, which is laid down on engineered landfill sites. Until it deteriorates, it minimizes the movement of leachate, and its toxic constituents into underlying aquifers or nearby rivers, thereby preventing pollution of the local water by means of filtration and drainage. The base liner also assists in providing mechanical support for the waste mass; it envelops the waste and isolates it from direct contact with the environment.
- **Side Liners:** These are lining materials placed at the sides of landfill sites. They have similar functions to the base liners by preventing leachate migration into the ground surface, provides mechanical resistance to external water pressure, providing enough contact for the overburden materials and finally preventing lateral migration of landfill gas.
- **Top Liners:** These are lining materials placed at the top of landfill sites, thus minimizing the rate of generation of leachate by preventing precipitation and surface water infiltration into the landfill. It also assists in accommodating differential settlement as a result of consolidation of the founding materials and also helps in erosion control.



**Figure 2.11: Compacted clay liner and components (Fashiur, 2000)**

#### **2.14.2 Requirements of compacted clay liner materials**

The main requirement of a liner material is its ability to act as a hydraulic and thermal barrier thus preventing leachate migration and the effects of heat generation. As such these properties of the soils (clays) need to be evaluated through laboratory testing. Several researchers have proposed certain requirements of clay liners. For example Daniel and Wu (1993); Mitchell and Jaber (1990) recommend that, the clay liner should have the following characteristics:

1. ***It must be durable and resistant to weathering;*** CCLs should have adequate durability and resistant to weathering, thus helping the material against the forces of alternating wet/dry and freeze/thaw cycles which prevents cracking that will definitely lead to the seepage of leachate to the ground water.
2. ***The material must be constructible;*** it is the ability of the material to be workable in terms of placement and compaction under field conditions. Usually CCL construction involves the mixing of clay with water at moisture

content generally wetter than the optimum value to target for minimum hydraulic conductivity.

3. ***It must be compatible with the leachate;*** normally CCL materials must maintain their strength and low permeability with no shrinkage after prolonged contact with leachate thus preventing cracking. A liner material is compatible with the leachate it comes in contact with, when the chemical reaction potential leading to degradation is low. Hence, tests for chemical compatibility are imperative in liner design.
4. ***It must have low permeability;*** hydraulic conductivity or permeability is one of the most important if not the most important parameter for CCL materials. The permeability defines the rate of seepage of leachate through the liner materials. Low permeability results in low seepage through the liner material while the reverse is true for high permeability thus minimizing or maximizing the effect of ground water contamination respectively.
5. ***Grain size distribution: clay fraction ( $< 2\mu\text{m}$ )  $\geq 10\%$  by weight.*** The presence of an adequate percentage of clay fractions in the soils is adequate to achieve the required minimum permeability. Hence grain size distribution is an important factor in the selection of CCL materials. Materials to be used as liners must have percentage of fines  $\geq 30\%$  and percentage of clay  $\geq 10\%$ .
6. ***Low diffusivity;*** diffusion is the process by which contaminants move from high concentrations to low concentrations. By maintaining a low diffusion coefficient within the lining material, low diffusivity is obtained. Diffusivity is independent of hydraulic conductivity, meaning achieving low permeability does not mean achieving low diffusivity since diffusion can also occur without seepage.

7. **High attenuation potential;** these are the various processes such as adsorption, precipitation, biological processes, redox reactions, acid–base reactions by which liner materials reduce the quantity of contaminant (leachate) generated within the landfill. Thus, a CCL material with a high degree of attenuation potential reduces the effect of ground water contamination.
8. **Low freeze/ thaw effects;** CCL materials constructed in cold regions may undergo changes in its structure due to freezing and thawing of the pore fluid which results in cracks and definitely lead to seepage of the contaminant through the liner material. It should be noted that, similar issues may not apply to CCL materials constructed in tropical zones such as Ghana.
9. **Ductility;** the liner material should be capable of withstanding a certain amount of force before fracturing or breaking. The introduction of tensile stress on lining materials during uneven settlement may result in cracks on them which lead to seepage. Hence, CCL must be of good ductility to avoid such situations upon being stress.
10. **Good stability;** the liner material should be one that can sustain its desirable properties throughout its service life and as such should not degrade with time. Processes that facilitate in the degradation of the liner include; its reaction with leachate and creep.

#### ***2.14.3 Thickness, strength, thermal and hydraulic conductivities recommendations for compacted clay liners***

Compacted clay liners should have a saturated hydraulic conductivity of the order  $\times 10^{-9}$  m/s ( $\times 10^{-7}$  cm/s) or less (Ghana Landfills Guidelines, 2002; EPA. 2000). A minimum acceptable thickness of 2 feet which often depends on the flow velocity of

the leachate is recommended for liner materials EPA (2000). Also, according to the United States Environmental protection Agency (USEPA) the compacted soil liner must have a permeability of not more than  $1 \times 10^{-7}$  cm/sec and an approximate thickness of at least 60cm (Anonymous, 1993). In addition, several authors and regulatory agencies have recommended different specifications for the hydraulic conductivity for liner materials. The low hydraulic conductivity will assist to lengthen the lifetime of the landfill by minimizing the leachate migration and the required thickness helps ensures that, the liner meets the required hydraulic conductivity standards and also minimize leachate migration as a result of any cracks or imperfections present in the liner.

Waste materials exert compressive stress on liner materials but up to date a required minimum strength of liner materials is not being specified because the compressive stress acting on the liner materials depends on factors such as: the amount of waste, the height of the landfill and the unit weight of the waste, etc. For a material to be used as a liner material it should have a minimum Unconfined Compressive Strength (UCS) of 200KPa to support a maximum height of 75m (Daniel and Wu, 1993; Bello, 2011b). Also, for materials to be used as base liners, their capability of achieving a maximum thermal conductivity of  $2 \text{ W/m}^{\circ}\text{C}$ , or less is recommended by Andersland and Ladanyi (2003). Further required characteristics of liners and the total lining system are described in the European regulations and national document (Witt and Zeh, 2005).

## CHAPTER THREE: EXPERIMENTAL

### 3.1 Materials

#### 3.1.1 The Clays

Clay samples used in the study were collected from Mfensi and Afari, both towns in the Ashanti Region of Ghana. The locations of the sites are shown in Figure 3.1. The Mfensi area lies within longitude  $6^{\circ}, 45'$  and  $6^{\circ}, 36.5'N$  and latitude  $01^{\circ}, 46'$  and  $01^{\circ}, 53.3'W$ , whereas Afari is bounded by longitude  $6^{\circ}, 42'$  and  $6^{\circ}, 11'N$  and latitude  $01^{\circ}, 46'$  and  $01^{\circ}, 56.5'W$ . Representative samples were collected from the sites for laboratory investigations.



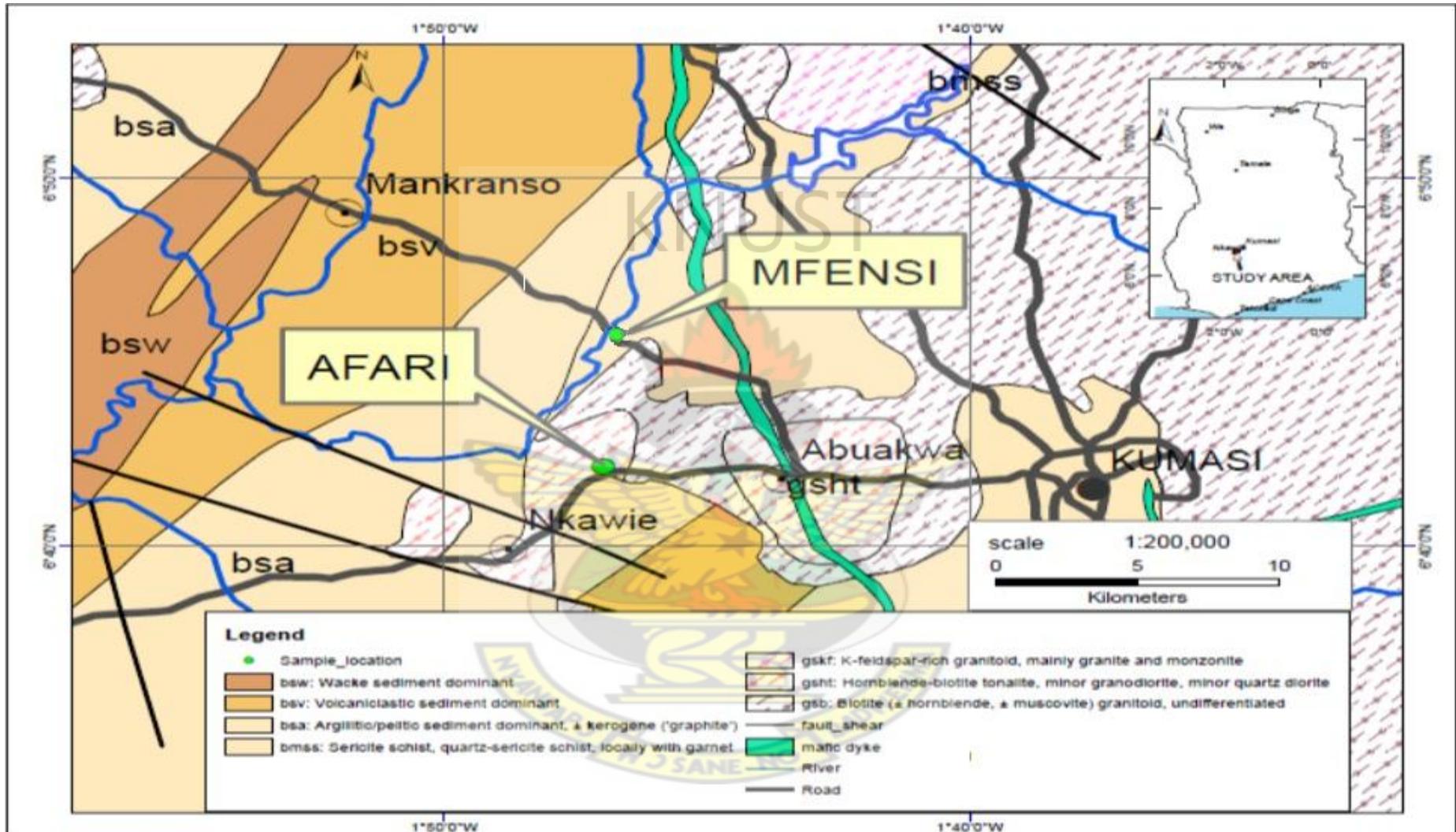


Figure 3.1: Geological map of the Ashanti Region indicating sampling locations

Reconnaissance survey was conducted on the two areas to identify representative points for sampling by trial pitting. A total of 8 areas were selected, 4 on each town. The trial pits were dug using shovel and pick-axe. The dimensions of the pit were 1.5meter-length by 1meter-breadth by 3.5m-depth. A total of 24 disturbed samples were collected for both clays from depths of 0.5m, 2.1m and 3.2m in both areas. Sampling was done laterally and vertically with aim of minimizing the effect of variations in the physical properties of the clays. Samples for each area were combine to produce one representative material for analyses because the physical variations (colour and texture) with depth were not so significant. Samples were bagged, labeled and transported to the laboratory for studies. Typical grab samples of the clays from the two towns are presented in Plates 3.1 and 3.2.



**Plate 3.1: Afari clay samples**



**Plate 3.2: Mfensi clay samples**

### ***3.1.2 The Leachate***

In order to assess the effects of leachate on the properties of the two clays, leachate was collected from an active aerobic cell at the Kumasi Engineered landfill site as shown in Plate 3.3 and used for some experiments. The leachate was collected from the cell using a container tied to a rope. A clean container was used so as to avoid contamination. The leachate was then transferred into clean tightly sealed bottles and transported to the laboratory and stored in a refrigerator.



**Plate 3.3: Kumasi landfill aerobic leachate cell**

## **3.2 Laboratory Studies**

### ***3.2.1 Sample Preparation***

The clay samples were air dried at room temperature (25°C–28°C) for a week, employing measures that would avoid contamination. The dried samples were then crushed manually into smaller sizes using mortar and pestle. The pulverized clay samples were stored in labeled plastic bags ready for testing. Each test was duplicated to ensure reliability of results.

### ***3.2.2 Sample Testing***

The samples were subjected to physical, chemical, physico-chemical, mineralogical, geotechnical as well as thermal analyses and are briefly discussed.

#### ***Physical Characteristics***

Physical properties such as; soil texture and colour of the clays were determined based on how the clay samples felt when handled in the palm and visual examination respectively.

#### **Geotechnical Tests**

##### ***i. Particle size distribution (PSD)***

The method employed for the determination of the particle size distribution was that specified by (BS1377, 1990) which is the combined analysis using both methods of sedimentation and sieve analysis. For sedimentation test, hydrometer method was employed, using sodium metahexaphosphate ( $\text{NaPO}_3$ )<sub>6</sub> as the dispersing agent.

##### ***ii. Atterberg limits***

The Atterberg limits determined were: the liquid limit (using the cone penetrometer method), plastic limit and linear shrinkage using the BS 1377, (1990) standard

specifications. The other was the colloidal activity of clays which is the ratio of the plasticity index to the clay-size fractions in the soil.

### *iii. Specific Gravity*

The density bottle technique was used in the determination of the specific gravity of the clays. The specific gravity tests were performed according to standard procedures outlined in BS1377 (1990) specification.

### *iv. Moisture Content*

Determination of the moisture content was done by oven drying as specified by the BS 1377 (1990).

### *v. Compaction Test*

The compaction characteristics of the clays were determined using the British Standard light Compaction Test. The test was conducted in accordance with BS 1377, (1990) specifications. The density-moisture relationships were determined for both clay-tap water and clay-leachate mixtures.

### *vi. Unconfined Compressive strength*

In the determination of the unconfined compressive strength (UCS) test in the laboratory, the samples were prepared by remoulding the clay to 100% optimum moisture content (OMC), so as to achieve maximum dry density (MDD). It should be noted that, at field conditions remoulding is done at 95% OMC. The top of the compacted samples were trimmed and three (3) small cylindrical tubes were pushed into the compacted clays to obtain cylindrical samples of dimension 7.1cm by height and 3.8cm by diameter. The samples were then tested for the unconfined compressive strength using the ELE compression test machine.

### *vii. Saturated hydraulic conductivity*

The hydraulic conductivity test was done using the falling head permeameter and detailed description of the test is presented in BS1377, (1990). The falling head was used because it is most suitable for fine grained soils such as clays. The samples were prepared by remoulding the clay at optimum moisture content and mounted in the permeameter so as to target for maximum dry density.

### **Chemical Analysis**

The major oxides and minor elements in the clays were determined using the X-Ray Fluorescence Spectrometer (XRF–Spectro X-LAB 2000) method at the Geological Survey Department, Accra. Clay samples passing through sieve No. 200 were used for the test. 4g each of the samples were mixed with 0.9g of powder Lico-wax binder and later placed in a homogenizer for complete mixing at a frequency of 15Hz for 3 minutes. The samples were removed and placed in a compressor and pressed under 5,000g of load to obtain the sample pellets of 15mm in diameter. Finally, the pellets were transferred to the Spectro X-LAB 2000 for their chemical analysis determination. Measurements were taken using an excitation source that emits Ag-K X-rays (22.1KeV) in which case all elements with lower characteristic excitation energies were accessible for detection in the samples. The system consists of a Si(Li) detector with a resolution of 170eV for the 5.90KeV line, coupled to a computer controlled ADC-card.

### **Mineralogical Analysis**

The mineralogical compositions of the clays were determined by the X-Ray Diffraction method (XRD) using Siemens Theta/2 Theta D 5000 with copper tube anode at the Material Engineering Department, KNUST.

## **Thermal Conductivity**

The thermal conductivities of both clays were determined by a steady state method using the Lee disc apparatus. The test was carried out in accordance with ASTM D5470-06 specification. The setup of the Lee's disc apparatus is as shown in Plate 3.4



**Plate 3.4: Setup of the Lee's Disc Apparatus**

## **Determination of physico-chemical characteristics of the clays**

The organic carbon content (OCC), effective cation exchange capacity (ECEC), exchangeable cations (EC), exchangeable acidity (EA) tests were the physico-chemical tests determined using standard procedures at the Soil Science Laboratory of the Faculty of Agriculture and Natural Resource, KNUST.

### **i. *Organic Carbon Content***

The Organic Carbon Contents of the clays (OCC) were determined using the Walkley and Black wet combustion method (Nelson and Sommers, 1982).

*ii. Exchangeable Cations*

The cations determined were Potassium, Sodium and Aluminium. The Potassium and Sodium cations were determined using Flame photometry (Moss, 1961) while Alumina was determined using wet chemistry.

*iii. Exchangeable Acidity and pH*

The Exchangeable Acidity was determined using the titration method while the pH was determined by the pH meter.

*iv. Effective Cation Exchange Capacity*

Determination of the effective cation exchange capacity was done by summing the exchangeable cations.

**Physico-Chemical Characterization of leachate**

Physico-chemical characterization as well as concentrations of various heavy metals, anions, organic and inorganic constituents of the leachate sample was determined using the inductive coupled plasma emission spectrometry following standard laboratory method at the Water and Sanitation Unit, KNUST.

## CHAPTER FOUR: RESULTS AND DISCUSSION

### 4.1 Nature and Characteristics of the clays

The clays used in the study were collected from between 0.5-3.2m below ground level from Mfensi and Afari towns in the Ashanti Region of Ghana. The Afari site is underlain by Hornblende-biotite tonalite and minor Granodiorite and minor quartz diorite while the Mfensi site is underlain by Sericite-schist, Quartz-sericite schist and locally with Garnet (Ghana Geological Survey Department, 2009). Both clays were soft and they had high water contents. Afari clay was yellowish in colour with shades of orange while Mfensi clay was greenish-grey in colour in their dry states. The clays were fine grained and lumpy.

