# An Experimental Investigation of Landfill Leachate Impact on Surrounding Soil

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*My parents*

*For dedicating their life for me and my wellbeing with endless love and support*

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# ABSTRACT

Landfill leachate is generated as a consequence of water percolation through the solid wastes, oxidation of the wastes, and corrosion of the wastes. Underdesigned landfill sites allow the leachate to easily pass through the soil strata. This may have an impact on the engineering properties of soils, such as the shear strength and the volume change (compressibility and swelling), and the chemical properties (adsorption and retention of heavy metals). In this thesis, a detailed experimental investigation was undertaken to investigate the effects of landfill leachate contamination on the geotechnical and geo-environmental properties of natural soils of Kuwait.

Two soils (a silty sand and a clayey sand) were used in the study. The soils were obtained from the Al-Jahra landfill site based in Kuwait. The leachate was collected from the Al-Qurain landfill site in Kuwait. The results from the direct shear and consolidation tests on compacted soil specimens that interacted with leachate and water indicated that, the influence of contamination was severe on the engineering properties of the clayey sand than that of the silty sand.

The geoenvironmental properties of the soils were studied to assess the transport and fate of heavy metals in the soils. Leaching column tests were carried out to establish the breakthrough curves which showed retention of heavy metals (As, Cr, Cu and Ni) by both soils. The results from batch isotherm adsorption tests were used to study the ability of the soils to adsorb heavy metals. The test results showed that, heavy metal adsorption was superior in the clayey sand than that occurred in the silty sand.

The leaching column test results was used to validate the HYDRUS 1D software package. The results from the model and the laboratory tests results were found to be in good agreements. The bearing capacity and settlement behavior of the soils were modelled. The settlement behavior of the soils was found to be more pronounced due to the presence of landfill leachate. The conclusions drawn from the experimental and numerical investigations favour a further understanding of some of the key issues associated with the transport and fate of leachate in the surrounding environment of a landfill site.

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# Chapter 1

# INTRODCTION

## 1.1 Introduction

Present day waste disposal is far more advanced than the indiscriminate dumping that occurred in the past, employing modern techniques to better manage a wide range of anthropogenic wastes. This disposal still doesn't necessarily occur under controlled conditions however, with only more developed countries ensuring complete environmental protection (Chu 1994).

One of the main objectives in the design of a landfill site should be the proper management of polluted water and leachate migration, therefore mitigating the risk of health and environmental damage. Leachate typically possess high concentrations of suspended organic matter and acids, which can degrade ground and surface water unless precautions are taken. Suitable sites should be specially selected with attention being given to the soil, to ensure that it does not become overloaded and unable to attenuate or retain the potential pollutants.

The State of Kuwait is located at the North-Western corner of the Arabian Gulf, occupying an area of 178180 $km^2$ and with a population of over 2 million and an annual growth rate of 4.7%. The State has very high municipal waste production per capita, estimated to be around 1.4kg per person every day (Al-Meshan and Mahrous 2002).

The soils of Kuwait have limited organic matter, with very low nutrient content and high amounts of calcareous material, as well as high gypsum & carbonate content. On average, the landfills of Kuwait receive 306 tons of municipal waste, 64 tons of agricultural waste, 3522 tons of construction waste and 1641000 gallons of liquid waste per day. Several tests run on the soil reveal it to have very little capacity to hold water, whereas the infiltration rates are observed to be high (Abdal and Al-Qallaf 1993).

Landfill sites are considered a major threat to groundwater resources, either through waste materials coming into contact with groundwater underflow, or through infiltration from precipitation (Taylor and Allen 2006). The landfilled solid waste often releases interstitial water and by-products that contaminate the water moving through the deposit, as well as liquids containing several different organic and inorganic compounds that sit at the bottom of the deposit and seep into the soil, affecting its physical and chemical properties (Al-Yaqout & Hamoda 2003).

Al-Barak (2008) observed a high concentration of total dissolved solids (TDS), nitrates and hardness in the groundwater at Kuwait landfill sites, as well as increased TSS and TDS leachate the deeper the municipal solid waste (MSW) was buried. The findings suggest that leachate from landfills has higher levels of dissolved solids and gases which contain hazardous materials such as volatile organic compounds and heavy metals. Through this analysis, it has been identified that conventional landfill design should be to store waste in a way that minimizes exposure to human and the environment (Al-Humoud 2006).

Removal of landfill contaminants requires significant financial investment, as well as technologies that are not currently used by organizations in Kuwait (Al-Muzaini et al. 1995). It has been identified that no proper monitoring programs are implemented by Kuwait, and therefore the natural soil and subsurface environments contain major health hazards and threats to the environment. It is argued that the landfill sites currently used for all types of waste by the Kuwait municipality do not follow the minimum environmental standards and conditions in terms of proper site selection, design and management (Al-Fares 2011). When combined with the aforementioned low absorption capacity and high infiltration rate of the natural soil, the increasing generation of waste materials and lack of proper leachate management in Kuwait gives rise to negative physical and chemical characteristics in the soil.

The research focusing on these issues is rare, so in order to come up with adequate safety precaution and improved standards and practices, it is vital that analysis of the effects of contaminated leachate on the physical and chemical properties of the natural soil in Kuwait takes place.

## 1.2 Research Aims and Objectives

The main aim of this study is to investigate the performance of the Al-Jahra landfill site, with a view to aid future design and construction of landfills in Kuwait. The objectives of the study are:

- To investigate the impact of leachate on the geotechnical and geoenvironmental properties of soils at the Al-Jahra landfill site of Kuwait.
- To explore the fate and transport of leachate through surrounding soils at the dumpsite.

## 1.3 Thesis Outline

A brief description of the chapters of this thesis is presented below.

***Chapter Two*** provides an explicit description of the existing literature associated with the environmental impacts of landfill sites, particularly on describing the effects of landfill waste on the chemical and physical characteristics of natural soil. Reported literature related to landfill sites in Kuwait has been given special attention. The literature review has been carried out to gain an insight into the relevant research activities related to landfill waste management in United State, United Kingdom and other countries.. This chapter includes all the information required to set rational grounds for the topic under keen observation. Consequently, the importance of this research is highlighted.

***Chapter Three*** of the research provides an overview of the methodologies that have been used to gather specific literature on the issues, including results that involve direct shear, compression, leaching column and adsorption isotherms tests.

***Chapter Four*** contains the results and findings of the direct shear and compression tests, in order to the influence of leachate on the soil properties.

***Chapter Five*** contains the results of the column tests and adsorption isotherms, to explore the ability of the soils used to retain and absorb heavy metals.

***Chapter Six*** covers the modelling of the test results that were obtained from the geotechnical (chapter 4) and geo environmental (chapter 5) investigations.

Finally, the main conclusions drawn from the study are presented in ***Chapter Seven*.**

# Chapter 2

# LITERATURE REVIEW

## 2.1 Introduction

A review of the literature suggests that landfill is an essential part of an effective waste management strategy. Municipal committees must prepare for future landfill needs by formulating long term plans and allocating suitable and sustainable land for landfill. It is pivotal to note that each district has an allotted space for their waste disposal or else waste will be dumped, creating further problems that will need to be dealt with (McDougall & White 2008).

Unmanaged dumping outside dedicated waste disposal areas leads to landfill leachate penetration of the ground, which directly affects the ground water supply. This chemical penetration also leads to a loss in composted soil, rendering the ground unfertile for long periods of time. Because of this, new research and technology is needed to help cultivate the land (Thiruvenkatachari et al. 2008).

In this chapter, the reported data and essential information regarding landfill principles and methods are presented. This includes the evaluation of different types of landfill leachate and liners. The effect of leachate and liners on the environment is also analyzed, along with the factors that give rise to the resulting conditions and the relative importance of these factors. Furthermore, the background of this topic will be covered through the examination of the existing research into the behavior of landfill leachate.

## 2.2 Principles of Waste Management

A central framework is laid by US environmental agency out that aids the creation of operational standards, which in turn assists in the controlling of the methods of waste disposal. This framework is required for both the treatment of waste and the engineering of landfill construction. The principles that govern waste disposal will help reduce the risk of pollution and lessen the negative impact that landfill waste has on the environment.

### 2.1.1 Landfill History

Waste is the direct consequence of many types of human activity, and has been a burden to deal with across the world and throughout history. Landfilling has emerged as the simplest and most economical method of disposing with this waste.

Waste is broadly classified into three main types; solid, liquid, and gas. Gaseous wastes are those that dissipate in the atmosphere, and can either be treated or untreated, depending on the composition of the gas and the regulations of the country where it is disposed. Liquid wastes are those that are disposed of into rivers or sewers, and are treated before disposal, depending on the legislation (Geismar 2014).

In many parts of the world however, problems exist with the creation and implementation of this kind of legislation, and unmanaged liquid waste is disposed of into different bodies of water or allowed to penetrate into the ground, polluting water bodies and giving rise to many other problems (Milosevic 2012).

The disposal of waste is seen as a major problem in most of the developing countries, with most waste being disposed of into landfill. This also true for solid waste in many developed nations, however, as in 1999, the main method of waste disposal in Western Europe was landfill. Despite policies to promote reuse and reduction of waste within the European Union, more than half of its member states dispose of 75% of their waste through landfill (Thiruvenkatachari et al. 2008), with Ireland disposing of 92% this way. While the proportion of waste that is landfilled is expected to decrease, the actual volume of municipal solid waste (MSW) is increasing significantly, at a rate of 3% per year for many developed nations, creating an ongoing waste disposal and groundwater pollution problem (Thomsen et al. 2012).

Modern landfills use liners made of plastic and other non-porous materials to stop the pollution from garbage leaking into the soil. Many landfills are located in areas with deposits of clay and other natural resources, which act as a liner. A system of drainage pipes is installed by the landfill operators to direct leachate, or liquid waste, into nearby wells and ponds where these liquid wastes are tested and treated (Milosevic 2012). After a landfill is full, the ground water around these landfills is quality tested for many years. In order to ensure safety, regulations are developed by the Environmental Protection Agency (EPA), which help in governing the operations of landfill sites and prevent the leakage of leachate and methane (Gallas et al. 2011).

A landfill is similar to an airtight storage container in that garbage does not break down very easily, as can be seen by the slow break down rates of biodegradables such as paper or grass clippings. Once classified as closed, landfill sites are often transformed into parks, ski slopes and gold coursed, however they are never built upon due to the impact of settling.

Newer types of landfill have been developed, such as bioreactors which make use of leachate air to encourage biodegrading inside the landfill. Much more waste can be stored in bioreactors than in traditional landfills, and Bella et al.(2011) reported that the methane gase produced by the breakdown of organic waste in the bioreactor can be used as an energy source. This methane has similar properties to natural gas, so can be used as fuel, or used to generate electricity by burning.

Previous research has shown that around 14% of all waste is burned, 31% is recycled, and 55% is stored in landfill.

Recycling is recommended by the EPA to save natural resources and protect the environment from pollution. Recycling also helps in decreasing the need for landfill, which in turn lessens the problems created by waste management. Recycling can be encouraged by placing bins in the home and calling for a national reduction in the disposal of waste through the garbage system, as well as through legislation. It has been shown that if proper national legislation is adopted, recycling can significantly reduce waste and environmental pollution (Bella et al. 2011).