#### 4.1.1 Chemical Composition of Afari and Mfensi Clays

The chemical compositions of the clays are similar although the oxides concentrations vary as presented in (Table 4.1). The dominant oxides in both clays were silicon, alumina and iron, which constituted about 89.85% for Mfensi clay and 80.11% for the Afari clay. High SiO<sub>2</sub> contents were observed in both clays, which accounts for the high quartz content noticed from XRD diffractograms (Figures 4.2 and 4.3). The results showed that, both clays are siliceous in nature. The presence of aluminum oxide contents of 25- 45% makes Mfensi clay fall under the class of Alumino-silicate refractories (Hassan and Adewara, 1993). Other major oxides in both clays included; Na<sub>2</sub>O, MgO, MnO, TiO<sub>2</sub>, CaO and K<sub>2</sub>O among others. The concentrations of these oxides were much higher in Afari clay than Mfensi clay except those of TiO<sub>2</sub> and K<sub>2</sub>O. The variations of minor elements of both clays are also presented in Table 4.1. It is seen that Sr, Zr, Ba, La, Ce occur in greater concentration in the Afari clay with the exception of Zr compared to the other minor elements with Ba being the highest.

**Table 4.1: Results of the chemical analysis of both Afari and Mfensi clay samples**

<b>Major Oxides (%)</b>	<b>Afari Clay</b>	<b>Mfensi Clay</b>
SiO <sub>2</sub>	51.47	61.19
TiO <sub>2</sub>	0.77	0.83
Al <sub>2</sub> O <sub>3</sub>	21.58	25.60
Fe <sub>2</sub> O <sub>3</sub>	7.06	3.06
SO <sub>3</sub>	0.09	0.06
MgO	2.29	1.69
K <sub>2</sub> O	0.63	1.57
CaO	0.79	0.12
MnO	0.03	0.02
Na <sub>2</sub> O	1.32	0.94
P <sub>2</sub> O <sub>5</sub>	0.05	0.08
LOI	12.62	4
<b>Minor Elements (ppm)</b>		
Co	34.7	< 19
Ni	96	15.9
Cu	14.1	4.8
Zn	49.2	31.3
Ga	22.5	17.8
Pb	1.2	2.4
Ge	1.5	1.3
As	2.1	1.4
Rb	11.6	52.8
Sr	443.6	37.8
Y	19.9	<0.6
Zr	339	553
Nb	19.5	18
Sn	<2.1	1.3
Cs	<10	17.9
Ba	886	369.6
La	181	34.2
Ce	408	51

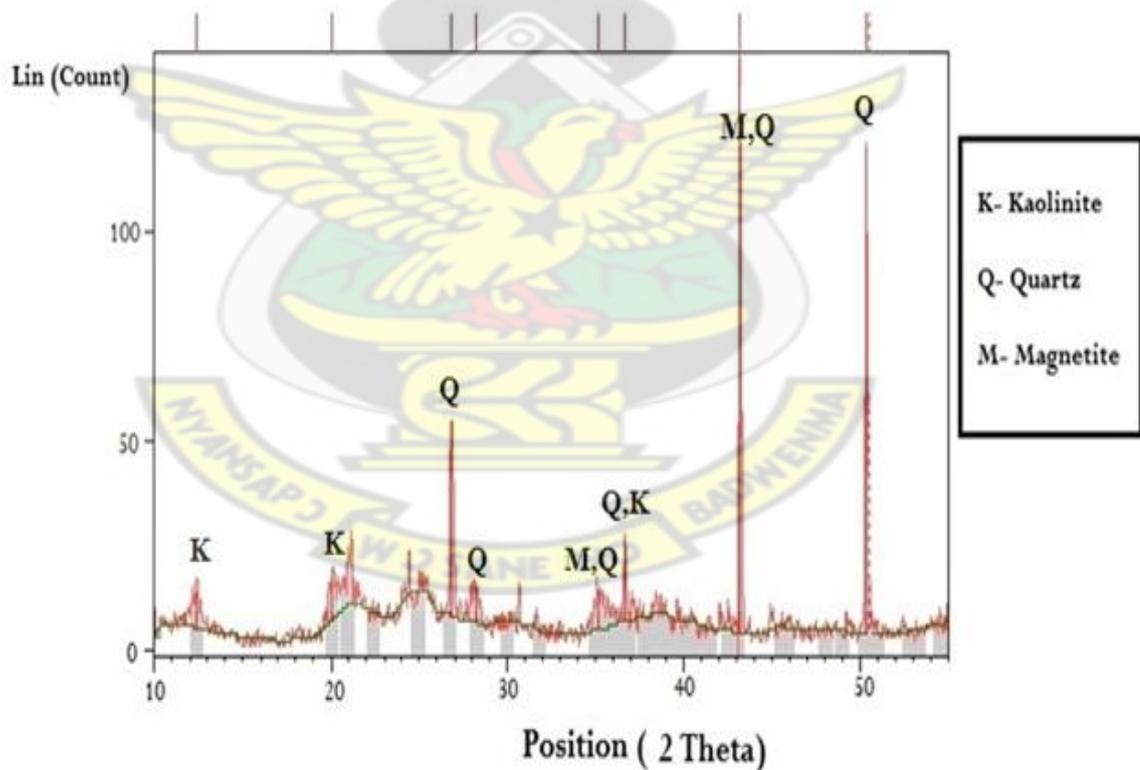
#### ***4.1.2 Mineralogical Composition of the Clays***

The X-ray diffractograms of both clays showed similar phases indicating similar mineralogy as seen in Figures 4.1 and 4.2 for Afari and Mfensi clay samples respectively. The results of XRD analyses indicate that, both clays are composed mainly of Kaolinite (clay mineral) and Quartz and Magnetite as non-clay minerals in varying concentrations as reflected in the intensity and peak heights of the X-ray diffractograms. Overlapping of the clay and non-clay minerals in both clays are common. The presence of the clay mineral kaolinite in both clays implies that, the clays are likely to perform effectively as barrier soils in containment and attenuation of contaminants generated (Allen, 2000). The presence of kaolinite in both clays also indicates that, they will exhibit low to moderate shrinkage on drying and low to moderate expansion on wetting since kaolinite has the least affinity for water among the clay minerals, with greater stability and confining ability (Oyediran and Iroegbuchu, 2013). In addition, it also makes the liner relatively immune to damage when exposed to chemicals since kaolinite has a fairly high anion exchange capacity giving it propensity to remove anionic species such as phosphate from solution (Abdussalam, 2005).

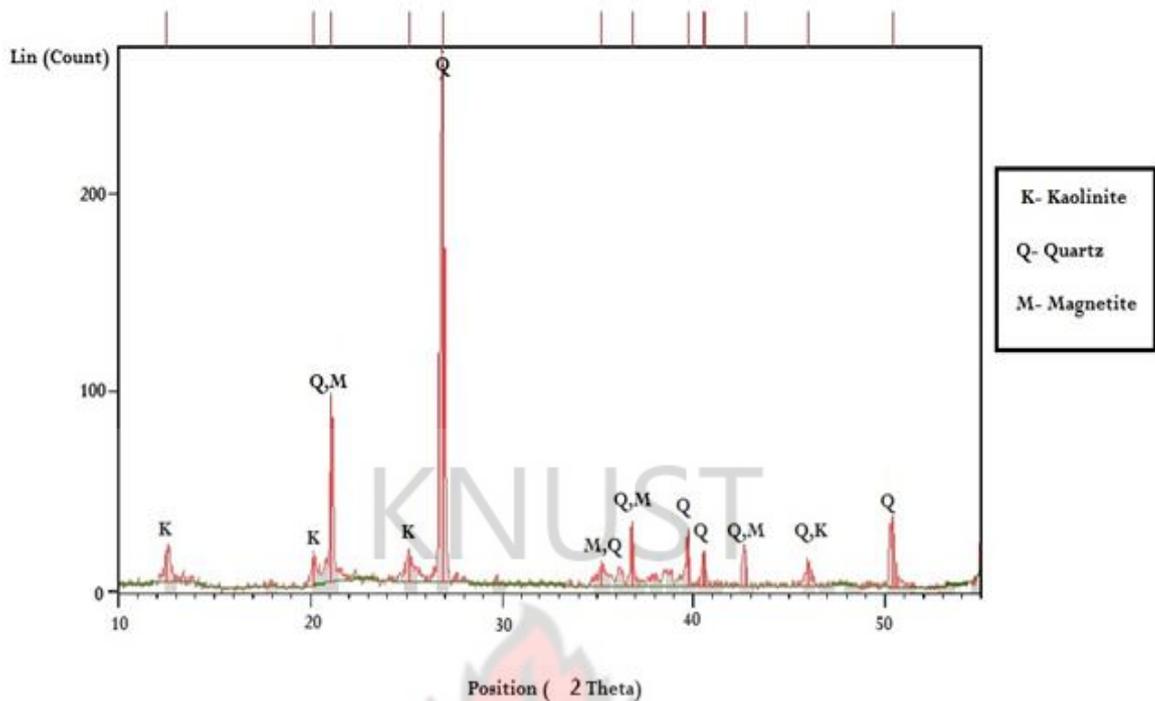
Afari clay's peaks revealed the presence of 2 major crystalline phases; quartz and a mixed clay assemblage of magnetite and quartz. The presence of relative smaller peaks of kaolinite, quartz and assemblage of quartz and kaolinite together with quartz and magnetite are common. The overlapping of magnetite and quartz peak had the highest peak intensity at a peak height greater than 100 counts. Also, quartz had a peak height greater than 100 counts for the highest peak but lower than the overlapping of quartz and magnetite peak. Moreover low peaks intensities of less than

50 counts were observed for magnetite and quartz peak and also for quartz and kaolinite.

On the other hand, Mfensi clay had quartz as the major crystalline phase at a peak height greater than 200 counts with minor fractions of kaolinite and quartz of peak heights less than 50 counts as reported by Andrews *et al.*, (2014). Overlapping of magnetite and quartz peaks and quartz and kaolinite peak are also common. It is noted that, strong peaks of quartz were detected in both diffractograms which can be attributed to the high concentration of SiO<sub>2</sub> in both clays (Amoanyi, 2012). Albite and montmorillonite were absent in Afari clay while muscovite was also absent in Mfensi clay contrary to findings by Amoanyi (2012).



**Figure 4.1: X- Ray diffraction pattern of Afari clay sample**



**Figure 4.2: X- Ray diffraction pattern of Mfensi clay sample**

#### **4.1.3 Physico – chemical characteristics of the clays**

The physico-chemical characteristics of the clays are presented in Table 4.2. The pH of the clays indicates that they are acidic. The organic matter contents of the clays were 0.48 % and 1.65 % for Afari and Mfensi clays respectively. The effective cation exchange capacity (ECEC) of clays which is the measure of the adsorption characteristics or exchange capacity of the clay minerals and an indicator of the type and amount of free cations and acidity that are adsorbed, expressed in mill equivalent per 100 grams of the clays (Abdussalam, 2005) were determined. Researchers such as Rowe *et al.*, (1995) and Kayabali (1997) have recommended that, soil liner materials should at least have an ECEC of 10 meq/100g. The ECEC of Afari clay was found to be 32.33 meq/100g higher than that of Mfensi clay which was 7.79 meq/100g, thus Afari clay is better in terms of its suitability for clay liners with respect to ECEC than Mfensi clay.

**Table 4.2: Physico – chemical properties of both clay samples**

<b>Properties</b>	<b>Afari clay</b>	<b>Mfensi clay</b>
pH	5.37	5.29
Organic matter (%)	0.48	1.65
Potassium*(meq/100g)	0.10	0.20
Sodium* (meq/100g)	1.17	0.25
Calcium* (meq/100g)	12.16	4.02
Magnesium* (meq/100g)	15.56	0.98
Aluminium* (meq/100g)	1.67	1.00
Hydrogen* (meq/100g)	1.67	1.34
<b>ECEC (<math>\Sigma</math> cations) meq/100g</b>	<b>32.33</b>	<b>7.79</b>

*\*Exchangeable cations*



## 4.2 Geotechnical Characteristics of the studied clays

The geotechnical characteristics of the studied clays are presented in Table 4.3

**Table 4.3: Geotechnical characteristics of the studied clays**

Parameters	Afare clay		Mfensi clay	
<b>Atterberg's Tests</b>				
Liquid limit (%)	64.78	81.65 *	42.85	47.31 *
Plastic limit (%)	24.26	22.43 *	20.42	19.62 *
Plasticity index (%)	40.52	59.22 *	22.43	27.69 *
Liquidity index (%)	0.12		0.58	
Linear Shrinkage (%)	17.7	17.45 *	10.4	11.95 *
Specific gravity $G_s$	2.68		2.72	
Natural moisture content (%)	29.09		33.40	
Activity	1.2		0.6	
<b>Grading</b>				
Sand (%)	43.51		20.5	
Silt (%)	22.31		41.5	
Clay (%)	34.17		38.0	
Fines contents (%)	63.70		88.33	
<b>Strength Parameters</b>				
Max. Dry density ( $Mg/m^3$ )	1.539	1.52 *	1.625	1.74 *
Opt. Moisture content (%)	18.98	16.4 *	20.0	17.0 *
Compressive strength (kPa)	242.92	268.98 *	331.73	364.90 *
<b>Conductivities</b>				
Hydraulic Conductivity (cm/s)	$4.637 \times 10^{-7}$	$1.005 \times 10^{-7*}$	$3.448 \times 10^{-7}$	$2.276 \times 10^{-8*}$

**\*Leachate was the mixing/permeating fluid**

#### ***4.2.1 Specific Gravity and Natural Moisture Content***

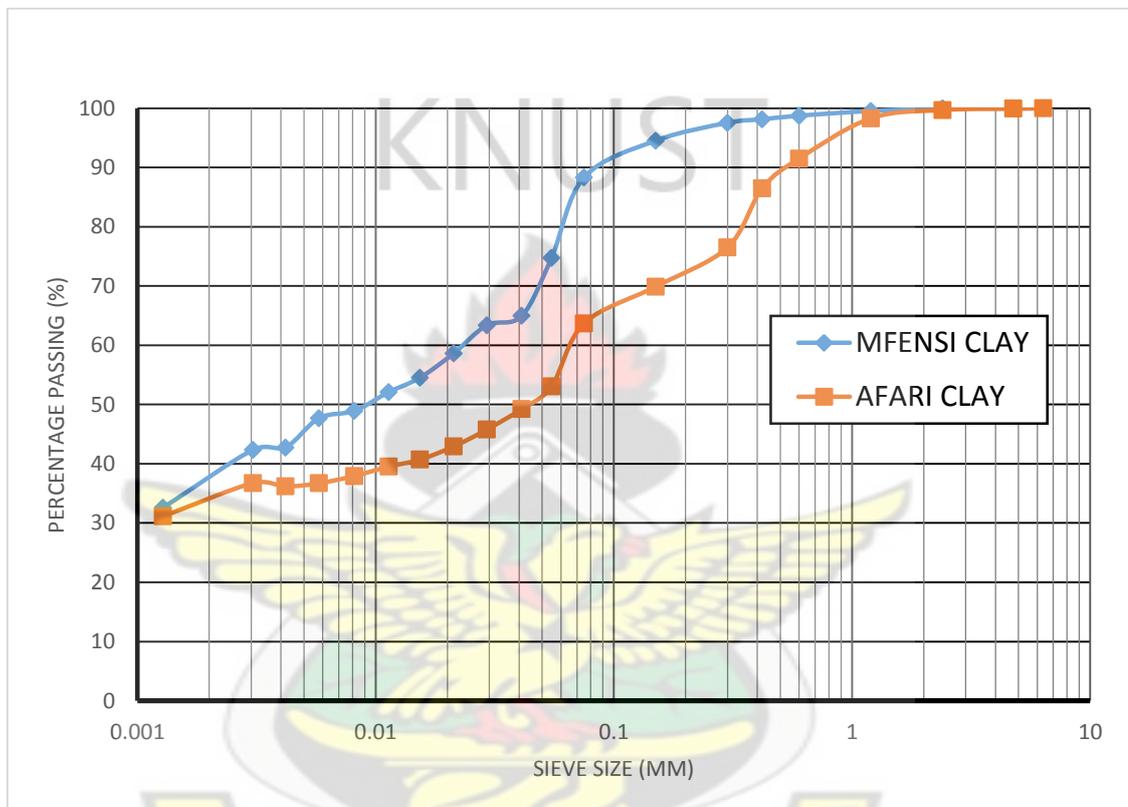
The average values for the specific gravity of Afari and Mfensi clay samples at 26°C are 2.68 and 2.72 respectively which are above the 2.5 minimum recommended in the ONORM S 2074 (1990) and USEPA (1982). The natural moisture contents of both clays were 29.09% and 33.40% for Afari and Mfensi clay samples respectively.

#### ***4.2.2 Particle Size Distribution and Textural Classification***

The particle size distribution curves of the two clay samples are shown in Figure 4.3 and the variation of the various grain sizes are tabulated in Table 4.4. They indicate that, the dominant size fraction in Afari clay is sand followed by clay and silt while that for the Mfensi clay is silt followed by clay and sand in reducing order of percentage. The sand size contents of the clays were 43.51% for Afari and 20.5% for Mfensi clay, and the results are within the range proposed by Kabir and Taha (2004) who recommended that, liner materials should contain at least 20% sand which would offer significant protection from volumetric shrinkage and impact adequate strength. The sand size fraction of the clay liner can also reduce the hydraulic conductivity as long as the sand size grains remain matrix supported by the clay fraction after compaction (Elliott and Watkins, 1997). Both clays meet this requirement and are expected to exhibit low permeability.

Furthermore both clays satisfy the recommendation of Declan and Paul (2003) for a minimum clay content of 10% for barrier soils and they also fall within the recommended  $\geq 30\%$  fines and less than 30% gravel for liner materials (Daniel and Wu, 1993). This requirement is further in line by the recommendation of Brunner and Keller (1972) for use of finer soils as barrier materials because of high specific surface area and low migration of leachate as soil texture becomes finer. The grading curves for both clays indicate that, they are well graded. According to DoE (1995),

they will tend to compact to a lower porosity and hence lower permeability than the uniformly graded. EPA (1990) recommended that, soils used as liner materials should have at least 20% fines to achieve a hydraulic conductivity of the order  $\times 10^{-7}$  cm/s or less. It can be concluded that, both clays satisfy the above recommendations to be used as liner materials based on their grading characteristics.