Certain guidelines for the disposal of dangerous and household waste have been laid out by the government-sponsored hazardous waste disposal facility. The specified waste materials include chemicals, fertilizers, medicines, insect killers and suppliers of automotive and such other materials. These waste materials must be disposed of according to the instructions set out by Europe Water Framework Directive, as otherwise pollution can occur (Thomsen et al. 2012).

Geismar (2014) reported that the harmful effects of waste on the environment can be avoided by storing unwanted waste in various disposal facilities. Rather than dumping local waste in holes and pits – which are typically unlined and offer no protection to the groundwater supply - it can be dealt with in specialist facilities where its spread and treatment can be regulated, and its impact on the environment reduced. To ensure this, various policies and agencies must be created in developing countries.

Many aspects of waste management have the potential to pollute or damage the environment, including the collection, storage, treatment, transport, and disposal of waste. Unmanaged groundwater also has the potential to pollute the environment, as the leachate migration that takes place at landfill sites is hard to control, and may end up contaminating the groundwater and causing wider problems. Therefore, adequately managing the leachate and groundwater is vital in mitigating damage to the environment (Gallas et al. 2011).

Milosevic (2012) considered that human wastes can be identified as wastes that are produced by the human use of different non-toxic substances such as paper and food, but also waste related to toxic substances such as batteries, paint, healthcare waste, asbestos, and sewage sludge. Solid wastes can be classified into the broad categories of commercial and non-dangerous industrial wastes, household waste, construction and demolition waste, toxic industrial waste, human and animal waste, and waste related to healthcare.

### 2.1.2 Landfill Types

Landfill can be classified into four main types, such as sanitary landfills, municipal solid waste (MSW) landfills, construction and demolition waste landfills, and industrial waste landfills.

#### 2.1.2.1 Sanitary landfills

Sanitary landfills make use of liner clay so that trash can be separated from the environment (Milosevic 2012). Sanitary landfills are used in the areas where it is a major requirement that discarded waste must be isolated from the environment until it is confirmed that the area is safe. The waste is considered safe when it is completely degraded; chemically, physically and biologically (Diamantis 2013).

Modern technology is used in sanitary landfills to prevent the leakage of dangerous substances. In sanitary landfills, two main types of methods are used (Bella et al. 2011). These are the trench method and the area method, with the trench method being considered more appropriate in areas of low waste. Both methods make us of the cell principle, using soil to cover compacted waste. (Thomsen et al. 2012). Both methods are illustrated in Figure 2.1.

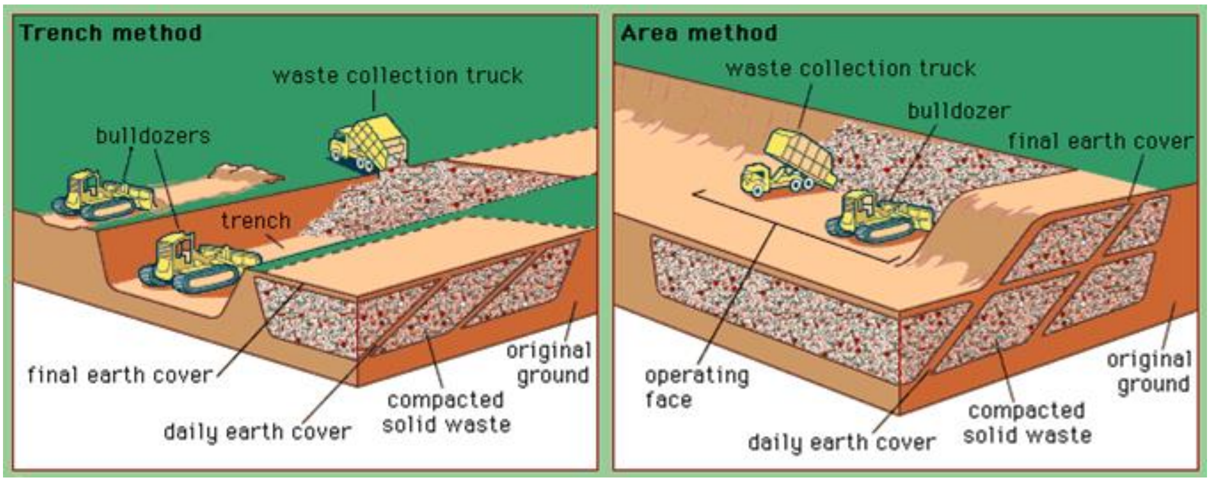


**Figure 2.1: Sanitary Landfill (Nijrabi, 2010)**

### 2.1.2.2 Municipal Solid Waste (MSW) Landfills

This type of landfill uses a synthetic plastic lining to isolate waste from the surrounding environment, and is contains household garbage collected and managed by the local and state governments (Geismar 2014). The allowed contents of MSW sites have been specified by the Environmental Protection Agency (EPA), with materials such as paints, chemicals, batteries, cleaners, motor oil, and pesticides being banned (Al-Jarallah & Aleisa 2014). Some household appliances are safe for disposal in an MSW site, but dangerous wastes such as bulk liquids or wastes that have free liquids, yard waste and scrap tires are not (Thomsen et al. 2012).

#### 2.1.2.3 Construction and Demolition Waste Landfills

Construction and demolition are used to dispose of materials used in the construction, renovation, and demolition of roads, bridges and buildings. These wastes mostly include gypsum, wood, asphalt, bricks, soil rock, glass, concrete, trees, and other building components (Geismar 2014). These contribute to pollution of the environment and when burned can emit toxic gases. It is essential for Construction and Demolition wastes to meet the operating, siting, design and closure and post-closure requirements. They are even prohibited from accepting debris that is minced (Milosevic 2012). The best way to avoid these wastes is to keep proper estimate of the raw materials that are needed for construction projects. Recycling these types of wastes does not only help in saving money but also helps reduce the amount of waste disposed of in landfills (Thomsen et al. 2012).

#### 2.1.2.4 Industrial Waste Landfills

The industrial wastes produced mostly by manufacturing companies generate methane (Gallas et al. 2011), which is considered to be a natural byproduct, the decomposition of which can generate clean and useable energy. However, if these wastes were recycled rather than dumped, they could also be used to create useful products (Milosevic 2012).

### 2.1.3 Waste in Kuwait

Waste in a country constantly rises as result of the natural growth of the population and the developing standard of living. Al-Meshan and Mahrous (2002) had been estimated that there were more than a million tons of municipal solid waste (MSW) produced annually in the state of Kuwait with a per capita rate of about 1.4kg/person/day. This alarming rate of waste production is drastically increasing as can be seen in Figures 2.2 and 2.3.

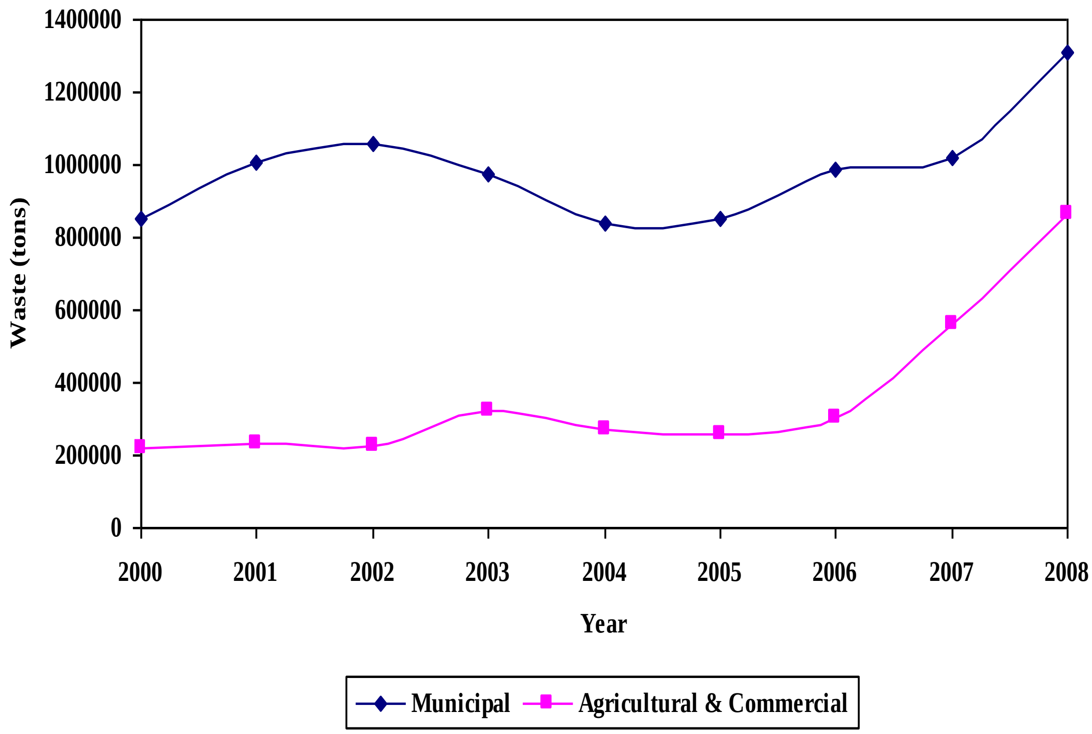


**Figure 2.2: Municipal, Agricultural and Commercial Wastes Production from 2000 to 2008 (Al-Fares et al. 2009)**

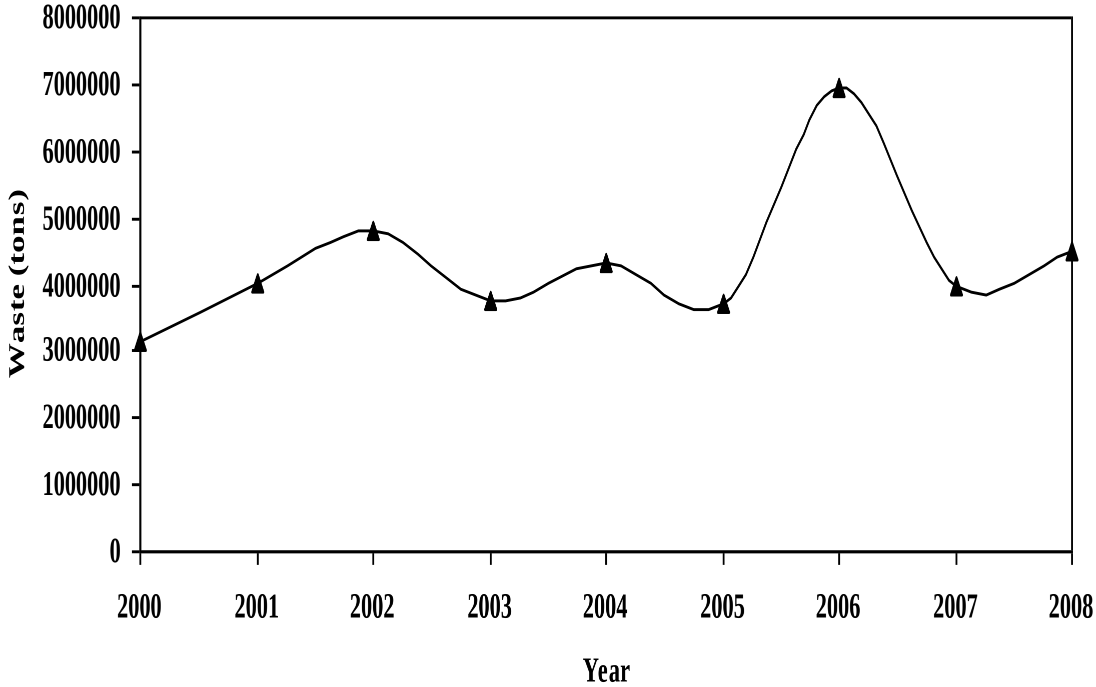


**Figure 2.3: Construction Wastes Production from 2000 to 2008 (Al-Fares et al. 2009)**

Table 2.1 shows the major components and quantity of solid waste found from various residential districts in the Kuwait. From the table we can see that organic substances are the major components of household wastes, at about 50%, with general waste such as of papers and plastic etc making up the rest. This kind of waste is different from advanced industrial counties where paper, metals and plastic are the main components, followed by organic wastes (Al-Humoud 2001).