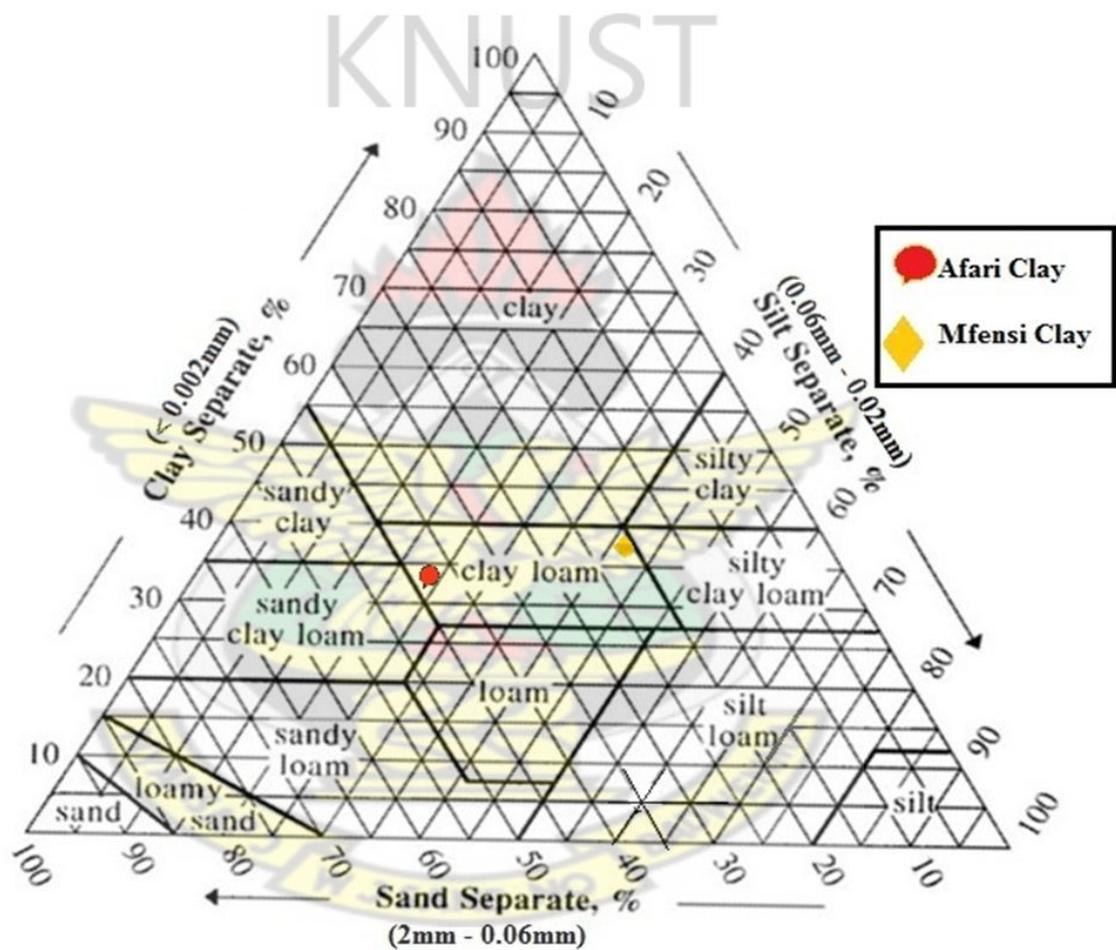


**Figure 4.3: Particle size distribution curves of the clays**

**Table 4.4: Grading Characteristics of the study clays**

Grading (%)	Afari Clay	Mfensi Clay
Sand	43.51	20.5
Silt	22.31	41.5
Clay	34.17	38.0
Fines contents	63.70	88.33

The textural classification of both clays is represented in Figure 4.4. Both clays classify as clay loam on the textural chart.



**Figure 4.4: Textural classification of the clays**

### 4.2.3 Atterberg Limits and Plasticity Characteristics

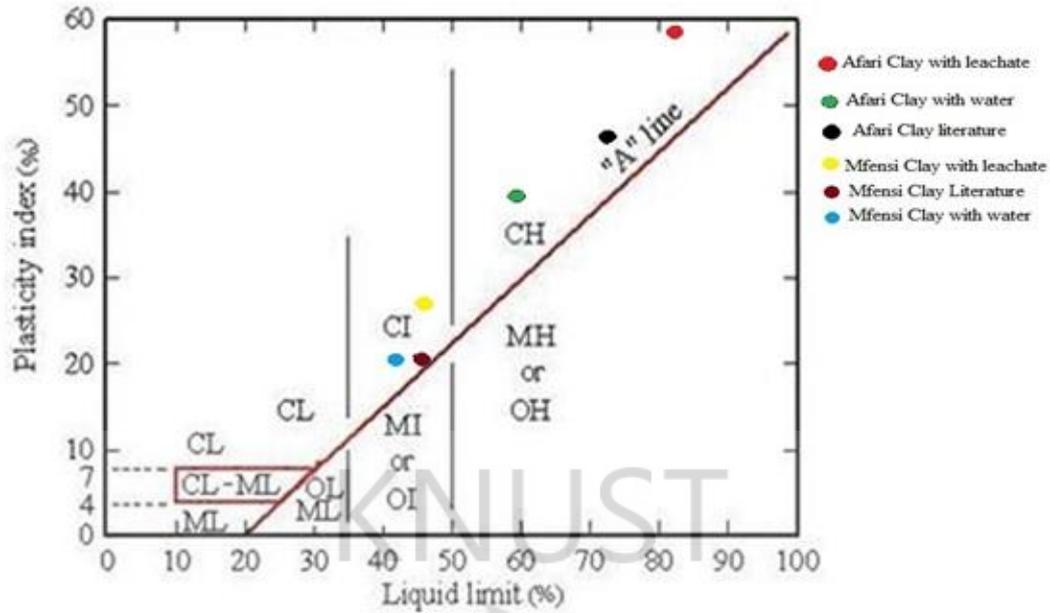
The Atterberg limits of the clays mixed with water and leachate are presented in Table 4.5.

**Table 4.5: Atterberg limits of the clays**

Property (%)	Mfensi clay		Afari clay	
	Water	Leachate	Water	Leachate
Liquid limit	42.85	47.31	64.78	81.65
Plastic limit	20.42	19.62	24.62	22.43
Plasticity index	22.43	27.69	40.52	59.22

The results show that, the liquid limits (LL) and the plasticity indices (PI) of both clays increased but the plastic limits (PL) reduced when the clays were mixed with leachate. It was also observed that, the LL and PL of Afari clay were higher than those of Mfensi clay. This increase in LL and PL of Afari clay can be attributed to its high sand content. Mitchell and Jaber (1990) recommended that, for materials to be used as base liners, the liquid limit should be  $\geq 30\%$ . Also, Declan and Paul (2003) indicated that, liner materials should not have liquid limits of more than 90%. These recommendations are in line with the views of Lawal and Abdullahi (2010) who indicated that, the greater the liquid limit of a sample, the higher its water retention capacity. Based on the results (clay + leachate and clay + water) the Atterberg limits of both clays meet the requirement for use as clay liner.

The plasticity indices of both clays exceed 20%. The results of the plasticity characteristics are in consonance with study by Andrews *et al.*, (2014). Daniel (1991) recommended that, soils with PI exceeding 35% are expected to display excessive shrinkage and settlement. Thus, Mfensi clay is better in terms of its suitability for clay liner with respect to shrinkage potential.



**Figure 4.5: Plasticity characteristics of both clays**

The plotted Atterberg limits of the clays with water and leachate on the casagrande's plasticity chart are shown in Figure 4.5, together with those reported in literature when mixed with water by Amoanyi (2012). All the samples lie above the A-Line. Jones *et al.*, (1993) stated that, materials that fall above the A-line are suitable or marginal for use as liners and those below the A-line are unsuitable. Based on the Unified Soil Classification System (USCS) the Afari clay classifies as inorganic clay of high plasticity (CH) and Mfensi clay, inorganic clay of intermediate plasticity (CI). Both clays also classify as A-7-6 by the American Association of State Highway and Transportation official system (AASHTO).

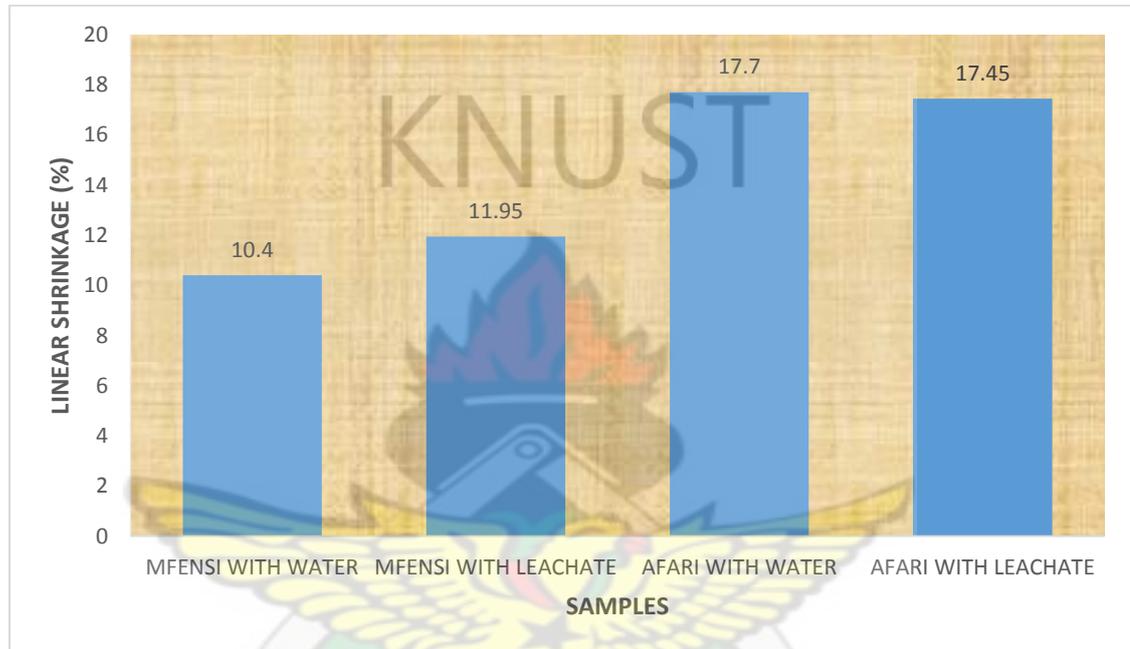
#### **4.2.4 Colloidal activity of the clays**

The colloidal activities of the clays were found to be 1.2 and 0.6 for Afari and Mfensi clays respectively. The Mfensi clay indicates low expansion potential and the Afari clay indicates medium expansion potential according to Skempton's (1953) classification (see Appendix A, Table1). Rowe *et al.*, (1995) recommended that soils

with an activity of 0.3 and above are suitable and can achieve a hydraulic conductivity of order  $\times 10^{-7}$  cm/s.

#### 4.2.5 Linear Shrinkages of the clays

Figure 4.6 show the percentage linear shrinkages of Mfensi and Afari clay samples when mixed with water and leachate.



**Figure 4.6: Percentage linear shrinkages of Afari and Mfensi clay**

Both samples had linear shrinkages less than 20%, though Afari clay recorded a higher value compared to Mfensi clay. Mfensi clay had 10.40% and 11.95% when mixed with water and leachate respectively. On the other hand, Afari clay had values of 17.7% and 17.45% for water and leachate respectively. An increase in shrinkage was observed for Mfensi clay when mixed with leachate (11.95%) while a decrease in shrinkage was observed for Afari clay when mixed with leachate (17.45%). Surface cracks were observed on the Mfensi clay samples after shrinkage test when mixed both with water and leachate. Cracks were however absent in the Afari clay. Such cracks can be prevented in the field by wetting the clay (liner) after compaction.

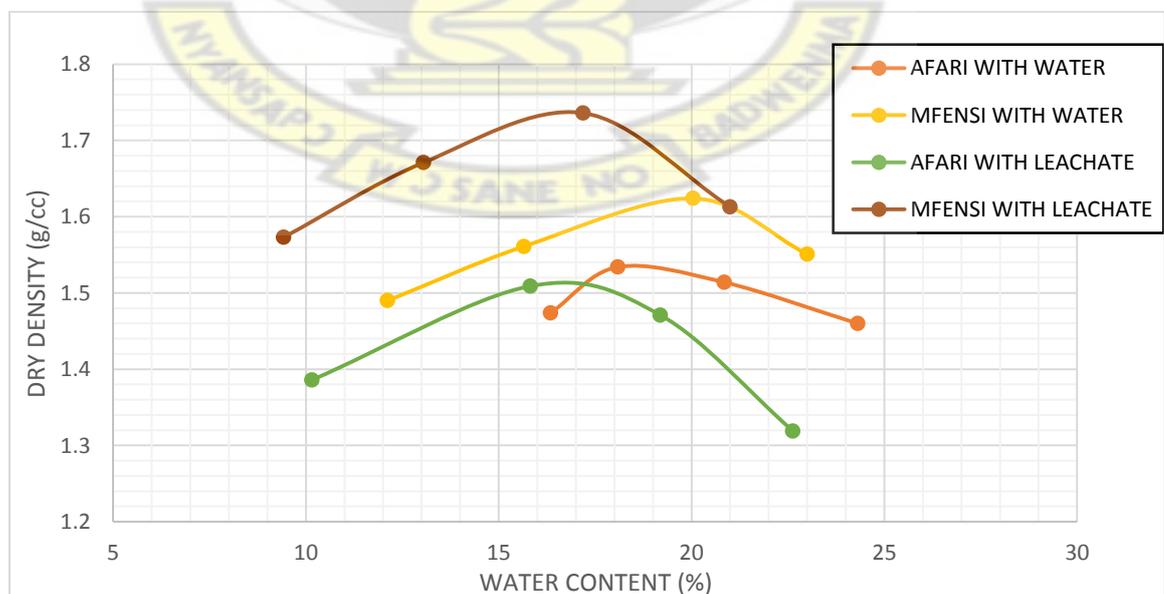
#### 4.2.6 Strength Characteristics of the clays

The strength properties of the clays were determined from compaction and unconfined compressive strength tests. The compaction characteristics of the clays are presented in Figure 4.7. The Maximum Dry Densities (MDD) and their corresponding Optimum Moisture Contents (OMC) are also presented in Table 4.6.

**Table 4.6. Strength Characteristics of the clays**

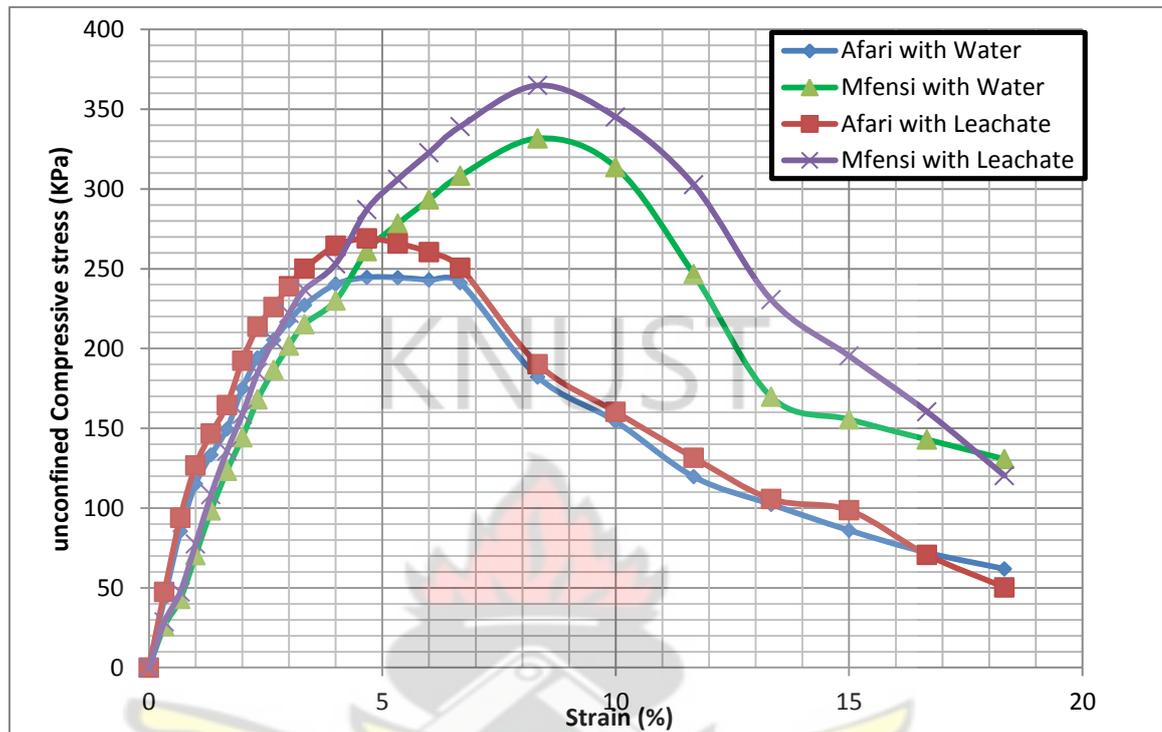
Property	Afari clay		Mfensi clay	
	Water	Leachate	Water	Leachate
MDD ( $\text{mg}/\text{m}^3$ )	1.539	1.520	1.625	1.74
OMC (%)	18.9	16.4	20.0	17.0

It is noted that, the MDD of Mfensi clay is higher than that of Afari clay when compacted with water and leachate as seen on table 4.6. The high MDD of Mfensi clay relative to Afari clay is attributed to its high specific gravity. Afari clay recorded a reduction in the MDD when compacted with leachate while an increase was recorded for Mfensi clay. Also compaction with leachate for both clays resulted in a reduction in the OMC with values of 16.4% and 17.0% for Afari and Mfensi clays respectively.



**Figure 4.7: Compaction Characteristics of the clays with water and leachate**

Figure 4.8 show the curves of the unconfined compressive stress (KPa) against strain (%) for the clays tested with water and leachate.



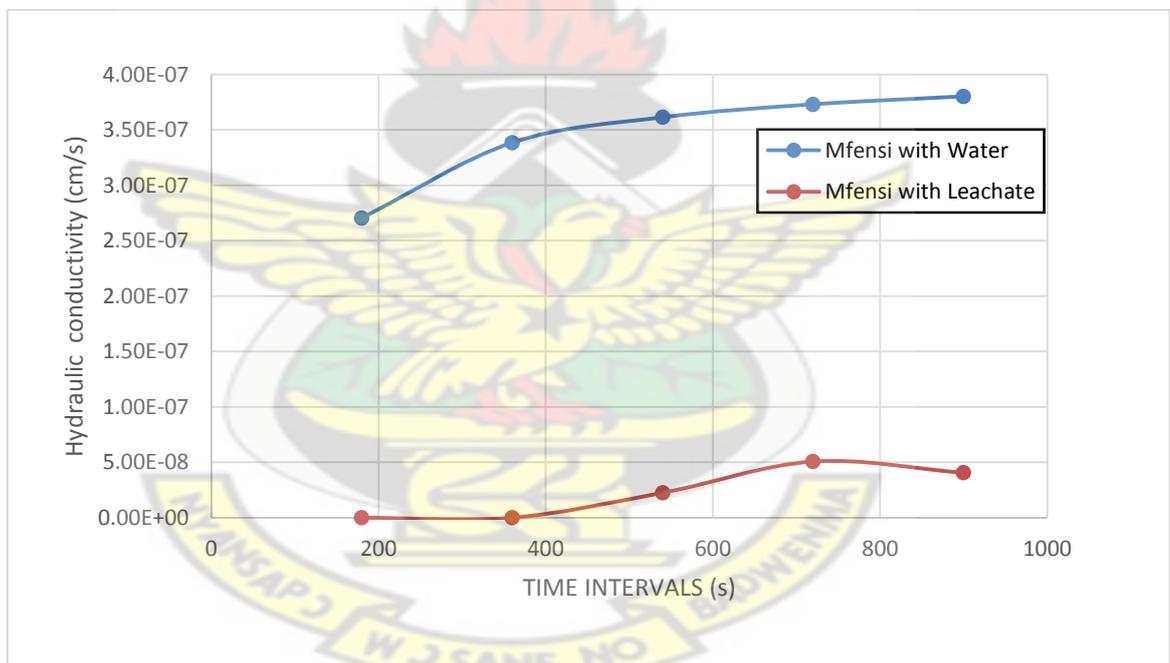
**Figure 4.8: UCS against strain for Afari and Mfensi clay samples**

It is seen from Figure 4.8 that, the compressive stress for both clays increases with increased axial strain up to a peak. This is as a result of the reduction in porosity and an increase in density when an axial load was applied to the samples. After reaching the peak stress, strain softening occurred which resulted to loss of friction and bonding in the clay particles, as such the unconfined compressive stress for both clays decreased with increased axial strain? Mfensi clay had a greater UCS value of 331.73KPa compared to Afari clay which recorded a value of 244.53KPa when water was used. On the other hand, when leachate was used, the UCS increases for both clays with Afari clay recording a value of 268.98KPa and Mfensi clay a value of 364.90KPa. The strength of soils depends on cohesion which is the ability of the particles to stick together, as such porosity is been reduced and density increases. The

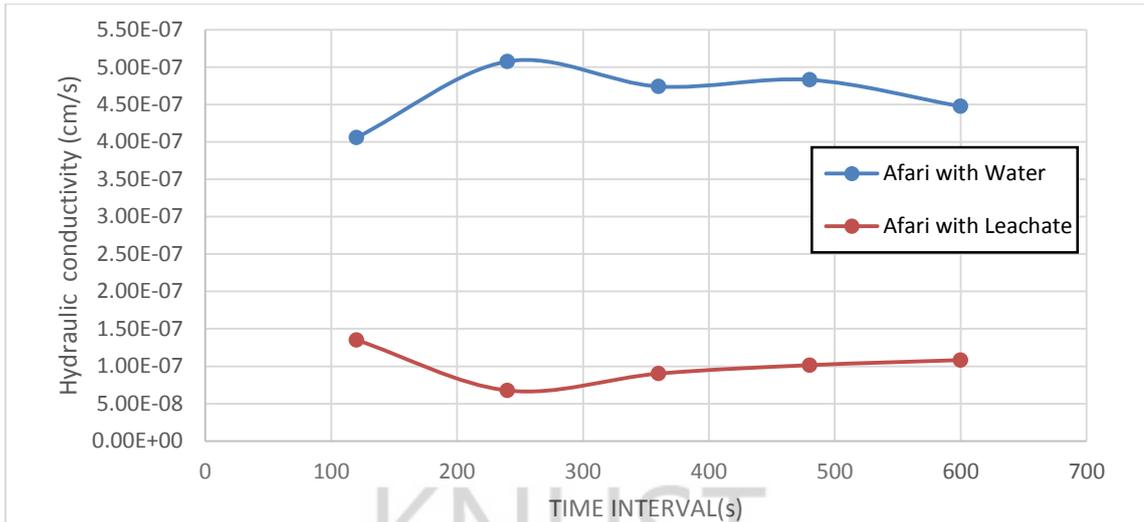
high UCS recorded for Mfensi clay could be due to the high percentage of fine fractions filling the void spaces and the interlocking of the coarse grains, hence reducing compressibility, porosity and deformation and thus increasing the shear strength characteristics. As such, it is concluded that, both clays meet the strength requirement of not less than 200KPa Daniel and Wu (1993) recommended for use as liner materials, when tested with water and leachate.

#### 4.2.7 Saturated Hydraulic Conductivity of the clays

The variations of hydraulic conductivity with time of the clays permeated with water and leachate are presented in Figures 4.9 and 4.10.



**Figure 4.9: Variation of hydraulic conductivity with time on Mfensi clay permeated with water and leachate.**



**Figure 4.10: Variation of hydraulic conductivity with time on Afari clay permeated with water and leachate**

It is observed that, the hydraulic conductivity of Mfensi clay when permeated with water slightly increased with increasing permeation period, thus hydraulic conductivity for Mfensi clay increased from  $2.705 \times 10^{-7} \text{ cm/s}$  to  $3.803 \times 10^{-7} \text{ cm/s}$  for the average permeability as seen from the trend curve in Figure 4.9. When the same clay sample was permeated with leachate, there was a reduction in the hydraulic conductivity from the order of  $\times 10^{-7} \text{ cm/s}$  when permeated with water to the order of  $\times 10^{-8} \text{ cm/s}$  when permeated with leachate as seen on the trend curve in Figure 4.9.

On the other hand, when Afari clay was permeated with water, the behavior of the curve showed two maxima over the range of time used in the testing as seen in Figure 4.10. When Afari clay was permeated with leachate, there was a sharp reduction in the hydraulic conductivity up to about 240sec followed by an increase at about 370sec and subsequently increased uniformly again as seen on the curve in Figure 4.10 .

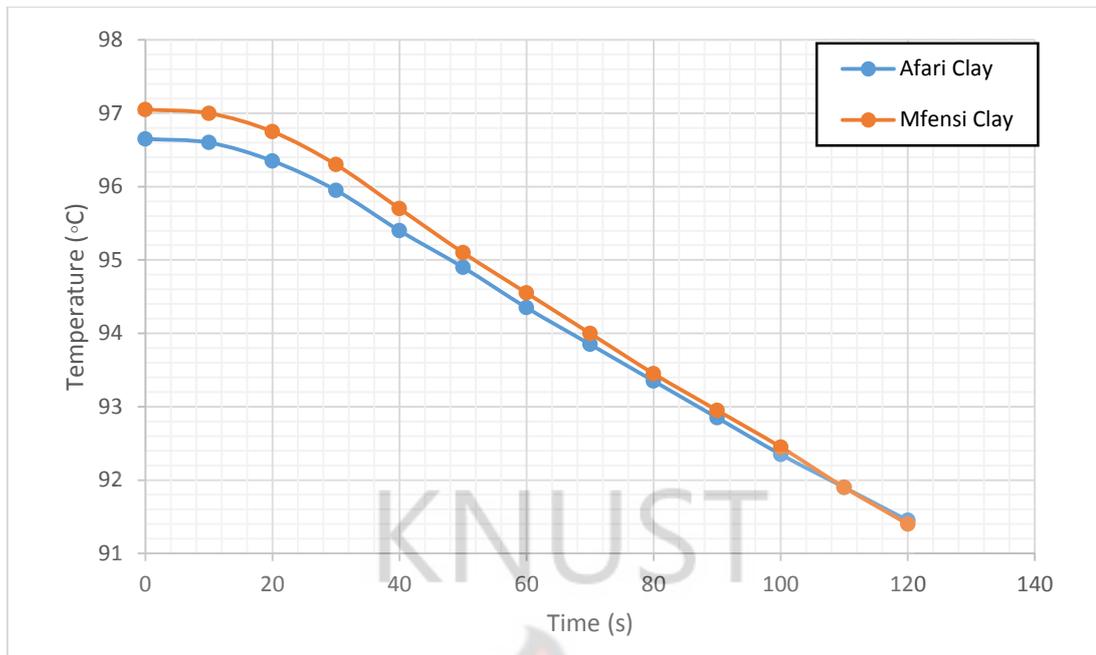
It is observed that, when both samples were permeated with tap water, the hydraulic conductivity for Mfensi clay was found to be lower than that of Afari clay with values of  $3.448 \times 10^{-7} \text{ cm/s}$  and  $4.637 \times 10^{-7} \text{ cm/s}$  respectively. This could be attributed to

its high clay size content which filled the voids between the coarse particles thus reducing the size of the pores controlling the flow and decreasing the hydraulic conductivity.

It is also found that, the leachate caused a reduction in the hydraulic conductivity of both compacted clays. Similar results have been reported by Rowe *et al.*, (1995) and Shackelford and Redmond (1995). They reported that, municipal solid waste leachate has the ability to cause a slight decrease in the hydraulic conductivity of compacted clays. This decrease in hydraulic conductivity could be due to the dissolution of clay minerals probably due to  $\text{Na}^+$  adsorption during leachate permeation, which could lead to an expansion in the double layer and plugging of the pore spaces, and also due to bacteria clogging of pore spaces (Bello and Osinubi, 2011a). It can also be associated to clogging of soil particles due to precipitation of the suspended particles (Sitaram *et al.*, 2014). Hence, it can be concluded that, both clays satisfy the appropriate hydraulic conductivity recommended for clay base liner materials.

### **4.3 Thermal Conductivities of the Clays**

A study of the thermal conductivities of Afari and Mfensi clays was performed with a view of understanding their ability to conduct or transfer heat mainly for application as liner materials, since the effects of heat on liner materials can be in the form of desiccation, changes in shear strength and hydraulic conductivity of the liner material. The graph of the cooling curves for both clay samples with time are presented in Figure 4.11.



**Figure 4.11: Cooling curves for the clays**

It is observed from Figure 4.11 that, the cooling curves for both clays do have slight difference and subsequently they will have different thermal conductivities. The cooling curve of Mfensi clay sample showed slightly high temperatures compared to that of Afari clay sample when it absorb heat, and as such it is most likely to cause gradual cracking of the liner material. Afari clay samples had lower thermal conductivities which ranged between  $0.02\text{W/m}^{\circ}\text{C}$  and  $0.03\text{W/m}^{\circ}\text{C}$  and a mean value of  $0.025\text{W/m}^{\circ}\text{C}$ . On the other hand, Mfensi clay samples also recorded low values of thermal conductivities but higher than those of Afari clay samples with values of  $0.21\text{W/m}^{\circ}\text{C}$  and  $0.22\text{W/m}^{\circ}\text{C}$  with a mean value of  $0.215\text{W/m}^{\circ}\text{C}$ . Thermal conductivity increases with increasing percentage of smaller particle size (fine particles), (Ayugi, 2011). This can be explained on the basis that, smaller particles will mesh closely leading to a better transfer of heat between them. Based on grading, Afari clay had 63.70% fines while Mfensi clay had 88.33% fines content. As such, there is an increase in particle-particle contact area for Mfensi clay, thus reducing the air spaces between the particles and increases the rate of heat transfer. It can be

concluded that, both clays had the required  $\leq 2$  W/m°C thermal conductivity to be used as liner materials, recommended by Andersland and Ladanyi (2003).

#### 4.4 Physico-chemical composition of the leachate

The physical and chemical (physico-chemical) constituents of the leachate collected from the Kumasi engineered landfill site is presented in Table 4.7.

**Table 4.7: Physico- chemical composition of the MSW Landfill leachate**

Parameters	Quantity present
<b>1 Heavy Metals (mg/L)</b>	
Zinc	0.65
Iron	35
Lead	0.057
Copper	0.03
Arsenic	0.57
Nickel	0.07
<b>2 Anions (mg/L)</b>	
NO <sub>3</sub>	5.28 – 5.5
SO <sub>4</sub> <sup>4-</sup>	15 – 36
PO <sub>4</sub> <sup>2-</sup>	3– 7.3
<b>3 Physico-chemical properties</b>	
BOD	150
pH	8.19 – 8.33
TDS	3.21- 3.22
EC (milli siemens)	4.49 -4.64
Hardness	1222
Turbidity (NTU)	2.64 -2.85
Density (g/ml)	1.01
Faecal coliform (N/100)	17×10 <sup>3</sup>
Total coliform (N/100)	62×10 <sup>3</sup>

According to Tchpanoglous *et al.*, (1993) who analyzed the relevant components of leachate from a matured landfill (> 10 years) as with the case of the Kumasi landfill, they indicted that, BOD ranged from 100 – 200, the pH of the leachate was of the range 6.6 – 7.5, anions such as PO<sub>4</sub><sup>2-</sup> had a range of 5 – 10mg/L, and SO<sub>4</sub><sup>4-</sup> of range 20 – 50mg/L. It is observed that, most of the physico-chemical properties of the leachate analyzed from the Kumasi engineered landfill are within the range of that presented by Tchpanoglous *et al.*, (1993).

## CHAPTER FIVE: SATURATED–UNSATURATED FINITE DIFFERENCE

### SIMULATION OF SEEPAGE THROUGH THE CLAYS

#### 5.1 Background

Seepage analyses are important in Geotechnical and Geo-environmental engineering. These analyses may be required in ground water contamination control, slope stability analysis, soil physics and the design of earth structures such as dykes or dams. Geotechnical engineers have focused their attention on saturated zones in seepage analysis, thus paying less attention to unsaturated zones; however, unsaturated flow plays an important role in many engineering problems. For instance, the movement of leachate beneath tailings impoundments and sanitary landfills take place mainly under unsaturated conditions (Neuman, 1973).

In recent years, the development of numerical techniques such as; finite difference method (FDM), finite element method (FEM) and pre-packaged software's have assisted engineers to solve extremely complex problems for a variety of boundary conditions and material properties related to seepage through soils. These numerical procedures have sufficient flexibility to be able to incorporate many different soil types, soils with spatially varying properties and temporal variations (USEPA, 1984). Moreover, the softwares could range from discipline specific products such as Geoslope software to general partial differential equation (PDE) solvers such as PDEase and FlexPDE. Casagrande (1937) proposed the solutions of the linear partial differential equation for seepage analysis with the use of graphical flow net method. The assumptions of the method were a homogeneous and isotropic soil and that water flows only in the saturated zone. The flow net solution proposed by Casagrande (1937) was for simple unconfined flow cases without flux boundary conditions. However, many seepage problems in practice are complex and flow is also through

the unsaturated zone. As such, the flow-net solution may not be applicable. In view of this, numerical methods have essentially replaced the flow net method for solving seepage problems due to the accuracy of numerical solutions (Lam and Fredlund, 1984).

### ***5.1.1 Description of the Physical Problem and Significance of Modeling***

The flow domain for liner breakthrough (shown in Figure 5.1) consists of the following: a layer of liquid in the impoundment of depth ( $h_2$ ); a soil liner of thickness ( $d$ ); a layer of underlying site soil, which may or may not be saturated; and a constantly saturated ground water layer of the same site soil. The soil liner is installed on top of the site soil and is compacted. After the impoundment is filled, the flow system is not in equilibrium, and liquid will flow vertically and horizontally down from the impoundment into the liner, and eventually into the site soil and saturated ground water zone, thus causing contamination. The goals of this modeling are to understand seepage analyses in two-dimension and simulate the flow of leachate in order to predict the breakthrough times and flow rates of the clays (the time the leachate will take to seep completely through the compacted clay liner material). As such, it can assist in determining the required liner thickness needed to prevent leachate from reaching the ground water during the design life of the landfill, thus minimizing contamination.

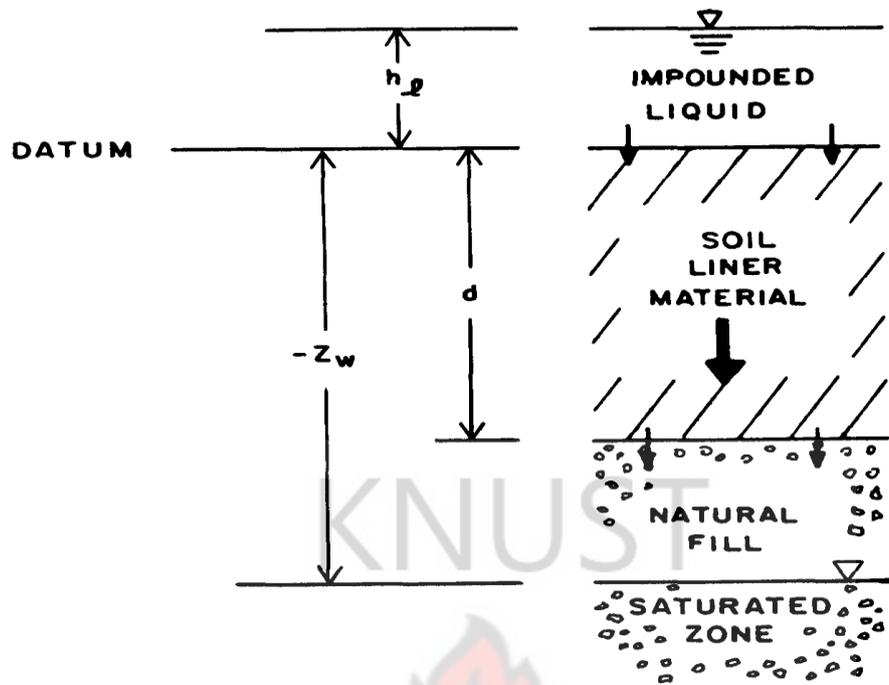
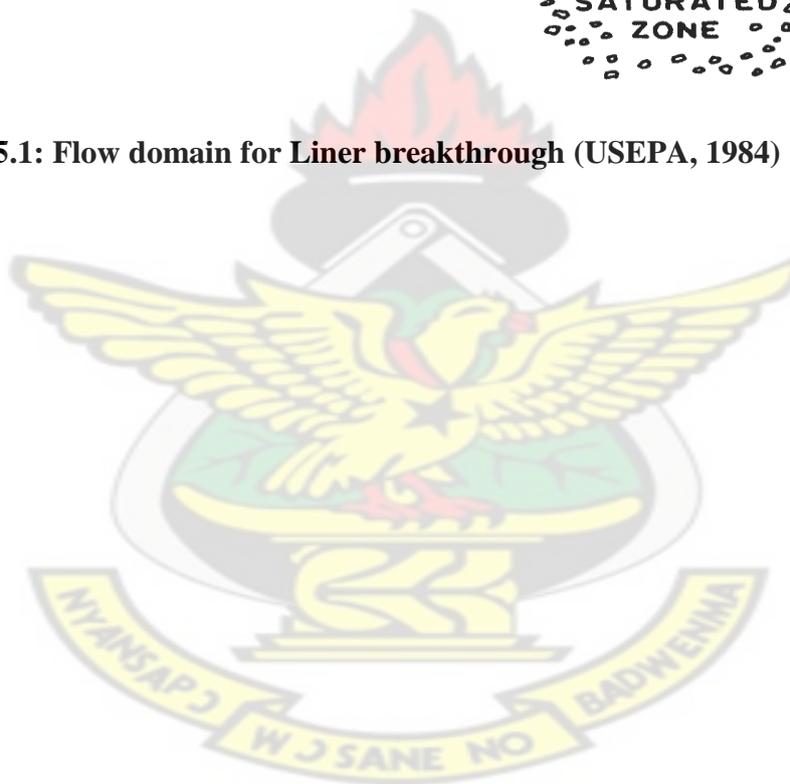


Figure 5.1: Flow domain for Liner breakthrough (USEPA, 1984)



### 5.1.2 Simulation Structure

The procedure for developing the models used in simulating flow through Afari and Mfensi clays using the finite difference formulation based on the Euler method is presented in Figure 5.2.