**Table 2.1: Kuwait municipal waste composition (Al-Humoud 2001)**

| Waste Component | Percentage (%) |
|---|---|
| Food | 50 |
| Paper and cardboard | 20.6 |
| Plastics | 12.6 |
| Metals | 2.6 |
| Glass | 3.3 |
| Textiles | 4.8 |
| Others | 8.6 |
| Moisture content | 55 |
| Density ( $kg/m^3$) | 593 |

Inhabited areas in Kuwait are divided into six main collection districts. Each district is further subdivided into cleansing areas, each being controlled by a cleaning center. Cleaning companies are contracted to do the collection of waste from different parts of the country, but not to do any preliminary sorting at the source of waste. Plastic bags are widely used for handling household refuse, and specially designed refuse compaction vehicles are used for collecting almost all domestic solid waste, though some open truck and side loaders are still used (Al-Meshan et al. 1999).

Landfilling is the main disposal system used in the State of Kuwait, though the landfills currently used by the Kuwait Municipality for all types of wastes do not meet the minimum required environmental standards and conditions in terms of the site selection, design and management. The landfill sites in Kuwait are at low places which have been previously used as sand and gravel quarries and therefore have a leveled soil surface. The geological and environmental conditions of the sites are not adequately regulated, and random landfill techniques without proper waste separation are often used.

The dumping sites in Kuwait occupy an approximate area of 29.5 square kilometers, which is around 0.166% of the total area of the State of Kuwait. Currently only 3 dumping sites are active with an approximate area of 8.35 square km; around 28.41% of the total area of dumping sites and 0.469% of the total area of the State of Kuwait. Figure 2.4 shows the location of the disposal sites in Kuwait. There are currently 3 active and 13 closed sites occupying large area (Al-Fares et al. 2009).

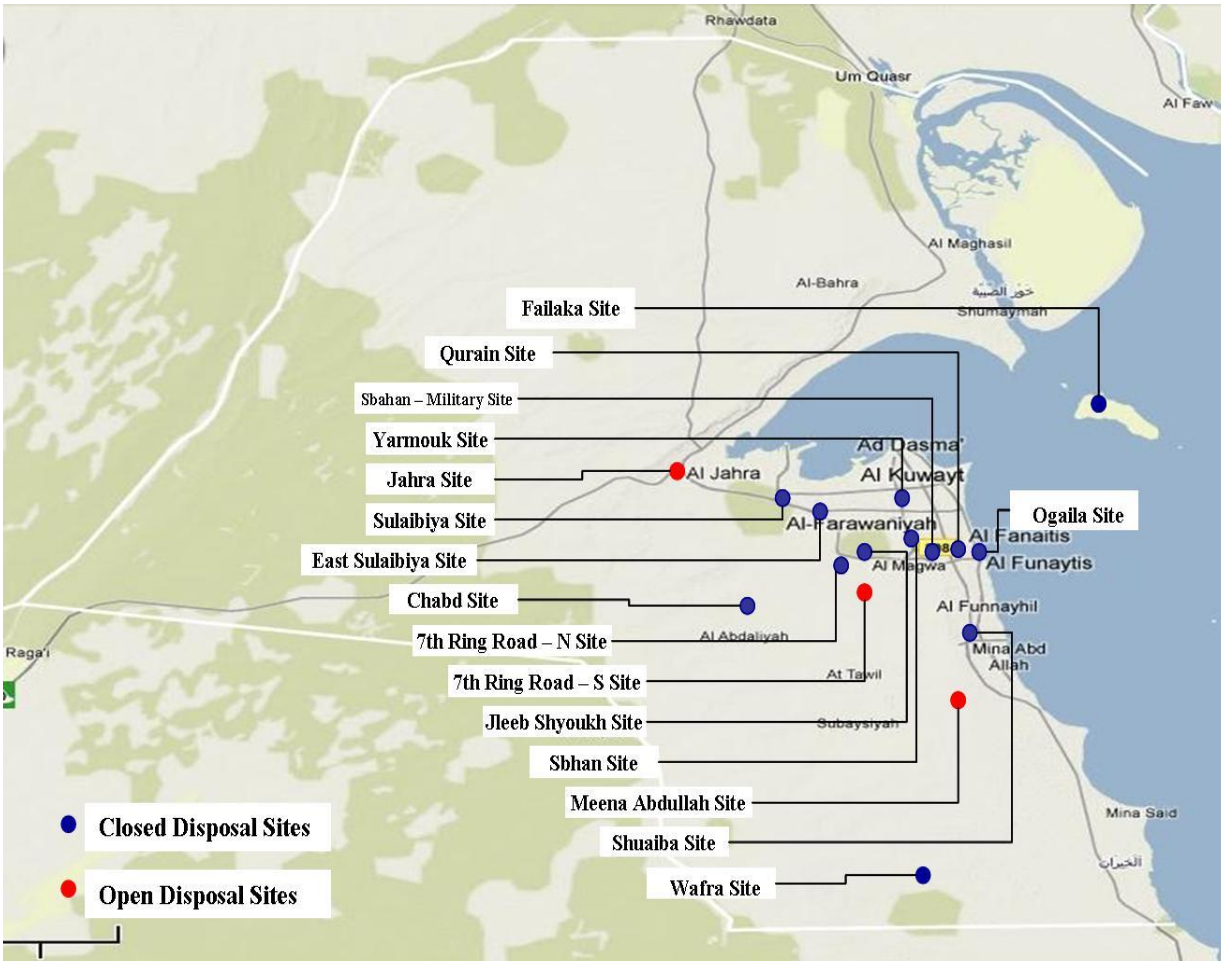


Figure 2.4: Location of 16 disposal sites at the state of kuwait (Al-Fares et al. 2009)

Kuwait has limited land resources, and all landfill sites in Kuwait are inappropriately located, with various communities using old sand and gravel pits because of their convenience. The landfill sites in Kuwait have no proper engineering design or planning, and during landfill operations no special compactors are used aside from caterpillar tractors used for moving and burying waste (Al-Sarawi et al. 2001).

The daily process of landfilling at active sites consists of spreading the wastes immediately upon unloading, to form layers of wate. These layers are then well compacted with the use of heavy vehicles (Bulldozers) before being spread. This waste layer is then covered with a layer of sand or soil 30cm thick, which is then also compacted (rolled). This process is repeated daily until the site is full, resulting in many layers of waste separated by sand or soil to reduce odor. The two main sites in Kuwait are Al-Qurain and the Al-Jahra site (Al-Meshan and Mahrous 2002). Figure 2.5 shows the methods of waste disposal in Kuwait. Figure 2.5 shows the 3 active sites received all types of waste such as MSW, liquid, agricultural and commercial in unlined and controlled dump site and no separation, recycling and treatment systems that may affect the ground water and the surrounding soils, including posing various other problems, such as emission of various gases and odors.

Figure 2.5a: Al-Jahra landfill (Al-Fares et al. 2009)

Figure 2.5b: Meena abdullah landfill (Al-Fares et al. 2009)


**Figure 2.5c: 7th ring road - northern landfill (Al-Fares et al. 2009)**

## 2.2 Landfill Engineering

Landfill engineering is the identification and construction of sites for waste storage. These landfill sites are constructed in areas where environmental impact of waste storage is minimal or non-existent and where they can be further converted into a harmless state in the long term.

There are certain aspects of landfill engineering that can create problems for the engineers during construction, so proper classification and design of landfill sites is important and must be taken into consideration (Nagendran et al. 2006).

### 2.2.1 Landfill liner

Landfilling has becoming a widespread practice in the modern societies due to its effectiveness at providing long term waste storage if built and managed using proper engineering tools and techniques. The use of landfill sites has increase to protect societies from the health issues associate with waste storage. (Naik 2008).

Modern landfills are highly engineered and controlled systems that utilize liners to minimize the impact of waste materials, particularly solid waste (Rio et al. 2009). It is important to minimize the impact of solid waste, as they can have a significant adverse effect on the environment and the health of the human beings and other living things in the surrounding area. The liners are typical made of compacted clay, geosynthetic clay, geomembrane, geotextiles or combinations of all these (Nagendran et al. 2006). The liner system is broadly used by modern societies due to its ability to create a barrier between waste and the environment (Naik 2008). These systems also include the draining of the leachates so that it can be collected and sent to treatment facilities.

Landfill sites that use the liner system are designed to be reliable and robust, remaining active for years or even decades (Thiruvenkatachari et al. 2008). This reliable and long-term approach is necessary in order for the barriers to effectively separate leachate, gasses, and solid waste from the environment. The cost of these sites is also considerable, so they have to be long lasting in order for their construction to be sustainable. A great deal of importance is placed on the design of these sites, as they are supposed to be an impermeable blockade between the immense collection of waste and the soil below and around it (Randers 2008).

When the efficiency of a liner based landfill system is measured, the level of protection that it provides from solid waste is focused on. The sites with the greatest level of efficiency are generally those with designs that have permeability and hydraulic conductivity, to effectively defend against the discharging forces of the leachate (Rio et al. 2009). A leachate management system is designed in such a way as to preserve low leachate at the very top of the liner system to reduce the hydraulic gradient. The hydraulic performance of a landfill liner is evaluated through its ability to control leakages passing through the contaminant in the liner, as well its capability to assuage the contaminants (Ayub & Khan 2011).

The time it takes leachate to pass through containments is also calculated to assess the effectiveness of the system. If the travel time increases then the liners are shown to have low conductivity, as this increased travel time can only be due to them. This potentially reduces the leachate toxicity due to biological and chemical degradation (Thiruvenkatachari et al. 2008). The materials used to construct the liners have also been shown to greatly influence the operational efficiency of the liner system (Rio et al. 2009).

During the design phase of the site, the minimum amount of leakage that could take place though the liners is calculated. Any areas where a greater amount of leakage occurs are required to be emphasized and brought to within the minimum (Nagendran et al. 2006). This helps in calculating the rates of leakage in the liners, with only acceptable rates of leakage being allowed. Even a little travel of the leachates is influenced by the material used in the liners, known conductivity of the liners (Thiruvenkatachari et al. 2008).