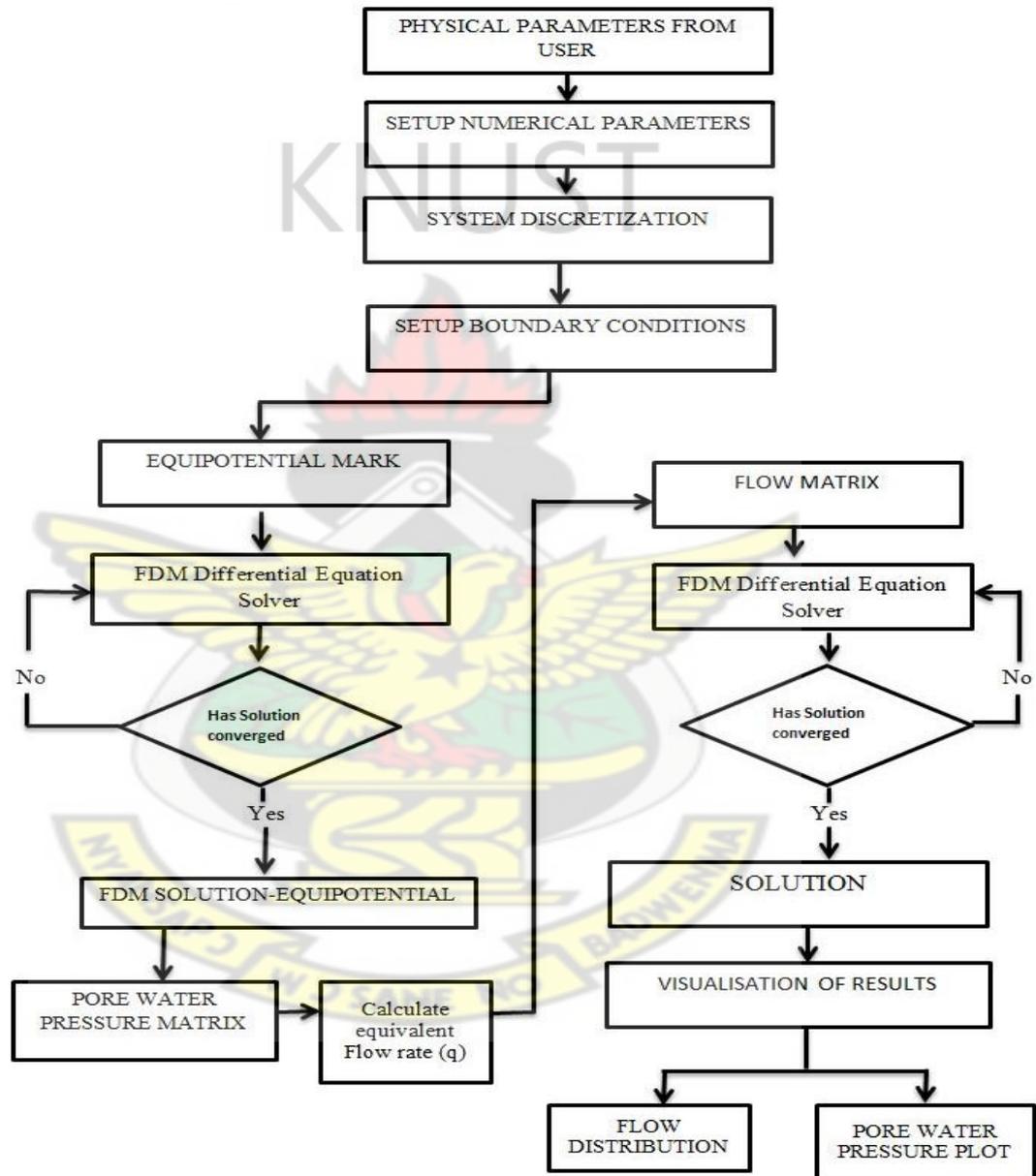


Figure 5.2: Computer simulation procedure flow chart

## 5.2 Methodology

### 5.2.1 Model Types

Seepage analyses for saturated-unsaturated soils are mathematically characterized by PDEs which are highly non-linear. As a result these nonlinearities in the PDEs, the modeling of saturated–unsaturated soil systems has proven to be a major problem especially using an analytical or closed-form solution, except for a few simple cases (USEPA, 1984). Therefore, numerical methods are thus applicable in providing solutions to the governing equations by taken into account the non-linearities of the systems and initial conditions. Also, another challenge in solving problems in relation to the modeling of saturated-unsaturated soils is the development of a numerical software package that ensures convergence at the right solution (Fredlund, 1996). The Laplace’s equation of continuity and Fredlund *et al.*, (2012) models were used in this study and both models describe seepage in a two-dimensional saturated and unsaturated soil system respectively. The models were numerically solved using the finite difference formulation based on the Euler method.

### 5.2.2 Numerical Simulation of Steady State Flow through the clays (Saturated case)

The flow of fluid through saturated soil is described by Laplace’s continuity equation. The most common form of Laplace’s equation for two-dimensional flow of fluid through saturated soil is as shown on equation (1).

$$K_x \frac{\partial^2 H}{\partial x^2} + K_y \frac{\partial^2 H}{\partial y^2} = 0 \quad (5.1)$$

**Where;**

$H$  = total head

$K_x$  and  $K_y$  = hydraulic conductivities in the X and Y directions respectively.

***The assumptions used in the simulation for steady state flow:***

1. Darcy's law for fluid flow in porous media is valid.
2. Irrotational flow (vorticity) is negligible, that is; no rotation of the fluid element. This assumption leads to the following two-dimensional relationship in velocity gradients.

$$\frac{\partial v_y}{\partial y} = \frac{\partial v_x}{\partial x} \quad (5.2)$$

***Where;***

$V_y$  and  $V_x$  are the velocities in the  $Y$  and  $X$  directions respectively. This relationship is satisfied for a uniform flow field and not a general flow field. Therefore, all flows are assume to be uniform,  $V_y = V_x$ .

3. The medium does not deform (total stresses are neglected or consider to be constant).
4. The soil is homogeneous and saturated.
5. Fluid flow is unaffected by temperature gradients or by solute concentration gradients.
6. Air phase is considered to be at constant atmospheric pressure.

If both clays are considered to have an isotropic nature, that is;  $K_x = K_y$ , then equation (5.1) becomes:

$$\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} = 0 \quad (5.3)$$

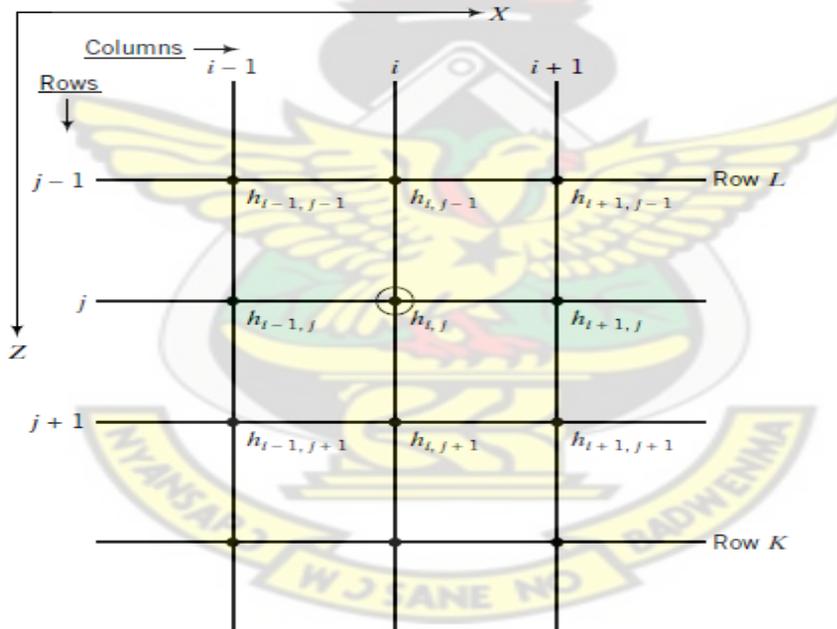
Using Taylor's series expansion based on the central Euler method or leapfrog method for simulation and neglecting terms of order 4 with an error term of order 2 since we have a very small step size. Equation (5.4) shows the finite difference formulation from equation (5.1)

$$K_x \frac{\partial^2 H}{\partial x^2} + K_y \frac{\partial^2 H}{\partial y^2} = \frac{K_x}{\Delta x^2} (h_{i+1,j} + h_{i-1,j} - 2h_{i,j}) + \frac{K_y}{\Delta y^2} (h_{i,j+1} + h_{i,j-1} - 2h_{i,j}) = 0 \quad (5.4)$$

(i, j) represents a nodal point or node number on the discretized flow domain as shown in Figure 5.3. These values at node i and j are used to approximate the derivatives in the governing equations. Letting  $\alpha = \frac{K_x}{K_y}$  and  $\Delta x = \Delta y$  for use in the simulation, then equation (5.4) turns to

$$\alpha \left( \frac{h_{i+1,j} + h_{i-1,j} - 2h_{i,j}}{\Delta x^2} \right) + \frac{1}{\alpha} \left( \frac{h_{i,j+1} + h_{i,j-1} - 2h_{i,j}}{\Delta y^2} \right) = 0 \quad (5.5)$$

$$\alpha (h_{i+1,j} + h_{i-1,j} - 2h_{i,j}) + \frac{1}{\alpha} (h_{i,j+1} + h_{i,j-1} - 2h_{i,j}) = 0 \quad (5.6)$$



**Figure 5.3: Discretized partial grid of the flow domain (Muni, 1999)**

***Boundary conditions used in the formulation for the simulations***

1. At the top of the liner,  $z = 0$ , the liquid pressure is controlled by the level of liquid in the impoundment.

2. Since confined flow is being considered, one or more of the boundaries would be impermeable. Flow cannot cross impermeable boundaries (flow lines) and, therefore for a horizontal impermeable surface

$$\frac{\partial h}{\partial x} = 0 \quad (5.7)$$

The Finite difference formulation (based on the central Euler) for equation (5.7) is:

$$\frac{\partial h}{\partial x} = \frac{1}{2\Delta x} (h_{i+1,j} - h_{i-1,j}) \quad (5.8)$$

$$\frac{1}{2\Delta x} (h_{i+1,j} - h_{i-1,j}) = 0 \quad (5.9)$$

These conditions were incorporated into the governing equations and were explicitly satisfied.

### ***5.2.3 Numerical Simulation of Transient State flow through the clays (unsaturated case)***

The steady-state flow partial differential equation can be expanded to include transient or unsteady state formulation. It is important to take matric suction into account when considering transient analysis. The most common equation for transient flow through soils is that of Fredlund *et al.*, (2012) and is given by equation (5.10)

$$\frac{\partial}{\partial x} \left( k_w \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_w \frac{\partial h}{\partial y} \right) = m_2^w \rho_f g \frac{\partial h_w}{\partial t} \quad (5.10)$$

#### ***The assumptions used in the simulation for transient state flow***

1. In addition to all the assumptions used for the steady state flow, the unsaturated coefficient of permeability was assumed to be equal to the saturated coefficient of permeability and was considered the same in both directions.

Applying the product rule to equation (5.10) we obtain:

$$k_w \frac{\partial^2 h}{\partial x^2} + \frac{\partial k_w}{\partial x} \cdot \frac{\partial h}{\partial x} + k_w \frac{\partial^2 h}{\partial y^2} + \frac{\partial k_w}{\partial y} \cdot \frac{\partial h}{\partial y} = m_2^w \gamma_f \frac{\partial h}{\partial t} \quad (5.11)$$

**Where;**

$k_w$  –Hydraulic conductivity ( $K_{wx} = K_{wy} = K_w$ )

$k_{wx}$  –Hydraulic conductivity in x- direction

$k_{wy}$  –Hydraulic conductivity in y – direction

$h$  –Potential head

$\gamma_f$  –Specific weight of flowing fluid (leachate)

$m_2^w$  –Coefficient of water storage function (slope of soil water characteristics curve (SWCC)).

An explicit finite difference scheme was used to solve the flow equation (5.11) based on the central Euler method, with boundary conditions applied as shown below;

$$k_w \frac{h_{i+1,j}^n - 2h_{i,j}^n + h_{i-1,j}^n}{\Delta x^2} + \frac{k_{w,i+1,j}^n - k_{w,i,j}^n}{\Delta x} \cdot \frac{h_{i+1,j}^n - h_{i,j}^n}{\Delta x} + k_w \frac{h_{i+1,j}^n - 2h_{i,j}^n + h_{i-1,j}^n}{\Delta y^2} + \frac{k_{w,i+1,j}^n - k_{w,i,j}^n}{\Delta y} \cdot \frac{h_{i+1,j}^n - h_{i,j}^n}{\Delta y} = m_2^w \cdot \gamma_f \frac{h_{i,j}^{n+1} - h_{i,j}^n}{\Delta t} \quad (5.12)$$

**Where,** n denotes the current time; n+1 denotes the future time;  $h^n$  is the vector of the known values of potential at the last time step and  $h^{n+1}$  is the unknown vector to be determined.

The equation setup for simulation which governs the flow characteristic, the head distribution and characterizes the flow regions with time step size  $\Delta t = t^{n+1} - t^n$  which depends on the mesh size and was sufficiently small, and spatial steps  $\Delta x$  and  $\Delta y$  is given by equation (5.13) obtained by rearranging equation (5.12).

$$\begin{aligned} & \frac{k_w \cdot \Delta t}{m_2^w \gamma_f \Delta x^2} (h_{i+1,j}^n - 2h_{i,j}^n + h_{i-1,j}^n) + \frac{\Delta t}{m_2^w \gamma_f \Delta x^2} (k_w^n_{i+1,j} - k_w^n_{i,j}) \cdot (h_{i+1,j}^n - h_{i,j}^n) + \\ & \frac{k_w \cdot \Delta t}{m_2^w \gamma_f \Delta y^2} (h_{i+1,j}^n - 2h_{i,j}^n + h_{i-1,j}^n) + \frac{\Delta t}{m_2^w \gamma_f \Delta y^2} (k_w^n_{i+1,j} - k_w^n_{i,j}) \cdot (h_{i+1,j}^n - h_{i,j}^n) + \\ & h_{i,j}^n = h_{i,j}^{n+1} \end{aligned} \quad (5.13)$$

### **Calculation of the time step**

In order to solve equation (5.13) at a given time step which is not a linear equation for the unknown  $h^{n+1}$ , a variety of iterations and linearization schemes were developed. The resulting linear matrix equation was solved iteratively based on the explicit scheme time domain which is conditionally stable, that is, the solution will not always converge and should only be used with small time steps. By intuition, coefficients without  $k_w$  in equation (5.13) were excluded. The time step was obtained by the Courant Friedrich Levy (CFL) condition of stability analysis. During the initial simulation, the coefficient with the smallest time step for which the solution converged was used to obtain the breakthrough time and a better accuracy of the result. Thus, the breakthrough time is given by:

$$\frac{K_w \Delta t}{m_2^w \gamma_f \Delta x^2} \leq \frac{1}{5} \quad (5.14)$$

$$\Delta t \leq \frac{m_2^w \gamma_f \Delta x^2}{5k_w} \quad (5.15)$$

**Where,**

$$\frac{1}{5} = \text{constant of stability for the time step.}$$

The constant of stability for the time step used was to ensure numerical stability of the system or to obtain a solution for the system. For any constant above or below it, the system becomes unstable and not a good reflection of the breakthrough time. In the explicit scheme formulation of equation (5.13), the solution at the present time (n)

was used to calculate the solution at future time (n+1). Subscripts represents nodes (i, j) in the flow domain as shown in Figure 5.3 and superscripts represents the time level. The accuracy of this method improves as the grid spacing decrease in size.