### 2.2.2 Liner Classification

Liners are designed and constructed locally, using easily available materials. For the most part, this means locally available clay rich soils. Other materials can include bentonite enriched soils which are found with low clay content, stretchy artificial membranes, and geosynthetic clay liners comprising of bentonite clay held between geosynthetic membranes (Rio et al. 2009).

During construction, two main methods are used; one is keeping the materials separate, and the other is using them together in the form a double layered barrier. If hazardous conditions are present in the site, then the construction of a multilayer of barriers should be considered (Ayub & Khan 2011). This shows that there are certain types of liners, and each of them has a specific use (Rio et al. 2009). Some of the types of liners, and the areas where their construction is emphasized, are given below.

#### 2.2.2.1 Single Liners

Single liners are the simplest type of liner system, constructed with basic materials and techniques, usually with low permeability. Due to their simplicity, they are not that effective at fulfilling the needs of present day landfill sites. Therefore, modern pits tend to emphasis the implementation of newer and more efficient liner technology (Rio et al. 2009). Despite this, single liners sites are already being constructed in Kuwait, with some already operational. This is a problem because in most cases if any one of the single liners fails then the soil becomes contaminated.

#### 2.2.2.2 Composite Liners

Composite liners are constructed with a geomembrane placed on the top of the compacted clay liner, and are more widely used worldwide. This liner is used the most due to the protection it offers, provided by the separate components. The geomembrane decreases the conductivity of the liner, as well as increasing the required leakage rate. The composite clay in this liner provides protection in case of liner failure by decreasing the advection and diffusion rates, which increases the breakthrough time of contaminants.

#### 2.2.2.3 Double and Multi Systems

Unlike single and composite liner systems which only have a single geomembrane, barrier systems, known as double- or multi-barrier, have two geomembranes, which are often set within the drainage medium around them. This is the most effective system as it has a backup plan for all possible malfunctions. In the case of a failure in the upper most layer of the liner, the drainage system would immediately detect the leakage and the leachate would pass into a collection system, protecting the groundwater. Multi barriers systems are often considered for use when large amounts of solid waste must be kept isolated from the environment. This is the most complex barrier as it has number of single and composite layers constructed within it (Ayub & Khan 2011).

#### 2.2.2.4 Compacted Clay Liners (CCL)

If natural clay is found in the area of the landfill its low permeability can be utilized as a barrier to prevent the migration of contaminants and protect the groundwater. Using these clay layers by themselves is not recommended, especially if uncompacted, as it is often not possible to prove there aren't any hydraulic imperfections (Rio et al. 2009). Therefore, Compacted Clay Liners are used in combination with additional mineral layers and gemombranes to form an effective protective layer. The compacted mineral layers should have a minimum thickness of 1m and a hydraulic conductivity of less than $10^{-9}$m/s. The natural clay should also be mixed with bentonite, and through the process of compaction any voids or defects in the clay will be reduced (Naik 2008).

The construction process involves lifts or layers of clay being compacted on top of each other. Adjacent lifts should be bonded well to prevent areas of high conductivity existing between layers (Nagendran et al. 2006). If layers are offset and bonded well, any vertical defects or discontinuities in adjacent lifts will be hydraulically disconnected. Compacted Clay Liner systems are prone to cracking under differential settlement, and are vulnerable to desiccation in dry regions, which increases the permeability of the liner (Daniel 1993).

#### 2.2.2.5 Bentonite Enriched Soils (BES)

Bentonite is often mixed with local soils to improve the hydraulic properties and achieve conductivity values of $10^{-10}$ m/s. Bentonite is a useful material in that it naturally swells, sealing small cracks and preventing leakage. In this way it acts as a kind of self-healing material (Nagendran et al. 2006).

#### 2.2.2.6 Flexible Membrane Liners (FML)

Flexible Membrane Liners are geomembrane liners that are flexible enough to be joined or welded together in large sections, folded, transported and unfolded on-site. They are constructed of numerous pieces, with the seams being carefully tested for faults (Rio et al. 2009). These tests include overall hydraulic conductivity which is recorded to be around $10^{-12}$ m/s. FML is usually made of High Density Polyethylene (HDPE) or Low Density Polyethylene (LDPE). Of the two, HDPE is usually preferred as it provides better chemical resistance then the LDPE and importantly makes site construction much easier. In some cases HDPE has a risk of cracking when settling with a low angle of friction occurs, noted to be typically 8°. LDPE on the other hand is more flexible and has an improved angle of friction, but has lower resistance compared to HDPE. Unfortunately, damage to the geomembrane due to the cracking is difficult to repair, and makes using them a risk (Rio et al. 2009).

#### 2.2.2.7 Geosynthetic Clay Liners (GCL)

Low conductivity clays such as Bentonite are commonly used in the Geosynthetic Clay Liners (GCL). Layers of Bentonite clay are placed between layers of geotextile and geomembrane. The GCL system is used for its effectiveness at protecting groundwater, but also its ease of transport and installation. (Rio et al. 2009). GCL systems are self-sufficient, utilizing the clay's natural ability to swell and seal any gaps between sheets, when the ground is hydrated. Any perforations in the geomembrane are also sealed by the bentonite, greatly reducing the migration of leachate that would otherwise occur. These properties give GCL systems an effective conductivity value of $10^{-11}$m/s (Daniel 1993).

## 2.3 Landfill Leachate

### 2.3.1 Landfill Leachate Generation

Leachate is created by liquid percolating through waste, with the chemical composition of the waste and the biochemical processes within it playing a role. As the liquid migrates through the waste, it encounters pathogenic micro-organisms and extracts solutes and suspended solids from the waste, thus becoming contaminated (Christensen 2001). Increased levels of leachate occur with increased precipitation, such as during the wetter seasons (Chiang 1995). The level of contamination in the Leachate is influenced by the type of waste it moves through, and the level of biodegradation of the waste. Leachate from biodegradable waste may hold a significant quantity of natural substances, including alkali nitrogen and chlorinated natural and inorganic salts. All these substances are poisonous to a number of organic entities, particularly to sea life, and can result in harm to human health (Renou 2008).

Atmospheric conditions such as rain and snow greatly impacts leachate creation (Frost 1977). Within the landfill site itself surface spillover can affect leachate quantity, as can groundwater penetration if the site is constructed below the water table. Besides precipitation and atmospheric conditions, the water content and level of compaction can affect leachate creation. Less compaction can give rise to more leachate due to the reduced penetration rate (Deng 2006).

As water travels through the waste, it collects contaminants in a few different ways. Contaminants could be absorbed into the water by disintegration or suspension (Lin 2000). As natural materials in the waste disintegrate and decompose due to biotic activity, metabolic intermediates and by-products can be absorbed. Moreover, Li (1999) noticed that these by-products can lead to metals being dissolved due to the lowered pH (Li 1999).

### 2.3.2 Landfill leachate composition

The composition of leachate is dependent on the location and conditions of the landfill, including the type of waste stored and how old the landfill is. Therefore, while generalizations can be made about normal waste and leachate, each leachate should be considered as distinct.

Recent studies have indicated that landfill leachate holds a higher toxin load than crude sewerage. Christensen et al. (2001) created a rundown of the bio-geochemistry of Leachate plumes produced by city, business and industrial waste masses (Chiang 1995). A good understanding of leachate is required understand the nature of leachate plumes.

Al-Salem (2009) reported there are four groups of pollutants likely to be found in landfill leachate;

1) Dissolved organic matter including methane, measured by COD and TOC

2) Heavy metals

3) Particular organic compounds

4) Inorganic compounds

The natural substances found in Leachate are measured through analysis of parameters such as COD, BOD and TOC. The dissolved natural carbon and inorganic constituents are generally calcium, magnesium, sodium, potassium, alkali, iron, manganese, chloride, sulfate, and bicarbonate (Christensen 1994).

The extent of these constituents varies profoundly between one landfill to another, with average sulfate fixations running from 8 to 7750Mg/l, iron from 3 to 5500Mg/l, chloride from 150 to 4500 Mg/l and arsenic from 0.01 to 1Mg/l (Christensen 1994).

### 2.3.3 Landfill Leachate Migration

Leachate migration is also influenced by the way in which waste is stored. Compacted waste has reduced permeability, but the layering of waste and topsoil in the site can create stream ways through which leachate can flow (Reinhard 1984).

It was discovered by Christensen (2001) the length of time that rainwater can remain in a landfill site varies from a couple of days to a few years. This is reflected in the transitory nature of Leachate "springs", which can show up in wet seasons but vanish in dry seasons, leaving stained soil. Because of this, assessments of leachate generation must focus periods towards the end of wet seasons or after high periods of precipitation.

Transport of contaminated leachate through the landfill to the groundwater and surface water happens through two main methods: advection and hydrodynamic dispersion. Advection is the mass of dissolved contaminant that is transported with the flow of groundwater (Frost 1977). Thus, understanding of the groundwater stream directs the advection, whose rate and bearing relies upon subsurface topography, geography, extraction wells, porosity and pressure driven conductivity. Darcy's law can describe the average linear speed of advection migration: the advective transport (Darcy's drainage speed) and mass flux are described by a 3-D stream by expecting the solute to moves with the normal and adventive stream (Christensen 1994).

Dispersion is the flow of Leachate created by the mixing of liquids and the variability in the substance and physical properties of the environment (Christensen 1994). Hydrodynamic dispersion is the procedure of mechanical mixing and atomic dispersion which is impacted by physical parameters, e.g hydraulic conductivity and porosity, that describe the penetrability of the medium and therefor impact the speed of the solute (Li 1999).

One of the fate mechanism that causes hindrance on account of sorption, or increased contaminant transport on account of desorption in groundwater streams, is sorption (assimilation/adsorption or desorption) of contaminants onto or out of solid particles, e.g residue (Reinhard 1984). In water treatment frameworks, contaminants may not be caught due to sorption. The rate at which this occurs needs to be ascertained in order to assess the effectiveness of the treatment and the real mass of contaminant present (Lin 2000).

Sorption may happen through particle trade; however, natural contaminants are not adsorbed by particle trade, but rather by Van der Waals force and hydrophobic holding (Deng 2006). Sorption may be shown as being in equilibrium utilizing a balance isotherm model, or a dynamic sorption model may be required if equilibrium is not reached (Christensen 2001). However , J.Conroy (1993) observed that the metals may be bound to solids through cation exchange, complex reactions, precipitation, or sorption. Retardation of metals will be essentially influenced by pH, as this parameter controls the structure in which the metals will exist (Lopez 2004).

### 2.3.4 Treatment of Leachate

Currently, the most widely used method of Leachate treatment is re-infusion and release into a municipal water treatment facility (Christensen 1994). This method is effective in that it increases the rate of leachate deterioration and creates landfill gas (Christensen 1994). This decreases the overall volume of leachate, but unfortunately also condenses the contaminants inside the fluid (Lopez 2004). The landfill gas created presents an opportunity though, as its primary constituents are methane and carbon dioxide, meaning it can be used as a fuel asset (Renou 2008).