#### **5.2.4 Determination of the Pore water pressure**

Considering a node (i, j) in the flow domain in Figure 5.3. The pore water pressure at any node  $u_{i,j}$  is given by;

$$u_{ij} = \gamma_l(h_{i,j} - z_{i,j}) \quad (5.16)$$

**Where;**

$z_{ij}$  = elevation head

$u_{ij}$  = pore water pressure

$h_{ij}$  = hydraulic head

$\gamma_l$  = specific gravity of leachate

#### **5.2.5 Determination of the Flow Rate**

The finite difference equations for flow lines (impermeable boundaries) are analogous to potential lines (permeable boundaries). The horizontal velocity of flow at a node ( $v_{i,j}$ ) is expressed by Darcy's law as:

$$v_{i,j} = k_x i_{i,j} \quad (5.17)$$

Where,  $i_{i,j}$  is the hydraulic gradient expressed as shown in equation (5.18) in the finite difference formulation using the forward difference scheme (forward Euler method)

$$i_{i,j} = \frac{(h_{i+1,j} - h_{i-1,j})}{2\Delta x} \quad (5.18)$$

Therefore,

$$v_{i,j} = \frac{k_x}{2\Delta x} (h_{i+1,j} - h_{i-1,j}) \quad (5.19)$$

The flow rate (q) can be expressed by Darcy's law as shown;

$$q = kAi \quad (5.20)$$

The finite difference solution for the above flow rate is as shown in equation (5.21)

$$q = \frac{k_x}{4} (h_{i+1,L} - h_{i-1,L} + 2 \sum_{j=L+1}^{K-1} (h_{i+1,j} - h_{i-1,j}) + h_{i+1,K} - h_{i-1,K}) \quad (5.21)$$

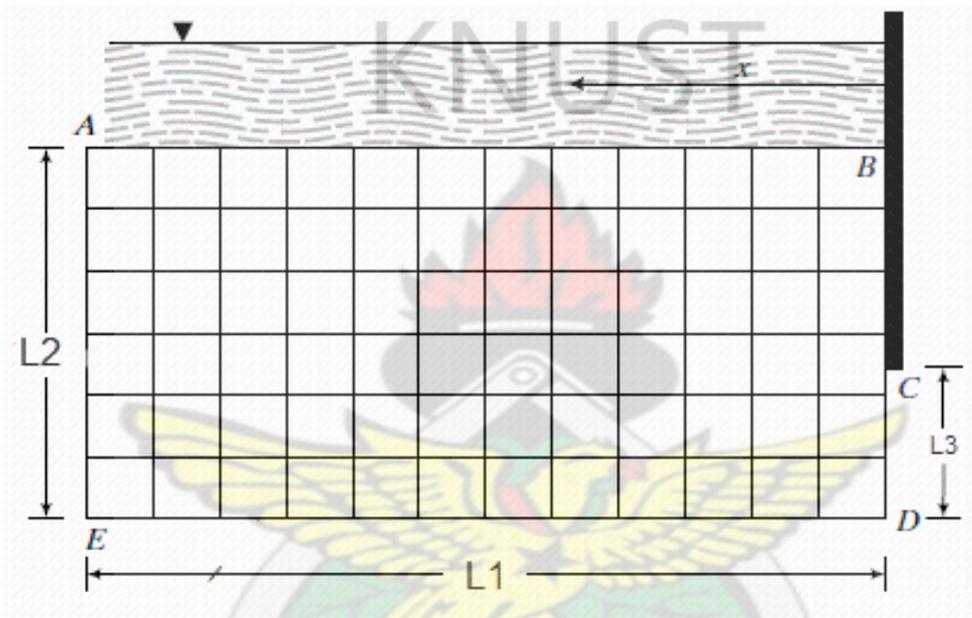
Where; L is the top row and K is the bottom row of a vertical plane across the flow domain defined by column 'i' in Figure 5.3.

### ***5.2.6 Procedures used in the preparation of the computer-assisted numerical analysis and simulation***

1. The flow domain was divided into square grids or blocks of elements (discretization). Within each block of element, the node spacing was constant.
2. Boundary conditions were applied. Impermeable boundaries had flow lines; that is;  $\frac{dh}{dx} = 0$ , and permeable boundaries equipotential lines.
3. The heads at the permeable or equipotential boundaries were determined.
4. The known heads were applied to the corresponding nodes and reasonable initial values for the interior nodes were assumed. Zero (0) was chosen as the initial value to target for numerical stability and also due to its minimal effect on the solution.
5. Appropriate equations were applied to each node taking into consideration the isotropic nature of the clays.
6. Iterations were carried out until the new node value differs from the old value by a small numerical tolerance.

7. Lastly, the pore water pressure curve, flow rates and breakthrough times were obtained using representative equations.

Figure 5.4 shows the flow domain used in the simulation set up for both clays which was divided into square grids. A sheet pile is placed at the right end to ensure a confined flow. Boundary conditions used were; Permeable boundaries: AB and CD (equipotential lines) Impermeable boundaries: BC, AE, ED (flow lines).



**Figure 5.4: Flow domain used for simulation (Muni, 1999)**

### **5.3 Algorithmic model development and simulation**

The equation coding was achieved using the MATLAB programming language as presented in appendix B. The programming technique used for the finite difference simulation of the mathematical models was done using the top-down method. Software development technique used was the agile technique (iterative technique). The graphical user interface (GUI) was developed using the MATLAB tool; GUIDE (Graphical User Interface Development Environment). The style of programming used in the integration of simulation code into the graphical user interface was an

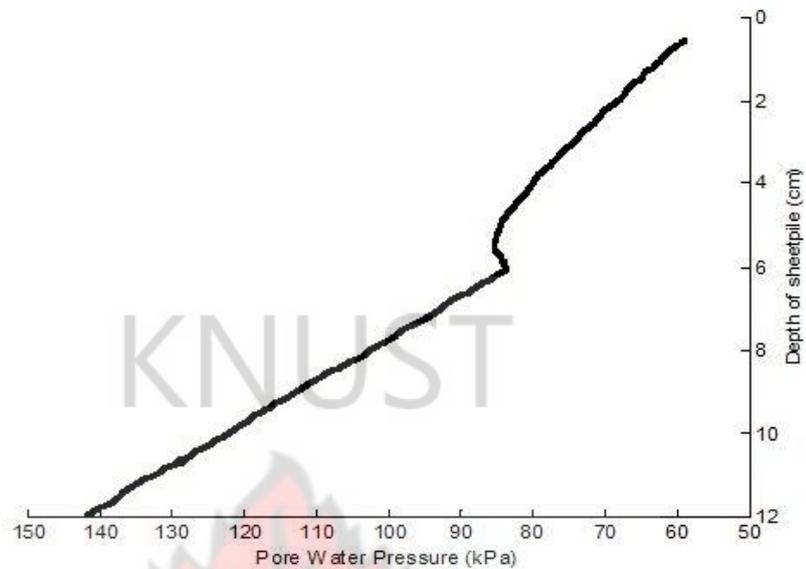
object oriented program. That is; there is no action until a button is triggered. The function used in the visualization of data was the “pcolor” function.

Algorithm was based on the FDM of numerically solving the above stated PDEs with no close form solution. The main elements of the model were well defined and quantified as input variables. Saturated hydraulic conductivity, coefficient of water storage and liner thicknesses were considered as some of the input variables. The relationships were mathematically linked and solved. Numerical principles were applied in the determination of the interrelationships between the leachate flow rates and the breakthrough times through the clays.

## **5.4 Results**

### ***5.4.1 Pore water pressure distribution through the clays***

Figure 5.5 indicate the simulated result for the distribution of pore water pressure with depth of the sheetpile and the liner material. The sheetpile is considered in the distribution of the pore water pressure due to the consideration of a confined flow. The kink in the pore water pressure distribution curve indicates the change in pore water pressure at the end of the sheet pile in contact with the surface of the liner material, thus a transition zone. The effect of an increase pore water pressure on the liner material can lead to cracking, thus increasing the permeability of the liner material and leading to ground/surface water contamination. It can be seen from Figure 5.5 that, as the depth of the sheetpile increases, pore water pressure also increases.

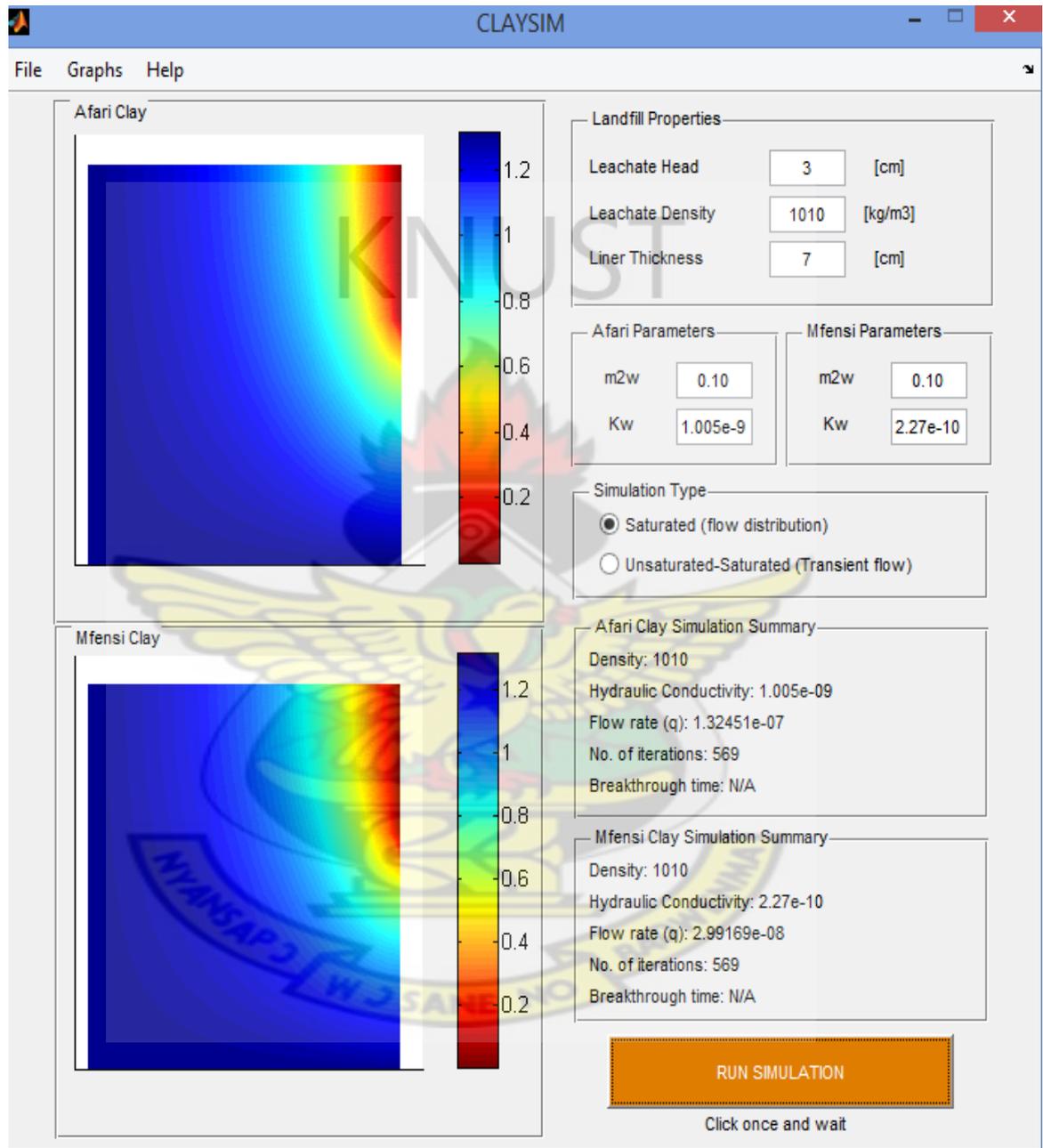


**Figure 5.5: Pore water pressure distribution for model Afari and Mfeni Clays**

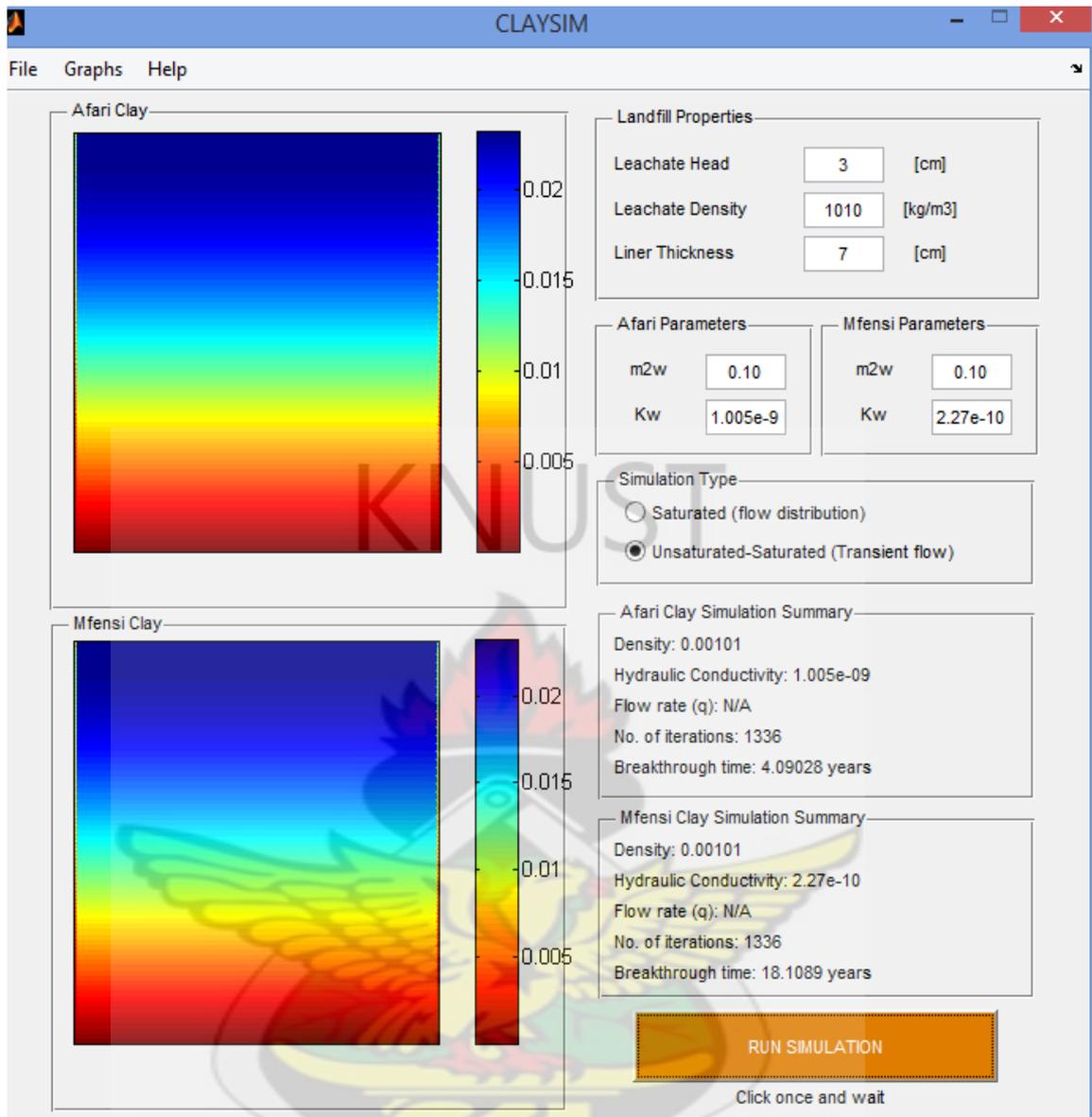
#### 5.4.2 Validation of the models

In order to check whether the models produce credible performance and work perfectly, there is a need for their validation. Validations of the models are to be carried out by applying them in the assessment of practical problems for leachate permeation through liner materials. Due to insufficient laboratory tests and parameters for validation such as the coefficient of water storage function ( $m_2^w$ ) and the coefficient of unsaturated hydraulic conductivity ( $K_w$ ), the models cannot be validated based on assumptions. Therefore a proper follow-up research is required in order to obtain experimental data for proper validation of the models. However, assume values for ( $m_2^w$ ) and ( $K_w$ ) were used to check how the models will have performed in case they were to be properly validated. Figures 5.6 and 5.7 shows the graphical representation of the graphic user interface (GUI) for the models for specifying inputs (landfill properties and experimental variables) and outputs

(breakthrough times and flow rates) parameters for steady and transient state flows respectively. The blue colour in the colour map represents the leachate flowing through the soil (represented by the red colour in the colour map).



**Figure 5.6: Graphical user interface for specifying input and output parameters for simulated steady state flow through Afari and Mfensi clays**



**Figure 5.7: Graphical user interface for specifying input and output parameters for simulated transient state flow through Afari and Mfensi clays**

### 5.5 Parametric Analysis

To investigate the performance of both clays as liner materials comprehensively, parametric analysis was conducted. This analysis allows us to nominate parameters for evaluation, define parameter range and analyse the results of each parameter variation. The values of the parameters studied are shown in Table 5.1. The parameters included; the leachate head, liner thickness and leachate density. The

parametric analysis was conducted to study the effects of each parameter as stated above on the breakthrough times and flow rates of both clays.

**Table 5.1: Variables used for parametric study**

Parameters	Values			
Leachate head (cm)	0.5	3	10	15
Liner thickness (cm)	7	11.7	15	18
Leachate density (kgm <sup>-3</sup> )	700	900	1010	1200
Coefficient of hydraulic conductivity (ms <sup>-1</sup> )	1.005 x 10 <sup>-9</sup> (Afari clay)		2.27 x10 <sup>-10</sup> (Mfensi clay)	
Water storage function (kPa <sup>-1</sup> )	1x 10 <sup>-1</sup>			

### 5.5.1 Leachate Head

The values of leachate head used are shown in Table 5.1. The breakthrough times and flow rates as presented in Table 5.2 were obtained from the simulated models. From the result it is observed that, the breakthrough times of both clays remain constant with increasing leachate head while the flow rates increase with an increase in leachate head. It can be concluded that, leachate head has no effect on the breakthrough times but significantly affects the flow rates.