Leachate is also released into to local watercourses, but due to restrictions placed on the chemical composition of the leachate released this way, it must be pretreated first (Li 1999). Leachate can be dealt with on-site or transported to specialist treatment facilities (Christensen 1994). Treatment normally involves using activated sludge to break up the organic substances, but in many cases is still not environmentally safe at this stage so is transported to neighborhood sewers (Christensen 1994).

To effectively address the issue of leachate treatment, it is important to also deal with old and neglected landfill sites that were constructed before proper regulations were put in place, and therefor lack an impermeable covering (Deng 2006). These old sites can have a large impact on the soil as they can contain a variety of manufactured and natural types of matter, whose deterioration creates considerable contamination (Lopez 2004).

The organic methods of deterioration can take up to 40 years after the site is closed, giving rise to exceedingly contaminated leachate due to the permeation of precipitation (Christensen 2001).

## 2.4 Impact of Underdesigned Landfills on Surrounding Soils

In this section, firstly the stress state of a soil is reviewed followed by the problems associated with underdesigned landfills.

### 2.4.1 Introduction

Generally, unsaturated soil is a combination of three main components; soil particles, air and water. The unsaturated soil is strongly inclined by the state of the stress in the pore – water pressure (Richards 1974).

The pore water pressure is negative and a change of pore – water pressure generates a change in the volume and strength of the soil. The negative pore – water pressure is called "total soil suction" in geotechnical engineering. The total suction is consisting of matric suction and osmotic suction.

The matric suction is defined as the difference between the pore air pressure ($u_a$) and pore water pressure ($u_w$) (Estabragh and Javadi 2012). The matric suction ($u_a$ - $u_w$) is related and controlled by a capillary effect and adsorption of water (Richards 1974). The individual capillaries can be defined as the pores between soil particles with an equivalent radius and a meniscus. In the large pores air first replaces some of the water, which forces the water to flow through the smaller pores with increased porosity to flow path. Figure 2.6 illustrated the effect of matric suction in the unsaturated soil particles.

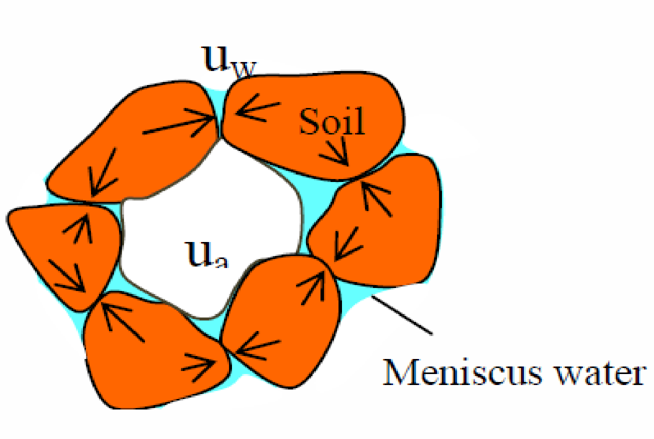


**Figure 2.6: The effect of matric suction in the unsaturated soil (Toan et al. 2012)**

The osmotic suction (π) is defined as the presence of solutes in the soil solution. The solutes could be inorganics salts or organics compounds.

The clay surface charge is negative due to isomorphous substitutions of electropositive elements (Lagaly and Koster 1993). A force exists between the negative charge at clay surface and the exchangeable cations. This force depends on the position of the charge and the valence of the exchangeable cations (Hasenpatt 1988).

Normally the solutions have different ionic concentration that contact with clay particles, with the cations near the surface of the clay particles trying to diffuse away to preserve electrical neutrality. This process leads to decreases of cation concentration on the surface the clay minerals. This produces an electrostatic surface property known as Diffuse Double Layer (DDL) Figure 2.7 shows the mechanism of attraction and concentration of these cations and the counter-ionic in the pore of water.

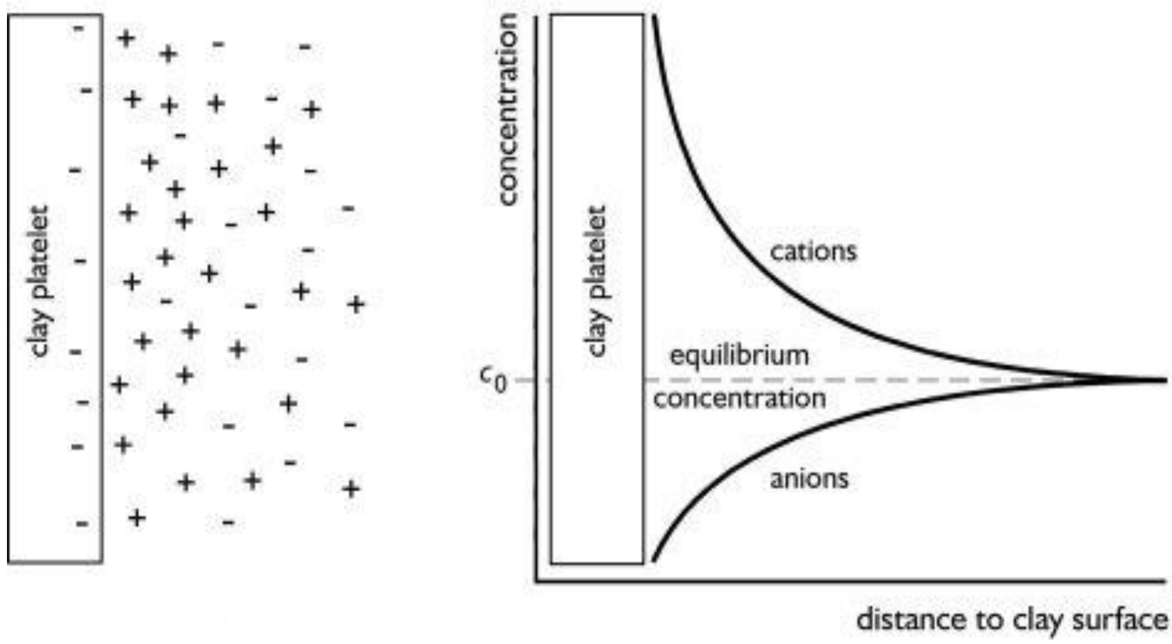


**Figure 2.7 Distribution of cations and anions adjacent to a clay platelet (Keijzer 2000)**

### 2.4.2 Soil Contamination

Soil contamination is a result of either solid or liquid hazardous substances mixing with the naturally occurring soil (Ismail et al. 2008). Leachate contamination may lead to significant effects on the behaviour of soils due to chemical reactions between the soil mineral particles and the contaminant (Sunil et al. 2009).

Leachate contaminated soils in Kuwait are a result of a lack of awareness of environmental standards of selection, design, and management at the landfill sites. These sites are often selected at lower ground locations that have previously been used as sand and gravel quarries, due to the leveling of the ground and the normal soil surface. There sites are not carefully selected using geological or environmental surveys, and the random land filling technique is often used without application of waste separation techniques. The main disposal system commonly used in the state of Kuwait is land filling (Al-Fares et al. 2009).

Al-Humoud (2001) revealed that household wastes make up 50% of the municipal solid waste from the various residential districts in the Kuwait, followed by paper at 20.6%, then plastic at 12.6%, and others components such as metals, glass, and textiles at 16%. The Kuwait municipality (2009) reported that the municipal solid waste reached 552,991 tons per year.

Similarly, the report by Koushki (2004) revealed that 50% of the municipal solid waste from the various residential districts in the Kuwait is the household wastes than 21% paper, 13% plastic, 6% glass, and 10% metal respectively.

Al-Yaqout and Hamoda (2003) studied the chemical characteristics of the Al-Qurain landfill leachate. The results showed high organic matter and heavy metal concentrations such as TDS at about 9900Mg/l, COD at 8000Mg/l, Mg around 268Mg/l, Cu at 122Mg/l, and Zn at 4.8Mg/l. Similarly, Al-Muzaini (2006) reported that the leachate of Al-Qurain landfill site produced high amount of hazardous and harmful contaminated leachate with pH value reaching 9.4.

### 2.4.2.1 Consistency Limits

Attom and Al-Sharif (1998) attributed the reduction in the plasticity index (PI) of clayey and silty sands to the addition of non-plastic material to the soil, with the non-plastic material reducing the plasticity index of the new mixture. The increase in liquid limit (LL) and plastic limit (PL) of contaminated clayey soils are mainly attributed to the increase in the double layer thickness of clay minerals (Shah et al. 2003). In general, contaminants may alter the mechanics of the consistency limits test when used for contaminated soils. The consistency limit tests were originally developed for natural soil-water systems (Meegoda and Ratnaweera 1994).

Similarly, Sunil et al. (2009) reported that leachate-contaminated soil samples showed an increase in the liquid limit and plasticity index values due to a change in nature of the pore fluid, which is shown by an increase in the clay content of the specific surface area of the soil which leads to high adsorption of water that changes the limit values.

#### 2.4.2.2 Compaction Characteristics

In a study conducted by Sunil et al. (2008) on contaminated lithomargic clay soil with leachate, the maximum dry unit weight ($\gamma_{d,\ max}$) decreased from an initial value of 15.89kN/m$^3$ to 14.03kN/m$^3$ and the optimum moisture content increased to 24.8% from an initial value of 20.1% when the soil was mixed with 20% of leachate by weight.

Similarly, Nayak et al. (2007) noticed that the maximum dry density for lateritic soil is 15.47kN/m$^3$ at an optimum moisture content of 19.52%. With the presence of leachate up to 5%, the compaction characteristics did not change much. With 10% leachate the maximum dry unit weight and optimum moisture content were 14.98kN/m$^3$ and 25.01%. However, with a further increase of leachate content up to 20% the compaction curve had an odd shape with inferior characteristics.

A recent study carried out by Al-Fares (2011) on contaminated silty soil with leachate shows a sudden drop of 0.4% in maximum dry unit weight when soil was mixed with leachate by weight at 15% and increased in optimum moisture content by 22%.

#### 2.4.2.3 Strength Characteristics

Shear strength of a soil mass is the internal resistance per unit area that the soil mass can offer to resist failure and sliding along any plane inside Das (1985). In soils generally the relationship between stress and strain is non-linear, and volume changes develop from the applied normal and shear stresses. The most commonly used strength theory is Mohr – Coulomb failure criteria, which state that considered that a material fails because of a critical combination of normal stress ($\sigma$) and shearing stress ($\tau_f$). Thus, the functional relationship can be expressed as:

$$\tau_f = c + \sigma \tan \phi \qquad \text{(Eq. 2.1)}$$

The $\tau_f = f(\sigma)$ in Eq. 2.1 according to Coulomb, shear strength $\tau_f$, is expressed in terms of cohesion (c) and angle of friction ($\phi$) on linear function.

Cohesion is defined as the bonding force between the fine-grained particles of a soil, and is stress-independent. Due to the comparatively large components in waste, cohesion is mostly interpreted as the interlocking of components in waste mechanics. Additionally, it is often defined as apparent cohesion, which is caused by capillary forces. The friction angle is related to the friction between the particles and is stress-dependent.

Sunil et al. (2009) carried out triaxial tests on clean lateritic soil, which was mixed with leachate at increments of 5%, 10% and 20% by weight of soil. They found a slight increase in cohesion and a decrease in friction angle as a result of leachate contamination for specimens tested. The increase in clay content of lateritic soil after interaction with the leachate increased the cohesion and decreased the friction angle.

In an investigation of the effect landfill leachate has on natural soil in Kuwait, Al-Fares (2011) carried out direct shear tests on natural soil mixed with leachate and reported that the shear strength parameters were dependent on the contaminated leachate content in the uncontaminated soil. Their study showed an increase of cohesion from 10kPa to 17kPa for uncontaminated soil, due to increases of leachate concentration up to 5% by weight of dry soil with no significant change in the angle of friction. However, when the concentration of leachate increased up to 15% by weight of dry soil the cohesion decreased to closely reach the cohesion of the clean soil with no noticeable change in the angle of friction. Furthermore, the cohesion increased from 10 kPa to 22 kPa and the angle of friction slightly decreased from 35 degree to 34 degree due to 20% leachate addition. However, Al-Fares (2011) attributed these changes to the increase in fine content of the soil as a result of soil – leachate interaction.

Reddy et al. (2009) carried out direct shear tests on landfill MSW samples in the USA. The samples had in-situ moisture content of 44% as well as being mixed with leachate at increments of 60%, 80% and 100% by weight of soil. They observed that the cohesion of landfilled MSW varied from 12–63kPa and the drained friction angle ranged from 31–35°. However they concluded that there is no specific increase or decrease for the range of moisture content tested. Alsothey concluded that there wasno specific correlation between shear strength and moisture content in the tested landfill MSW samples.

#### 2.4.2.4 Compressibility Characteristics

Compressibility of soil is defined as an increase of stress caused by construction of foundation or other loads compresses soil layers (Das 1985). The compression is sometimes caused by (a) deformation of soil particles. (b) Relocations of soil particles, and (c) expulsion of water or air from the void space. In general, the soil settlement is caused by loads and may be divided into three broad categories:

1. Immediate settlement (or elastics settlement) which is caused by the elastic deformation of dry soil and of moist and saturated soils without any change in the moisture content.

2. Primary consolidation settlement which is the result of a volume change in saturated cohesive soils because of the expulsion of the water that occupies the void spaces.

3. Secondary consolidation settlement which is observed in saturated cohesive soils and is the result of the plastic adjustment of soil fabrics. It is an additional to compression that occurs at constant effective stress.

Hoeks (1983) showed the importance of the settlement of soil contaminated with leachate within the landfill because it might be a cause of a number of problems to a closed landfill sites like excessive differential settlement resulting in breakage of gas or leachate extraction pipes, which may then result in a dangerous build-up of lowland gas or cause saturation of the waste mass.

Ojuri et al. (2012) studied the effect of high concentrations of heavy metals in the landfill leachate on the behavior of clayey soil in Nigeria. Five specimens of clay soil mixed with nitrate solution were tested in an oedometer apparatus for consolidation test with various concentrations (0, 30, 60, 120 and 200 Mg/l) under constant pressure. The compression index and swelling index ($C_c$ and $C_s$) decreased with an increase in degree of nitrate contamination (0.46 and 0.0063, 0.43 and 0.0060, 0.36 and 0.053, 0.28 and 0.041, and 0.24 and 0.037 for concentration of 0, 30, 60, 120 and 200 Mg/l respectively). The coefficient of consolidation "$C_v$" increased with an increasing degree of nitrate contamination (6.4, 8.12, 12.62, 15.914, and 18.86 $cm^2$/sec respectively). This implies that the soil compressed and rate of settlement are affected. These properties directly influence the performance of shallow structural foundations.

Similarly Resmiet et al. (2011) focused in their study about the major contaminated element in leachates caused from landfill sites and carried out the consolidation tests on uncontaminated clayey soil with artificially fed lead nitrate. The soil samples soaked in various lead solutions concentration (200, 500, 1000, and 2000 ppm) were kept in containers and left for adsorption to take place, with occasional stirring. The results showed the values of the coefficient of consolidation $C_v$ increased with increasing sorbed concentration of lead.

### 2.4.2.5 Permeability Characteristics

Das (1985) explained the soil permeability as the ability of the soil to allow water/liquid to flow through soil pores or voids.. The permeability can be used to classify the soil profile, high permeability is seen in loose soil and low permeability is seen in dense soil. The permeability of soil is one of the most important soil properties to geotechnical engineers, due to the factors stated below:

1. Permeability influences the rate of settlement of a saturated soil under load.
2. The stability of slopes and retaining structures can be often depending on the permeability of the soils concerned.
3. Filters made of soils are designed based up on their permeability.

Nayak et al. (2007) reported that changes in soil structure occur after contamination with leachate, with the void ratio of soil increasing when the pore water is replaced by leachate, as pore fluid and the hydraulic conductivity raise as a result of dissolution of clay minerals by the leachate.

They studied the behaviour of interaction between uncontaminated lateritic soil mixed with leachate in the amount of 5%, 10% and 20% by weight. The results showed an increase in the permeability of soil that was mixed with 20% contaminated leachate to 50% mixture, which ranged from $2.69 \times 10^{-5}$ cm/s to $5.66 \times 10^{-5}$ cm/s.

Similarly, Sunil et al. (2008) observed that when 5% of contaminated leachate concentration was mixed with lithomargic clay by weight, the hydraulic conductivity increased to $1.7x10^{-6}$cm/sec (6.25% increase compared with base value). At 10% leachate concentration the hydraulic conductivity of the soil tested increased to $2.3x10^{-6}$cm/sec (43.75% increase compared with base value). Similarly when the soil was mixed with 20% leachate the increase in hydraulic conductivity was about 75% when compared with the base value.

A recent experimental study carried out by Al-Fares (2011) on hydraulic conductivity of leachate contaminated soil show that the permeability of natural silty sand that is mixed with contaminated landfill leachate in different percentages by dry weight, increased as the leachate concentration increased from $5.32x10^{-7}$ cm/sec to $1.32x10^{-6}$cm/sec as the leachate concentration increased from 0% leachate to 20% leachate.

Similarly Resmiet et al. (2011), noticed the increase of hydraulic conductivity of clayey soil soaked in various lead solutions concentration (200, 500, 1000, and 2000) ppm as increase of lead concentration (0.23, 0.28, 0.33, and 0.4) $x10^{-7}$cm/s respectively.

In most of the studies presented during this literature review, the pH scale value of lowland leachate was over 7.8 or 6; but several suggested that the powerfully acidic and powerfully basic liquids will dissolve clay minerals and cause the destruction of soil structure. Moreover, Naidu (1994) noticed that the rise of the pH scale value within the soil may influence the corrosion of reinforcement.

#### 2.4.2.6 Retention Mechanism in Contaminated Soils

Retention reactions in soils are important processes that govern the fate of chemical contaminants such as heavy metals in groundwater (Kulikowska 2008). Substantial metal particles may have lethal impacts on plants, creatures or people, and their poisonous quality is connected to their mobility in soil. Heavy metal mobility relies on the properties of the soil (Trebouet 2001), and the danger of these metals increases with increased mobility.

One critical procedure influencing substantial metal versatility in soil is sorption. Sorption is the phenomenon in which metal particles, which normally bear a positive charge, are pulled in to robust particles in the soil and natural matter which bear a negative charge (Kurniawan 2006). This coupling is frequently reversible, and metals bound to the solids are in balance with metals in the soil water. This implies that strongly held metal particles are expelled from the soil water and get less versatile than weakly held particles (Lyngkilde 1992).

It has long been felt that "heavy" soils, that is, high mud substance soils, have a tendency to immobilize heavy metals. Because of this, waste disposal organisations feel safe when disposing of their waste into clayey soils, providing they are managed by an environment body (Bolong 2009).

Harter (1983) and McBride (1979) reported that the retention of metals does not increase until the pH is greater than seven. This effect is in part because of particular adsorption of the hydrolyzed metal compared to the free metal particle. It was likewise indicated that the extent of hydrolyzed metals builds with pH. For instance, hydrolysis of Cu happens at pH 6, Cd at pH 8, Zn at pH 5.5. The other impact of pH is on adsorption locales, which are pH subordinate. As the pH decreases, the amount of negative locales diminishes. In addition, as the pH gets more acidic, metal cations need compete for the negatively charged locales.

An initial estimation of the adsorbents conduct is possible by a visual comparison of the breakthrough curves. The breakthrough curves allow the discovering data including time required to achieve most extreme adsorption, materials service time, the time it could be utilized before substitution, and character of the breakthrough; fast or smooth. It can be noticed that all materials adsorb different metals with similar patterns (Kalmykova 2004).

Kurniawan (2006) noticed that the concentrated on the sorption limit of copper, chromium, lead, and cadmium through cluster balance investigates five types of soils (sand and sediment, sandy) from Estonia. Two grams of the air-dried sample was added to each test tube along with 10 mL of the parent metal solution, after 16hrs of shaking at room temperature (21°C), the samples were separated by centrifugation and analyzed. The results showed that the content of quartz and carbonates influence of sorption capacity of soil, especially the cadmium and lead increased attraction towards soils, as the content of carbonates and Manganese containing components increased.

Du and Hayashi (2005) studied the potential sorption of heavy metals (Cd and Pb) on Ariake clay. The results of the adsorption isotherm or equilibrium concentration and sorbed concentration showed that with an increase in the solid - solution ratio, the amount of sorbed Cd decreased and the equilibrium concentrations of $Pb^{2+}$ in the batch tests were found to be almost zero, indirectly indicating that the Ariake clay has higher retention ability for Pb than Cd.

Hatton and Pickering (1980) discovered that the quatity of metal ions sorbed by the solids increased with increasing pH over the range 3 to 6 and with mixtures of clay-cellulose or illite-humic acid. However, a reduction in adsorption of copper and zinc ions occurs when the samples were mixed with Na+ to form kaolinite or montmorillonite.

Yong et al. (2001) reported that heavy metal concentration in the effluent of leachate obtained from column test with four different types of soil from different location around South Wales to the influent concentration of Pb, Cu, and Zn with no breakthrough for the four soils. Furthermore, the permeability becomes constant or increases slightly with increasing of the pore volume. They also reported that the pH values of the effluent for the soils between the range 7.5 and 9.5 that indicate all heavy metals were precipitated in the soil column.

Yong et al. (2001) examined the retention of the heavy metals (Pb, Cu, and Zn) in the three soil types from South Wales. The leaching experiments were conducted under constant air pressure of 10kPa. The column test was first saturated with distilled water for 2 pore volumes and then saturated with leachate obtained from MSW landfill up to 5 pore volumes. The discharge leachate was then collected and analyzed. The results showed that the retention of heavy metals in the three soils was very high, with only a small breakthrough detected in the effluent following the 5 pore volume of leaching with the test leachate.

Similarly, Zuhairi et al. (2008) conducted a study based on a previous leaching column test suggested by Yong (2001) and Zuhairi (2000), which measured the retention of heavy metals (Pb, Cu, Ni, and Zn) on three types of natural soils from Selangor area in Malaysia. The breakthrough curves observed that the relative concentration of the heavy metals increased with the increasing number of pore volumes, Ni and Zn were the most mobile heavy metals and sorption of heavy metals was high.