**Table 5.2: Breakthrough time and flow rate values with corresponding heads**

Head Values(cm)	Mfensi Clay		Afari Clay	
	Breakthrough Times (years)	Flow rates (m <sup>3</sup> s <sup>-1</sup> )	Break through times (years)	Flow rates (m <sup>3</sup> s <sup>-1</sup> )
0.5	50.6	5.29 x 10 <sup>-9</sup>	11.4	2.34 x 10 <sup>-8</sup>
3	50.6	3.10 x 10 <sup>-8</sup>	11.4	1.37 x10 <sup>-7</sup>
10	50.6	1.03 x 10 <sup>-7</sup>	11.4	4.56 x 10 <sup>-7</sup>
18	50.6	1.85 x 10 <sup>-7</sup>	11.4	8.20 x 10 <sup>-7</sup>

### 5.5.2 Liner thickness

The thicknesses of the clays used in the analysis are 7cm, 11.7cm, 15cm and 18cm. After simulation the breakthrough times and flow rates obtained are presented in Table 5.3. From the result it is seen that, the breakthrough times and flow rates of both clays increase with increasing liner thickness. This can be explained on the basis that, it will take a longer time for the leachate to seep through a liner with a longer or larger thickness than that with a smaller or shorter thickness. Mfensi clay had higher breakthrough times relative to Afari clay, though the increased in flow rates were not so significant. Thus, liner thickness has a significant implication in the consideration of the breakthrough time of liner materials which is of importance.

**Table 5.3: Breakthrough time and flow rate values with liner thickness**

Thickness Values (cm)	Mfensi Clay		Afari Clay	
	Breakthrough Times (years)	Flow rates ( $\text{m}^3 \text{s}^{-1}$ )	Breakthrough times (years)	Flow rates ( $\text{m}^3 \text{s}^{-1}$ )
7	18.1	$2.99 \times 10^{-8}$	4.1	$1.32 \times 10^{-7}$
11.7	50	$3.10 \times 10^{-8}$	11.4	$1.37 \times 10^{-7}$
15	83.2	$3.26 \times 10^{-8}$	18.8	$1.44 \times 10^{-7}$
18	119.7	$3.31 \times 10^{-8}$	27	$1.46 \times 10^{-7}$

### 5.5.3 Leachate density

Leachate densities used in the study are shown in Table 5.1. The breakthrough times and flow rates of the clays after simulation are presented in Table 5.4. It is seen from the results that, an increase in leachate density led to an increase in the breakthrough times for both clays and had no effect on the flow rates. Therefore, measures should be taken to increase the density of the leachate so as to obtain required higher breakthrough time needed for liner materials.

**Table 5.4: Breakthrough time and flow rate values with corresponding density values**

Densities (Kgm <sup>-3</sup> )	Mfensi Clay		Afari Clay	
	Breakthrough Times (years)	Flow rates (m <sup>3</sup> s <sup>-1</sup> )	Breakthrough time (years)	Flow rates (m <sup>3</sup> s <sup>-1</sup> )
700	35.1	3.10 x 10 <sup>-8</sup>	7.9	1.37 x 10 <sup>-7</sup>
900	45.1	3.10 x 10 <sup>-8</sup>	10.2	1.37 x 10 <sup>-7</sup>
1010	50.6	3.10 x 10 <sup>-8</sup>	11.4	1.37 x 10 <sup>-7</sup>
1200	60.1	3.10 x 10 <sup>-8</sup>	13.6	1.37 x 10 <sup>-7</sup>

## 5.6 Conclusion

From the modeling the following conclusions are drawn:

- 1 Mfensi clay has a better anti-leakage behaviour, because it has a higher breakthrough time and lower flow rate relative to Afari clay. Thus, making Mfensi clay more effective in application as liner material for minimizing ground water contamination than Afari clay.
- 2 The breakthrough time of both clays were found to reduce with decreasing liner thickness and leachate density. It was also noted that, varying the leachate head has no impact on the breakthrough time. On the other hand, the flow rate of both clays increase with an increase in liner thickness and leachate head, while varying the leachate density had no impact on the flow rate.

## CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

### 6.1 Conclusion

The study investigated the geological engineering properties of Afari and Mfensi clays in their natural state for possible use as liner materials for municipal solid waste landfill sites in Ghana.

From the research the following conclusions were made:

1. The chemical composition of the clays studied revealed that the most abundant oxides are silica, alumina and iron oxides. The mineralogy of the clays from XRD analyses are similar and are composed of kaolinite, quartz and magnetite. The pH of the clays indicates that they are acidic with values of 5.37 and 5.29 for Afari and Mfensi clays respectively.
2. The leachate had significant effects on some geotechnical properties of the clays, namely; Atterberg's limits, compaction, UCS and hydraulic conductivity. There was an increase in the plasticity index and liquid limit of Afari clay from 50.89% to 59.23% and 62.70% to 81.65% respectively while a reduction was recorded for the plastic limit from 24.67% to 22.43%. On the other hand, Mfensi clay also experienced an increase in the plasticity index and liquid limit with values of 22.43% to 27.69% and 42.85% to 47.31% respectively and a reduction was also experienced in the plastic limit with values of 20.42% to 19.62%. The leachate also caused an increase in the UCS of both clays from 242.92KPa to 268.98KPa and 331.73KPa to 364.90KPa for Afari and Mfensi clays respectively.
3. The study proved that both clays can be used as liner materials for the construction of MSW landfill sites since they had geotechnical and thermal

properties within the recommended standards for use as liner materials for MSW landfill sites.

4. From the simulation, Afari clay had a higher flow rate and lower breakthrough time relative to Mfensi clay. This indicates that, Mfensi clay is more effective for application as liner material than Afari clay.

## 6.2 Recommendations

From the study it is recommended that:

1. The clays are suitable for use as clay liners in municipal waste systems and as such, their usage is recommended. The author is of the view that the low value of the ECEC obtained for Mfensi clay and the high value of the PI obtained for Afari clay as compared with standards should not be used as a basis to reject the materials for use as clay liners if suitable materials are not readily available within economical haulage distances, because among the many properties determined, only one of them failed for each clay type.
2. Studies should be conducted on the clays mineralogy after permeation with leachate. This will explain the structural changes that have occurred due to the permeation and will give a direct indication for the cause of the variation in hydraulic conductivity and strength of the compacted clays.
3. Studies should be conducted for the determination of the unsaturated hydraulic conductivity coefficient and the water storage function so as to obtain real experimental data for effective validation of the models.
4. Studies should be conducted in mathematically modeling the stresses and heat acting on the liner material since both factors does have effects on the liner breakthrough time and flow rate.

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## APPENDIX A

**Table 1. Rating of soils based on Activity of the clay fraction (Skempton, 1953)**

ACTIVITY	POTENTIAL EXPENSION
< 0.75	LOW
0.75- 1.25	MEDIUM
>1.25	HIGH

KNUST



## APPENDIX B

### Equations and ClaySim Computer Program Codes used

```
function varargout = CLAYSIM(varargin)
% CLAYSIM MATLAB code for CLAYSIM.fig
%   CLAYSIM, by itself, creates a new CLAYSIM or raises the existing
%   singleton*.
%
%   H = CLAYSIM returns the handle to a new CLAYSIM or the handle to
%   the existing singleton*.
%
%   CLAYSIM('CALLBACK', hObject,eventData,handles,...) calls the local
%   function named CALLBACK in CLAYSIM.M with the given input arguments.
%
%   CLAYSIM('Property','Value',...) creates a new CLAYSIM or raises the
%   existing singleton*. Starting from the left, property value pairs are
%   applied to the GUI before CLAYSIM_OpeningFcn gets called. An
%   unrecognized property name or invalid value makes property application
%   stop. All inputs are passed to CLAYSIM_OpeningFcn via varargin.
%
%   *See GUI Options on GUIDE's Tools menu. Choose "GUI allows only one
%   instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES
% Edit the above text to modify the response to help CLAYSIM
% Last Modified by GUIDE v2.5 24-Feb-2015 21:55:36
% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',    mfilename, ...
                  'gui_Singleton', gui_Singleton, ...
                  'gui_OpeningFcn', @CLAYSIM_OpeningFcn, ...
                  'gui_OutputFcn', @CLAYSIM_OutputFcn, ...
```

```

        'gui_LayoutFcn', [], ...
        'gui_Callback', []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end
if nargin
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT
% --- Executes just before CLAYSIM is made visible.
function CLAYSIM_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to CLAYSIM (see VARARGIN)
% Choose default command line output for CLAYSIM
handles.output = hObject;
% Update handles structure
guidata(hObject, handles);
% UIWAIT makes CLAYSIM wait for user response (see UIRESUME)
% uiwait(handles.figure1);
axes(handles.axes1)
set(gca,'xtick',[],'ytick',[])
axes(handles.axes2)
set(gca,'xtick',[],'ytick',[])
% --- Outputs from this function are returned to the command line.
function varargout = CLAYSIM_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB

```

```

% handles structure with handles and user data (see GUIDATA)
% Get default command line output from handles structure
varargout{1} = handles.output;
% --- Executes on button press in runsimulation.
function runsimulation_Callback(hObject, eventdata, handles)
% hObject handle to runsimulation (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
%Extract radiobuttons and checkbox states
global stopstate stopstatem gsize ylength pormat gsize ylengthm pormatm
sat = get(handles.sat_radio,'Value');
unsat = get(handles.trans_radio,'Value');
%Case 1: Simulation coding for Steady Stateflow through the clays (Saturated Case)
if sat == 1 && unsat == 0
    fprintf('Saturated Soil Condition (flow distribution)\n')
%Afari
Clay=====
==
ylength = str2double(get(handles.liner_thickness,'String'));
h1 = str2double(get(handles.leach_head,'String'));
hydcoef = str2double(get(handles.afari_kw,'String'));
rho = str2double(get(handles.leach_density,'String'));
xlength = ylength*2;
no_gridy = 2*ylength;
no_gridx = xlength/(ylength/(no_gridy));
%Calculate grid components above and below sheeppile
no_cells = ceil(no_gridy/2);
sheetpilehead = h1/2; %
%Discretization and solution
equipot = zeros(no_gridy,no_gridx);
error = 1e-5;
countmax = 10000;

```

```

count = 0;
while count < countmax
    count = count+1;
    equipinit = equipot;
    equipot(1,:) = h1;
    for k = no_cells:size(equipot,1)
        equipot(k,end) = sheetpilehead;
    end
    for k = 2 : no_cells-1
        equipot(k,end) = (equipot(k+1,end)+equipot(k-1,end)+2*equipot(k,end-1))/4;
    end
    for i = 2:size(equipot,1)-1
        for j = 2:size(equipot,2)-1
            equipot(i,j) = (equipot(i,j-1)+equipot(i,j+1)+equipot(i+1,j)+equipot(i-1,j))/4;
        end
    end
    for k = 2:size(equipot,1)-1
        equipot(k,1) = (equipot(k+1,1)+equipot(k-1,1)+2*equipot(k,2))/4;
    end
    equipot(end,1) = (equipot(end-1,1)+equipot(end,2))/2;
    for k = 2:size(equipot,2)-1
        equipot(end,k) = (equipot(end,k-1) + equipot(end,k+1) + 2*equipot(end-1,k))/4;
    end
    % checking for convergence
    if max(max(abs(equipot-equipinit))) <= error
        break
    end
end
end
%Pore water pressure
extract1 = equipot(2,2);
for k = 3: (size(equipot,2)-3)
    extract1 = equipot(2,k) + extract1;
end

```

```

extract2 = equipot(4,2);
for k = 3: (size(equipot,2)-3)
    extract2 = equipot(4,k) + extract2;
end
qapostr = (equipot(2,1)-equipot(4,1)+equipot(2,end)-equipot(4,end)+2*extract1-
2*extract2)/4;
%fprintf('q" = %g\n',qapostr)
pormat = zeros(no_gridy,no_gridx);
gsize = ylength/no_gridy;
for i = 1: size(equipot,1)
    for j = 1:size(equipot,2)
        pormat(i,j) = 9.8*(equipot(i,j)+0+((gsize*i)-gsize));
    end
end
end
% Flow matrix with independent iteration
flowmat = zeros(no_gridy,no_gridx);
count2 = 0;
while count2<countmax
    count2 = count2+1;
    flowmatinit = flowmat;
    flowmat(:,1) = qapostr;
    flowmat(end,:) = qapostr;
    for k = 1 : no_cells-1
        flowmat(k,end) = 0;
    end
    for i = 2:size(flowmat,1)-1
        for j = 2:size(flowmat,2)-1
            flowmat(i,j) = (flowmat(i,j-1)+flowmat(i,j+1)+flowmat(i+1,j)+flowmat(i-1,j))/4;
        end
    end
end
for k = 2:(size(equipot,2)-1)
    flowmat(1,k) = (flowmat(1,k-1)+flowmat(1,k+1)+(2*flowmat(2,k)))/4;
end
end

```

```

for k = no_cells:(size(equipot,1)-1)
    flowmat(k,end) = (flowmat(k-1,end)+flowmat(k+1,end)+(2*flowmat(k,end-1)))/4;
end
% checking for convergence
if max(max(abs(flowmat-flowmatinit))) <= error
    break
end
if mod(count2,25) == 0
    axes(handles.axes1); reset(handles.axes1)
    set(gca,'YDir','reverse');
    set(gca,'XDir','normal');
    set(gca,'YAxisLocation','left');
    set(gca,'Xtick',[],'Ytick',[]);
    %title('Flow distribution');
    hold on ; colormap(flipud(jet))
    pcolor(flowmat)
    shading interp
    colorbar
end
end
%Plot final convergence
axes(handles.axes1); reset(handles.axes1)
set(gca,'YDir','reverse');
set(gca,'XDir','normal');
set(gca,'YAxisLocation','left');
set(gca,'Xtick',[],'Ytick',[]);
%title('Flow distribution');
hold on ; colormap(flipud(jet))
pcolor(flowmat)
shading interp
colorbar
hold off
%Calculation of flow rate

```

```

q = qapostr*100*hydcoef;
%disp(flowmat)
%Set Afari summary sheet
rhostr = sprintf('Density: %g',rho);
set(handles.afari_sum_leachdensity,'String',rhostr)
kstr = sprintf('Hydraulic Conductivity: %g',hydcoef);
set(handles.afari_sum_kw,'String',kstr)
set(handles.afari_sum_btime,'String','Breakthrough time: N/A')
qstr = sprintf('Flow rate (q): %g',q);
set(handles.afari_sum_q,'String',qstr)
iterstr = sprintf('No. of iterations: %g',count2);
set(handles.afari_sum_iter,'String',iterstr)

%=====
%Mfensi
Clay=====
==
ylengthm = str2double(get(handles.liner_thickness,'String'));
h1m = str2double(get(handles.leach_head,'String'));
hydcoefm = str2double(get(handles.mfensi_kw,'String'));
rhom = str2double(get(handles.leach_density,'String'));
xlengthm = ylengthm*2;
no_gridym = 2*ylengthm;
no_gridxm = xlengthm/(ylengthm/(no_gridym));
%Calculate grid components above and below sheetpile
no_cellsm = ceil(no_gridym/2);
sheetpileheadm = h1m/2; %
%Discretization and solution
equipotm = zeros(no_gridym,no_gridxm);
errorm = 1e-5;
countmaxm = 10000;
countm = 0;
while countm<countmaxm
    countm = countm+1;

```

```

equipinitm = equipotm;
equipotm(1,:) = h1m;
for k = no_cellsm:size(equipotm,1)
    equipotm(k,end) = sheetpileheadm;
end
for k = 2 : no_cellsm-1
    equipotm(k,end) = (equipotm(k+1,end)+equipotm(k-1,end)+2*equipotm(k,end-
1))/4;
end
for i = 2:size(equipotm,1)-1
    for j = 2:size(equipotm,2)-1
        equipotm(i,j) = (equipotm(i,j-1)+equipotm(i,j+1)+equipotm(i+1,j)+equipotm(i-
1,j))/4;
    end
end
for k = 2:size(equipotm,1)-1
    equipotm(k,1) = (equipotm(k+1,1)+equipotm(k-1,1)+2*equipotm(k,2))/4;
end
equipotm(end,1) = (equipotm(end-1,1)+equipotm(end,2))/2;
for k = 2:size(equipotm,2)-1
    equipotm(end,k) = (equipotm(end,k-1) + equipotm(end,k+1) + 2*equipotm(end-
1,k))/4;
end
% checking for convergence
if max(max(abs(equipotm-equipinitm))) <= errorm
    break
end
end
%Pore water pressure
extract1m = equipotm(2,2);
for k = 3: (size(equipotm,2)-3)
    extract1m = equipotm(2,k) + extract1m;
end

```

```

extract2m = equipotm(4,2);
for k = 3: (size(equipotm,2)-3)
    extract2m = equipotm(4,k) + extract2m;
end
qapostrm = (equipotm(2,1)-equipotm(4,1)+equipotm(2,end)-
equipotm(4,end)+2*extract1m-2*extract2m)/4;
%fprintf('q" = %g\n',qapostr)
pormatm = zeros(no_gridym,no_gridxm);
gsizem = ylengthm/no_gridym;
for i = 1: size(equipotm,1)
    for j = 1:size(equipotm,2)
        pormatm(i,j) = 9.8*(equipotm(i,j)+0+((gsizem*i)-gsizem));
    end
end
% Flow matrix with independent iteration
flowmatm = zeros(no_gridym,no_gridxm);
count2m = 0;
while count2m<countmaxm
    count2m = count2m+1;
    flowmatinitm = flowmatm;
    flowmatm(:,1) = qapostrm;
    flowmatm(end,:) = qapostrm;
    for k = 1 : no_cellsm-1
        flowmatm(k,end) = 0;
    end
    for i = 2:size(flowmatm,1)-1
        for j = 2:size(flowmatm,2)-1
            flowmatm(i,j) = (flowmatm(i,j-
1)+flowmatm(i,j+1)+flowmatm(i+1,j)+flowmatm(i-1,j))/4;
        end
    end
end
for k = 2:(size(equipotm,2)-1)
    flowmatm(1,k) = (flowmatm(1,k-1)+flowmatm(1,k+1)+(2*flowmatm(2,k)))/4;

```

```

end
for k = no_cellsm:(size(equipotm,1)-1)
    flowmatm(k,end) = (flowmatm(k-
1,end)+flowmatm(k+1,end)+(2*flowmatm(k,end-1)))/4;
end
% checking for convergence
if max(max(abs(flowmatm-flowmatinitm))) <= errorm
    break
end
if mod(count2m,25) == 0
axes(handles.axes2); reset(handles.axes2)
set(gca,'YDir','reverse');
set(gca,'XDir','normal');
set(gca,'YAxisLocation','left');
set(gca,'Xtick',[],'Ytick',[]);
%title('Flow distribution');
hold on ; colormap(flipud(jet))
pcolor(flowmatm)
shading interp
colorbar
end
end
%Final plot for Mfensi
axes(handles.axes2); reset(handles.axes2)
set(gca,'YDir','reverse');
set(gca,'XDir','normal');
set(gca,'YAxisLocation','left');
set(gca,'Xtick',[],'Ytick',[]);
%title('Flow distribution');
hold on ; colormap(flipud(jet))
pcolor(flowmatm)
shading interp
colorbar