Tan et al. (2006) noticed that the breakthrough curve can be defined as desorption or mobility curve. The very acidic leachate showed good interaction with the natural pH soil especially at the top part of the column test reported by Yong et al. (2001).

### 2.4.3 Groundwater Contaminations

The groundwater system is most at risk in areas that have a shallow water table and high precipitation. Traditionally, several sites were designed on the principle of 'dilute and disperse', where leachate was able to drain into nearby groundwater systems. While most of the analysis into leachate plumes concentrates on these older sites and people in sensitive areas, containment sites also show proof of leachate contamination of the groundwater with leachate plumes (Deutsch 1997).

Any receptors or groundwater abstraction points near the location need protection from the potential pollution, and the water samples taken from the wells make sure any changes in material concentration can be monitored. Leachate plumes may additionally be detected because of an increase in groundwater temperature directly down gradient of the location as the degradation process releases energy (MacFarlane et al. 1983).

Most contamination plumes are small and do not exceed the dimension of the landfills, indicating temperature change as the primary mode of mass transport. The natural attenuation capability of the encompassing sediment could limit the impact of the plume to an area of 1000m or less (Johnson et al. 1999).

## 2.5 Concluding Remarks

Kuwait maintains a sustainable rate of solid waste production and thus it is time to manage and maintain a proper framework to control and avoid the rising contamination of waste in surrounding soils and the groundwater (Alhumoud & Al-Kandari 2008). From a detailed review of the literature, it can be concluded that with the exception of pH, the different concentration values of solutes may significantly influence the environment. Therefore, it is important to introduce novel engineering techniques for studying the behaviour of solid waste that in turn are relevant to the private sector industries, which anticipate efficient recycling of wastes. This will assist the municipality, as it will reduce the amount of waste collected and would be essential in reducing the environmental impacts that are gradually increasing over time. This recycled materials can be extensively used for industrial purposes and for improvements in soil, as well as an energy source (Alhumoud & Al-Kandari 2008).

This review also explored the relevant data and information on the principles of landfill construction, the types of leachate and landfill liner. It also reviewed the fundamental effects on the environment, including factors affecting it. The importance of waste disposal systems is also critically analyzed, reflecting the urgent needs for reforms by the municipal corporation of Kuwait. In order to tackle the growing problem of solid wastes, systematic approaches on the local, national and regional levels should be explored and implemented, based on the prevailing conditions and priorities.

From the review of the literature, it was noted that most of the studies in the past were carried out to investigate the effects of the addition of landfill leachate on the strength and compressibility behaviour of natural soils. However, in reality the interaction between the natural soils and leachate occurs in different ways which will be investigated in this study by applying novel experimental techniques that are more representative of the in-situ conditions.

# Chapter 3

# MATERIALS AND METHODS

## 3.1 Introduction

This chapter describes the details of the laboratory experiments carried out. A wide-range of laboratory tests were carried out to investigate the effects of leachate contamination on the geotechnical and geoenvironmental properties of natural soils. Parameters measured in this chapter will be used to support the analysis of contaminated leachate behavior presented in later chapters.

A review of the literature indicated that, the main issue raised about Kuwait landfills is that in most cases unlined and uncontrolled landfills are used. Therefore, the leachate easily escapes into, and interacts with, the surrounding soils. To understand this phenomenon, it can be divided into 3 phases of interaction (Figure 3.1). The first phase is the leachate flow through the soil mass. Saturation of soils occur due to the leachate. Finally after the flow ceases and drainage has completed, there will be a gradual reduction of the moisture content of soils.

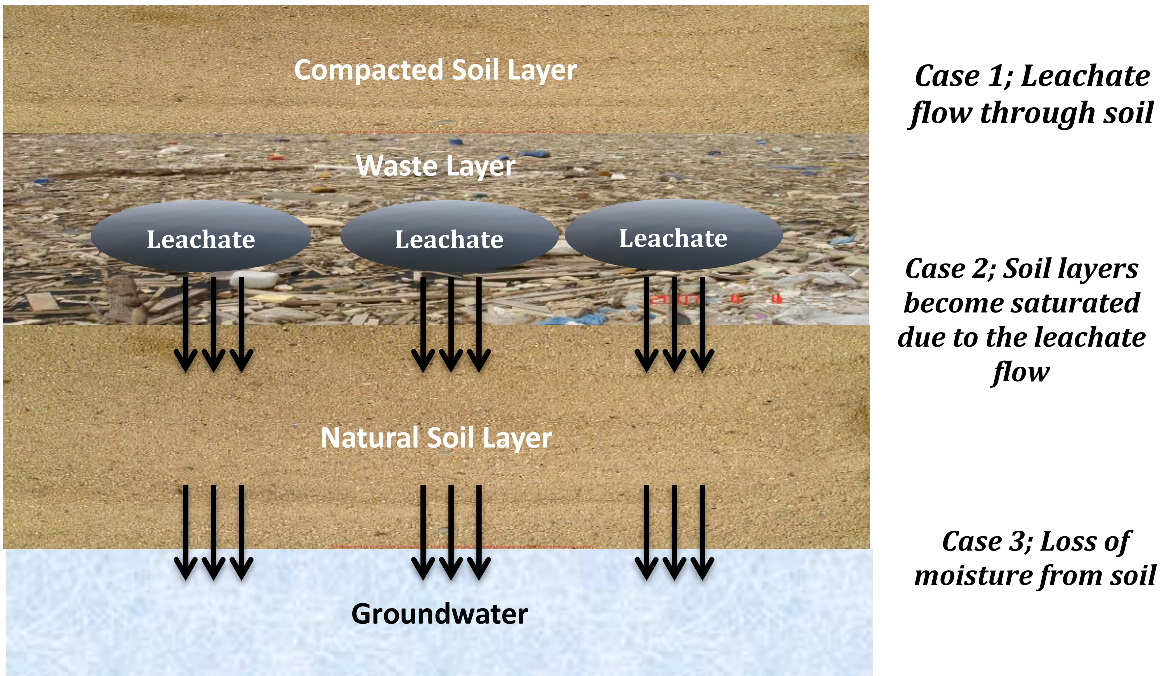


**Figure 3.1: Movement of leachate in the unlined and uncontrolled landfills**

To replicate the above phenomena in the laboratory, the chosen soils were treated with leachate using a number of different methods. Soil-leachate mixtures were tested leachate content of 0%, 10%, 20%, and 40% by weight of soils. This method is usually used to measure the positive or negative influence of the moisture. In the second method, soil specimens were inundated with leachate or water to simulate realistic interactions between different fluids and soil. The third method involved submerging specimens in the different fluids until chemical equilibrium was reached to simulate the long-term case when leachate has passed through the soil and the soil has returned to dry conditions.

To explore the influence of leachate on various relevant properties of soils as compared to that occur with water, both the leachate and a water control group were tested on two types of soil (a silty sand and a clayey sand).

Section 3.2 presents the procedures adopted to determine the basic properties of the soils. Section 3.3 presents the procedures adopted to determine the leachate properties. Section 3.4 describes the shear strength and compressibility tests on natural and contaminated soils, and tests involving interaction of soil with leachate and water. Section 3.5 details the procedure adopted to determine geoenvironmental properties.

## 3.2 Soil Properties

Soil samples for this study were collected from the Al-Jahra landfill site. The landfill site is situated about 4 km south-west of Kuwait city as shown in Figure 3.2. The strata of the Al-Jahra area are formed mainly by two types of soil; silty sand and clayey sand, samples of which were obtained from a previous investigation undertaken by a private company (Jeragh 2009, 2012). Since 1986, about two square kilometer of land area has been used as a waste disposal site in Al-Jahra. This landfill site primarily consists of a non-engineered deserted sand quarry.


**Figure 3.2: The map of Al-Jahra landfill site (U.S. Central Intelligence Agency 2006)**

The Al-Jahra site was decommissioned in April 2006. According to the Kuwait Municipality, (Personal Communication 2008), this landfill site was reactivated in August 2007 by the Kuwait Municipality. However, the waste that was dumped at this site was not disposed of in properly designed landfills. A need to assess the environmental impact of the Al-Jahra dumpsite then emerged in order to avoid the likely negative contaminant migration that is likely to affect the residents living in the areas close to the dumpsite.

The current research will play an important role as it will offer crucial details needed to help the decision-making process in the re-development aims of the site, which will ensure the safeguarding of groundwater resources, public well-being and the surrounding area in general.

The soil profile of the Al-Jahra site is presented in Figure 3.3. Four boreholes were excavated to understand the underlying soil type and formation. The first layer (top 5 to 6m) of soil was full of contaminated soil. The second layer was about 3m deep and was composed of very dense fine to medium clayey sand. The relative densities of the soil were defined by using the result of a 63.5kg hammer stroke falling through a distance of 0.76 cm over the depth (Jeragh 2009). The third layer was 2.0m deep and consisted of fine to medium silty and clayey sand. The fourth layer was comprised of approximately 3.0m of very dense clayey sand. The water table was about 18.5m below the ground surface.

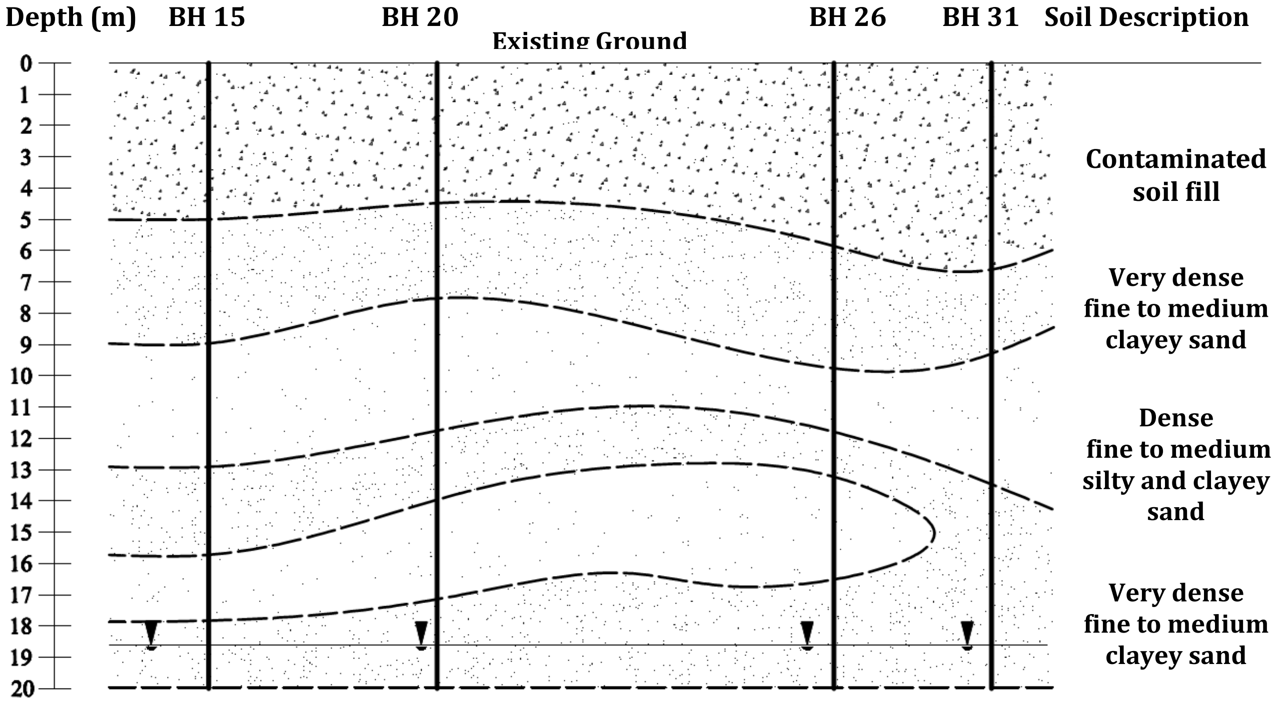


**Figure 3.3: Soil conditions at Al-Jahra site (Jeragh 2009)**

The soils used in the experiment were natural soils obtained from test pits of 0.5 to 3 m depth of the Al-Jahra landfill boundary. Al-Fares (2011) reported that the collected samples from the Al-Jahra landfill boundary were uncontaminated. The soils were classified at the civil engineering laboratories of Kuwait University following the ASTM standards described below.