```

```

hold off
%Calculation of flow rate
qm = qapostm*100*hydcoefm;
%disp(flowmat)
%Set Mfensi summary sheet
rhostrm = sprintf('Density: %g',rhom);
set(handles.mfensi_sum_leachdensity,'String',rhostrm)
kstr = sprintf('Hydraulic Conductivity: %g',hydcoefm);
set(handles.mfensi_sum_kw,'String',kstr)
set(handles.mfensi_sum_btime,'String','Breakthrough time: N/A')
qstrm = sprintf('Flow rate (q): %g',qm);
set(handles.mfensi_sum_q,'String',qstrm)
iterstrm = sprintf('No. of iterations: %g',count2m);
set(handles.mfensi_sum_iter,'String',iterstrm)
%Notify user simualation is complete
msgbox('Solution Converged Successfully','CLAYSIM');
%=====
%Case 2: Simulation Coding for TransientStateflow through the clays
(Unsaturated Case)
elseif unsat == 1 && sat == 0
    fprintf('Transient water flow through unsaturated soil\n')
% Afari
Clay=====
==
% Solves the transient seepage problem with an explicit finite difference
%scheme
%Physical parameters
ylength = str2double(get(handles.liner_thickness,'String'));
h1 = str2double(get(handles.leach_head,'String'));
kw = str2double(get(handles.afari_kw,'String'));
rho = (str2double(get(handles.leach_density,'String')))*1e-6;
m2w = str2double(get(handles.afari_m2w,'String'));
xlength = ylength; % Lenght of REV [cm] (usually twice depth)

```

```

gamma = rho*9.81e2; % Specific weight of leachate
day = 3600*24; % # seconds per day
year = 365.25*day; % # seconds per year
%Numerical parameters
nx = 101; % # gridpoints in x-direction
ny = 51; % # gridpoints in z-direction
nt = 1000000; % Number of timesteps to compute
dx = xlength/(nx-1); % Spacing of grid in x-direction
dy = ylength/(ny-1); % Spacing of grid in z-direction
% Compute stable timestep [Courant-Friedrich-Levy (CFL) Condition]
dims = min([dx dy]);
dt = ((dims^2)*m2w*gamma)/(5*kw);
%Hydraulic conductivity profile matrix
kwm = ones(ny,nx);
kwm = kwm.*kw;
%flow matrix initial conditions
h = zeros(ny,nx);
h(end,:) = h1;
%h(:,1) = h1/2;
%h(:,end) = h1/2;
time = 0;
error = h1/3.4e5; %scaled error
for n = 1:nt
    % Compute flow
    fnew = zeros(ny,nx);
    s1 = (kw*dt)/(m2w*gamma*dx^2);
    s2 = (kw*dt)/(m2w*gamma*dy^2);
    s3 = dt/(m2w*gamma*dx^2);
    s4 = dt/(m2w*gamma*dy^2);
    for j = 2:nx-1 %iterate over first row (2 to nx-1)
        fnew(1,j) = h(1,j) + s1*(h(1,j+1)-2*h(1,j)+h(1,j-1)) + ...
            s2*(h(1,j+1)-2*h(1,j)+h(1,j-1)) + ...
            s3*((kwm(1,j+1)-kwm(1,j)) * (h(1,j+1))) + ...

```

```

        s4*((kwm(1,j+1)-kwm(1,1)) * (h(1,j+1)));
end
for i = 2:ny-1 %iterate over first column (2 to ny-1)
    fnew(i,1) = h(i,1) + s1*(h(i+1,1)-2*h(i,1)+h(i-1,1)) + ...
        s2*(h(i+1,1)-2*h(i,1)+h(i-1,1)) + ...
        s3*((kwm(i+1,1)-kwm(i,1)) * (h(i+1,1))) + ...
        s4*((kwm(i+1,1)-kwm(i,1)) * (h(i+1,1)));
end
for i = 2:ny-1 %iterate over last column (2 to nx-1)
    fnew(i,end) = h(i,end) + s1*(h(i+1,end)-2*h(i,end)+h(i-1,end)) + ...
        s2*(h(i+1,end)-2*h(i,end)+h(i-1,end)) + ...
        s3*((kwm(i+1,end)-kwm(i,end)) * (h(i+1,end))) + ...
        s4*((kwm(i+1,end)-kwm(i,end)) * (h(i+1,end)));
end
for j=2:nx-1
    for i=2:ny-1 %iterate over internal matrix
        fnew(i,j) = h(i,j) + s1*(h(i+1,j)-2*h(i,j)+h(i-1,j)) + ...
            s2*(h(i+1,j)-2*h(i,j)+h(i-1,j)) + ...
            s3*((kwm(i+1,j)-kwm(i,j)) * (h(i+1,j))) + ...
            s4*((kwm(i+1,j)-kwm(i,j)) * (h(i+1,j)));
    end
end
for j=2:nx-1 %last row fdm calculation
    fnew(end,j) = h(i,j) + s1*(h(i+1,j)-2*h(i,j)+h(i-1,j)) + ...
        s2*(h(i+1,j)-2*h(i,j)+h(i-1,j)) + ...
        s3*((kwm(i+1,j)-kwm(i,j)) * (h(i+1,j))) + ...
        s4*((kwm(i+1,j)-kwm(i,j)) * (h(i+1,j)));
end
time = time+dt;
% Plot solution every 20 timesteps
if (mod(n,20)==0)
    axes(handles.axes1), reset(handles.axes1) ; colormap(flipud(jet))
    pcolor(fnew); shading interp; colorbar

```

```

hold on
set(gca,'Xtick',[],'Ytick',[]);
inter_time = sprintf('Breakthrough time: %g days',(time/day));
set(handles.afari_sum_btime,'String',inter_time)
drawnow
end
%convergence criteria
if max(max(abs(fnew-h))) <= error
    break
end
h = fnew;
end
%Set Afari summary sheet
rhostr = sprintf('Density: %g',rho);
set(handles.afari_sum_leachdensity,'String',rhostr)
kstr = sprintf('Hydraulic Conductivity: %g',kw);
set(handles.afari_sum_kw,'String',kstr)
if time/day <= 365
    breaktime = sprintf('Breakthrough time: %g days',time/day);
else
    breaktime = sprintf('Breakthrough time: %g years',time/year);
end
set(handles.afari_sum_btime,'String',breaktime)
qstr = sprintf('Flow rate (q): N/A');
set(handles.afari_sum_q,'String',qstr)
iterstr = sprintf('No. of iterations: %g',n);
set(handles.afari_sum_iter,'String',iterstr)
%Mfensi
Clay=====
% Solves the transient seepage problem with an explicit finite difference
%scheme
%Physical parameters
ylengthmt = str2double(get(handles.liner_thickness,'String'));

```

```

h1mt = str2double(get(handles.leach_head,'String'));
kwmt = str2double(get(handles.mfensi_kw,'String'));
rhoht = (str2double(get(handles.leach_density,'String')))*1e-6;
m2wmt = str2double(get(handles.mfensi_m2w,'String'));
xlengthmt = ylengthmt; % Lenght of REV [cm] (usually twice depth)
gammamt = rhoht*9.81e2; % Specific weight of leachate
daymt = 3600*24; % # seconds per day
yearmt = 365.25*daymt; % # seconds per year
%Numerical parameters
nxmt = 101; % # gridpoints in x-direction
nymt = 51; % # gridpoints in z-direction
ntmt = 1000000; % Number of timesteps to compute
dxmt = xlengthmt/(nxmt-1); % Spacing of grid in x-direction
dymt = ylengthmt/(nymt-1); % Spacing of grid in z-direction
% Compute stable timestep [Courant-Friedrich-Levy (CFL) Condition]
dimsmt = min([dxmt dymt]);
dtmt = ((dimsmt^2)*m2wmt*gammamt)/(5*kwmt);
%Hydraulic conductivity profile matrix
kwmt = ones(nyymt,nxmt);
kwmt = kwmt.*kwmt;
%flow matrix initial conditions
hmt = zeros(nyymt,nxmt);
hmt(end,:) = h1mt;
%h(:,1) = h1/2;
%h(:,end) = h1/2;
timent = 0;
errormt = h1mt/3.4e5; %scaled error
for nmt = 1:ntmt
    % Compute flow
    fnewmt = zeros(nyymt,nxmt);
    s1mt = (kwmt*dtmt)/(m2wmt*gammamt*dxmt^2);
    s2mt = (kwmt*dtmt)/(m2wmt*gammamt*dymt^2);
    s3mt = dtmt/(m2wmt*gammamt*dxmt^2);

```

```

s4mt = dtmt/(m2wmt*gammamt*dymt^2);
for j = 2:nxmt-1 %iterate over first row (2 to nx-1)
    fnewmt(1,j) = hmt(1,j) + s1mt*(hmt(1,j+1)-2*hmt(1,j)+hmt(1,j-1)) + ...
        s2mt*(hmt(1,j+1)-2*hmt(1,j)+hmt(1,j-1)) + ...
        s3mt*((kwmmmt(1,j+1)-kwmmmt(1,j)) * (hmt(1,j+1))) + ...
        s4mt*((kwmmmt(1,j+1)-kwmmmt(1,1)) * (hmt(1,j+1)));
end
for i = 2:nymt-1 %iterate over first column (2 to ny-1)
    fnewmt(i,1) = hmt(i,1) + s1mt*(hmt(i+1,1)-2*hmt(i,1)+hmt(i-1,1)) + ...
        s2mt*(hmt(i+1,1)-2*hmt(i,1)+hmt(i-1,1)) + ...
        s3mt*((kwmmmt(i+1,1)-kwmmmt(i,1)) * (hmt(i+1,1))) + ...
        s4mt*((kwmmmt(i+1,1)-kwmmmt(i,1)) * (hmt(i+1,1)));
end
for i = 2:nymt-1 %iterate over last column (2 to nx-1)
    fnewmt(i,end) = hmt(i,end) + s1mt*(hmt(i+1,end)-2*hmt(i,end)+hmt(i-1,end)) +
...
        s2mt*(hmt(i+1,end)-2*hmt(i,end)+hmt(i-1,end)) + ...
        s3mt*((kwmmmt(i+1,end)-kwmmmt(i,end)) * (hmt(i+1,end))) + ...
        s4mt*((kwmmmt(i+1,end)-kwmmmt(i,end)) * (hmt(i+1,end)));
end
for j=2:nx-1
    for i=2:ny-1 %iterate over internal matrix
        fnewmt(i,j) = hmt(i,j) + s1mt*(hmt(i+1,j)-2*hmt(i,j)+hmt(i-1,j)) + ...
            s2mt*(hmt(i+1,j)-2*hmt(i,j)+hmt(i-1,j)) + ...
            s3mt*((kwmmmt(i+1,j)-kwmmmt(i,j)) * (hmt(i+1,j))) + ...
            s4mt*((kwmmmt(i+1,j)-kwmmmt(i,j)) * (hmt(i+1,j)));
        end
    end
    for j=2:nxmt-1 %last row fdm calculation
        fnewmt(end,j) = hmt(i,j) + s1mt*(hmt(i+1,j)-2*hmt(i,j)+hmt(i-1,j)) + ...
            s2mt*(hmt(i+1,j)-2*hmt(i,j)+hmt(i-1,j)) + ...
            s3mt*((kwmmmt(i+1,j)-kwmmmt(i,j)) * (hmt(i+1,j))) + ...
            s4mt*((kwmmmt(i+1,j)-kwmmmt(i,j)) * (hmt(i+1,j)));
    end
end

```

```

end
timeint = timeint+dtint;
% Plot solution every 20 timesteps
if (mod(nmt,20)==0)
    axes(handles.axes2), reset(handles.axes2) ; colormap(flipud(jet))
    pcolor(fnewmt); shading interp; colorbar
    hold on
    set(gca,'Xtick',[],'Ytick',[]);
    inter_timeint = sprintf('Breakthrough time: %g days',(timeint/dayint));
    set(handles.mfensi_sum_btime,'String',inter_timeint)
    drawnow
end
%convergence criteria
if max(max(abs(fnewmt-hmt))) <= errormt
    break
end
hmt = fnewmt;
end
%Set Mfensi summary sheet
rhostrmt = sprintf('Density: %g',rhoimt);
set(handles.mfensi_sum_leachdensity,'String',rhostrmt)
kstrmt = sprintf('Hydraulic Conductivity: %g',kwimt);
set(handles.mfensi_sum_kw,'String',kstrmt)
if timeint/dayint <= 365
    breaktimeint = sprintf('Breakthrough time: %g days',timeint/dayint);
else
    breaktimeint = sprintf('Breakthrough time: %g years',timeint/yearint);
end
set(handles.mfensi_sum_btime,'String',breaktimeint)
qstrmt = sprintf('Flow rate (q): N/A');
set(handles.mfensi_sum_q,'String',qstrmt)
iterstrmt = sprintf('No. of iterations: %g',n);
set(handles.mfensi_sum_iter,'String',iterstrmt)

```

```

%Notify user simulation is complete
msgbox('Simulation Complete','CLAYSIM');
end
function mfensi_kw_Callback(hObject, eventdata, handles)
% hObject handle to mfensi_kw (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of mfensi_kw as text
% str2double(get(hObject,'String')) returns contents of mfensi_kw as a double
% --- Executes during object creation, after setting all properties.
function mfensi_kw_CreateFcn(hObject, eventdata, handles)
% hObject handle to mfensi_kw (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called
% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
set(hObject,'BackgroundColor','white');
end
function mfensi_m2w_Callback(hObject, eventdata, handles)
% hObject handle to mfensi_m2w (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of mfensi_m2w as text
% str2double(get(hObject,'String')) returns contents of mfensi_m2w as a double
% --- Executes during object creation, after setting all properties.
function mfensi_m2w_CreateFcn(hObject, eventdata, handles)
% hObject handle to mfensi_m2w (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called
% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.

```

```

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
function afari_m2w_Callback(hObject, eventdata, handles)
% hObject    handle to afari_m2w (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of afari_m2w as text
%    str2double(get(hObject,'String')) returns contents of afari_m2w as a double
% --- Executes during object creation, after setting all properties.
function afari_m2w_CreateFcn(hObject, eventdata, handles)
% hObject    handle to afari_m2w (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called
% Hint: edit controls usually have a white background on Windows.
%    See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
function afari_kw_Callback(hObject, eventdata, handles)
% hObject    handle to afari_kw (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of afari_kw as text
%    str2double(get(hObject,'String')) returns contents of afari_kw as a double
% --- Executes during object creation, after setting all properties.
function afari_kw_CreateFcn(hObject, eventdata, handles)
% hObject    handle to afari_kw (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called
% Hint: edit controls usually have a white background on Windows.

```

```

% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
function leach_head_Callback(hObject, eventdata, handles)
% hObject handle to leach_head (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of leach_head as text
% str2double(get(hObject,'String')) returns contents of leach_head as a double
% --- Executes during object creation, after setting all properties.
function leach_head_CreateFcn(hObject, eventdata, handles)
% hObject handle to leach_head (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called
% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
function leach_density_Callback(hObject, eventdata, handles)
% hObject handle to leach_density (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of leach_density as text
% str2double(get(hObject,'String')) returns contents of leach_density as a double
% --- Executes during object creation, after setting all properties.
function leach_density_CreateFcn(hObject, eventdata, handles)
% hObject handle to leach_density (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called

```

```

% Hint: edit controls usually have a white background on Windows.
%   See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
function liner_thickness_Callback(hObject, eventdata, handles)
% hObject   handle to liner_thickness (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles   structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of liner_thickness as text
%   str2double(get(hObject,'String')) returns contents of liner_thickness as a double
% --- Executes during object creation, after setting all properties.
function liner_thickness_CreateFcn(hObject, eventdata, handles)
% hObject   handle to liner_thickness (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles   empty - handles not created until after all CreateFens called
% Hint: edit controls usually have a white background on Windows.
%   See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
% --- Executes on button press in stop_mfensi.
function stop_mfensi_Callback(hObject, eventdata, handles)
% hObject   handle to stop_mfensi (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles   structure with handles and user data (see GUIDATA)
global stopstatem
stopstatem = 1;
% --- Executes on button press in stop_afari.
function stop_afari_Callback(hObject, eventdata, handles)
% hObject   handle to stop_afari (see GCBO)

```

```

% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
global stopstate
stopstate = 1;
% -----
function Untitled_1_Callback(hObject, eventdata, handles)
% hObject handle to Untitled_1 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
% -----
function Untitled_3_Callback(hObject, eventdata, handles)
% hObject handle to Untitled_3 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
% -----
function Untitled_6_Callback(hObject, eventdata, handles)
% hObject handle to Untitled_6 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
% -----
function contents_Callback(hObject, eventdata, handles)
% hObject handle to contents (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
% -----
function about_Callback(hObject, eventdata, handles)
% hObject handle to about (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
run About_ClaySim
% -----
function poregraf_afari_Callback(hObject, eventdata, handles)

```

```

% hObject handle to poregraf_afari (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
global gsize ylength pormat
xdata = transpose(0:gsize:ylength);
xdata = xdata(xdata~=0); %-xdata data reparse
ydata = pormat(:,end);
figure
set(gca,'YDir','reverse');
set(gca,'XDir','reverse');
set(gca,'YAxisLocation','right');
xlabel('Pore Water Pressure (kPa)'); ylabel('Depth of sheetpile (cm)');
hold on
plot(ydata,xdata)
hold off
% -----
function poregraf_mfensi_Callback(hObject, eventdata, handles)
% hObject handle to poregraf_mfensi (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
global gsize ylength pormatm
xdata = transpose(0:gsize:ylengthm);
xdata = xdata(xdata~=0); %-xdata data reparse
ydata = pormatm(:,end);
figure
set(gca,'YDir','reverse');
set(gca,'XDir','reverse');
set(gca,'YAxisLocation','right');
xlabel('Pore Water Pressure (kPa)'); ylabel('Depth of sheetpile (cm)');
hold on
plot(ydata,xdata)
hold off
% -----

```

```
function exit_Callback(hObject, eventdata, handles)
% hObject    handle to exit (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
close
```

# KNUST