### 3.2.1 Particle Size Distribution

To obtain the particle size distribution of the soil samples, the procedure suggested by ASTM D422 (2007a) was followed. The tests were carried out using 398.1g of washed silty sand and 758.7g of washed clayey sand. ASTM standard sieves of No 4, 10, 100, 200 were used.

### 3.2.2 Compaction

The maximum dry density and optimum moisture content of the soils were determined using the modified Proctor test (ASTM D1557 2012a). Soils were compacted into equal five layers (25 blows/layer) using a 2.5 kg hammer dropped from 304.5mm height at predetermined moisture contents. The variation of dry density against the moisture content was plotted for determining the compaction properties.

### 3.2.3 Atterberg Limits

The Atterberg limits refer to a set of index tests performed on soils to determine the relative activity of the soils and their relationship to moisture content (ASTM D4318 2010a). The liquid limit, is defined as the level of moisture content at which soil begins to behave as a liquid material and starts to flow. The liquid limit was determined using liquid limit apparatus of ASTM D4318 (2010a).

The plastic limit, which represents the degree to which puddled or reworked soil can be permanently deformed without rupturing, was carried out using the method of ASTM D4318 (2010a), where a thread of soil was rolled on a glass plate.

### 3.2.4 Field Density

The field density of the Al-Jahra soil was determined at the investigation site according to the sand–cone method of ASTM D1556 (2007b). The cone was filled with Ottawa sand, which is defined as uniform in density and grading, uncemented, durable, and free-flowing silica sand passed through No.20 U.S. sieve and retained on No.30 conformed by ASTM standard, and then weighed. The dry unit weigh of the soil in the field was determined in terms of $Mg/m^3$.

### 3.2.5 Natural Moisture Content

The water content of a given soil is defined as the ratio, expressed as a percentage, of the mass of dry soil and water content. In line with ASTM D2216 (2010b), the moisture content was determined as a percentage of the quotient of the mass of water and the dry mass of sample.

### 3.2.6 Specific Gravity

The specific gravity ($G_s$) of the soil was determined using the standard pycnometer method ASTM C128 (2012b). The specific gravity is defined as the ratio of the mass of a unit volume of a material to the mass density of distilled water at a stated temperature

### 3.2.7 Chemical Characterisation

The chemical characteristics of the Al-Jahra soil are described below in terms of the pH value and organic matter content.

#### 3.2.7.1 pH Value

The pH value of soil was determined using Electrometric method BS 1377 part 1 (1990). Three readings of pH were taken after stirring the suspension each time and recorded.

#### 3.2.7.2 Organic Matter

The organic matter content of the soil was determined using the method of BS 1377 (1990). The organic matter of the soil was determined as the percentage loss in soil mass when the soil was combusted in a muffle oven.

## 3.3 Leachate

The leachate used in the experiment was collected from the Al-Qurain landfill located about 15 km south-east of Kuwait city as shown in Figure 3. Al-Fares (2011) reported that due to the absence of a collection system of leachate in the Kuwait landfills, the Al-Qurain landfill is the only source of real leachate in Kuwait. The Al-Qurain landfill was closed in 1985 due to complaints from residents and the waste then placed in the Al-Jahra landfill, 7th ring road and Al-Sulaibiya landfills (Al-Muzaini 2006). The Kuwait environmental public authority initiated a project to rehabilitation the Al-Qurian landfill in 1999 by equipping the site with an active landfill gas ventilation system and plant for leachate collection and pre-treatment (Al-Ahamd et al. 2012).

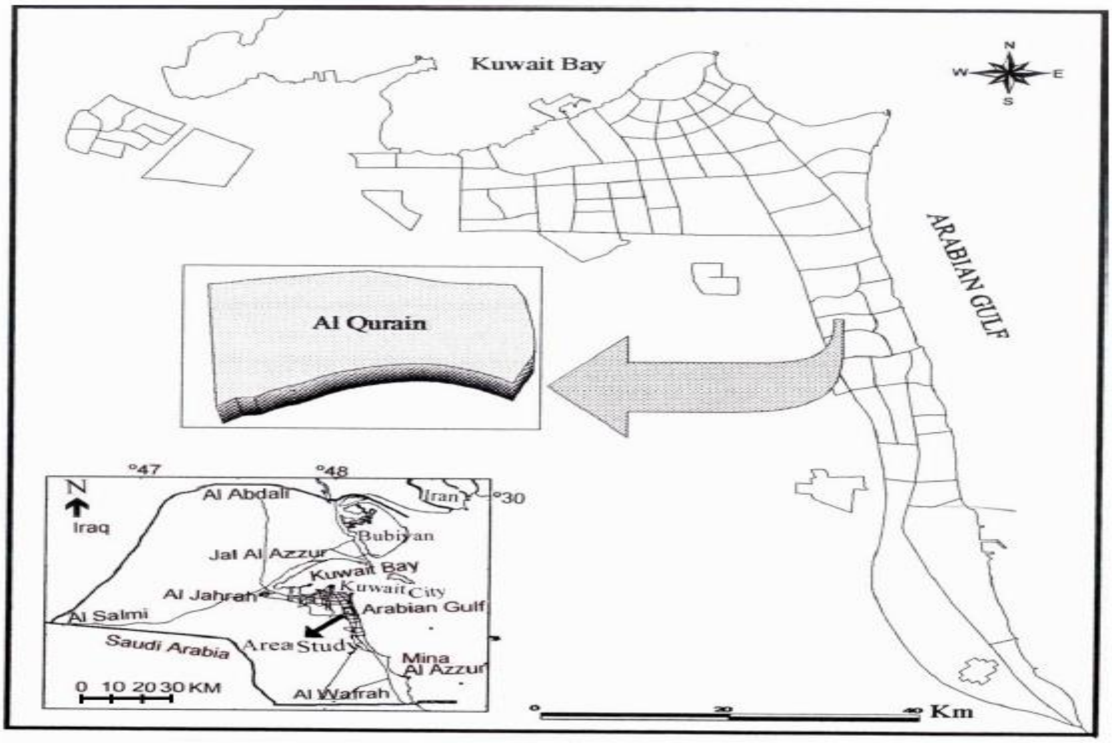


**Figure 3.4: Map of Al-Qurain landfill site (Al-Muzaini 2006)**

The Al-Jahra landfill is still running with two new landfills opened recently as other sites were closed. The leachate samples that will be used in this study have been collected from the pond facility of Al-Qurain landfill using clean glass bottles then tightly sealed and kept in an icebox. The samples were then transported to the laboratory and kept in the refrigerator at 4°C prior to using in the study.

### 3.3.1 Chemical Characterisation

The chemical properties of the leachate analyzed in this study are: pH, total dissolved solids (TDS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), total organic carbon (TOC), electrical conductivity (EC), chloride content ($Cl^-$), alkalinity content and heavy metals. The American Public Health Association (APHA) standard was followed for analysis of leachate samples in the Chemical

Engineering department laboratories (CED) at Kuwait University. The selections of the chemical tests were based as per CED recommendation. .

#### 3.3.1.1 pH Value

The pH value of leachate was determined using the Electrometric method following APHA 4500B (2005). The pH electrode was immersed in the sample beaker. The pH reading was recorded once the reading stabilized.

#### 3.3.1.2 Total Dissolved Solid

The dissolved solid (TDS) of contaminated leachate was measured following APHA 2540C (2005). The TDS was calculated in terms of Mg/l as the loss in leachate mass occurred when the leachate was dehydrated in a furnace at 180°C

#### 3.3.1.3 Chemical Oxygen Demand

The chemical oxygen demand (COD), defined as the amount of a specified oxidant that reacts with the sample under controlled conditions, was calculated using APHA 5220B (2005). The COD was determined in terms of Mg $O_2$/l when the color of titrated solution changed from blue-green to reddish brown.

#### 3.3.1.4 Biological Oxygen Demand

The biological oxygen demand (BOD) is used to determine the relative oxygen requirements of wastewaters, effluents and polluted waters that are useful in evaluating the BOD removal efficiency of such treatment systems. It measures the molecular oxygen utilized during a specified incubation period for the biochemical degradation of organic and inorganic material.

The BOD was measured following APHA 5210B (2005). The BOD was calculated in units of Mg/l after 5 days of incubation period at 20°C.

#### 3.3.1.5 Total Organic Carbon

The total organic carbon (TOC) was measured following APHA 5310B (2005). The sample was transferred to an auto sampler vial of the TOC analyzer apparatus called SHIMADZU.V and 20µl of the sample was injected in the apparatus. TOC concentration was read directly from the analyzer apparatus.

#### 3.3.1.6 Electrical Conductivity

The electrical conductivity (EC) is used to measure the ability of an aqueous solution to carry an electric current. The EC was determined using a conductivity cell containing a platinized electrode and following APHA 2510B (2005).

#### 3.3.1.7 Chloride Content

The chloride content ($Cl^-$) was measured using APHA 4500B (2005). The $Cl^-$ was determined in terms of Mg/l when the color of titrated solution changed to a pinkish yellow end point.

#### 3.3.1.8 Alkalinity Content

The alkalinity content was determined using APHA 2320B (2005). The total alkalinity was calculated as per Mg of $CaCO_3$/mL as the pH value of sample reached 4.5.

#### 3.3.1.9 Heavy Metals

The heavy metals content was determined by Inductively Coupled Plasma/Mass Spectrometry (ICP-MS) using method APHA 3125B (2005). The heavy metals were determined as per Mg/l in the ICP-MS after the leachate was refluxed and heated at 95°C.

## 3.4 Strength and Compressibility Behavior of Natural and Contaminated Soils

### 3.4.1 Introduction

The laboratory tests undertaken in this study can be categorised under five series of tests. Various tests that were carried out under each test series are shown in the form of a flow chart in Figure 3.5.

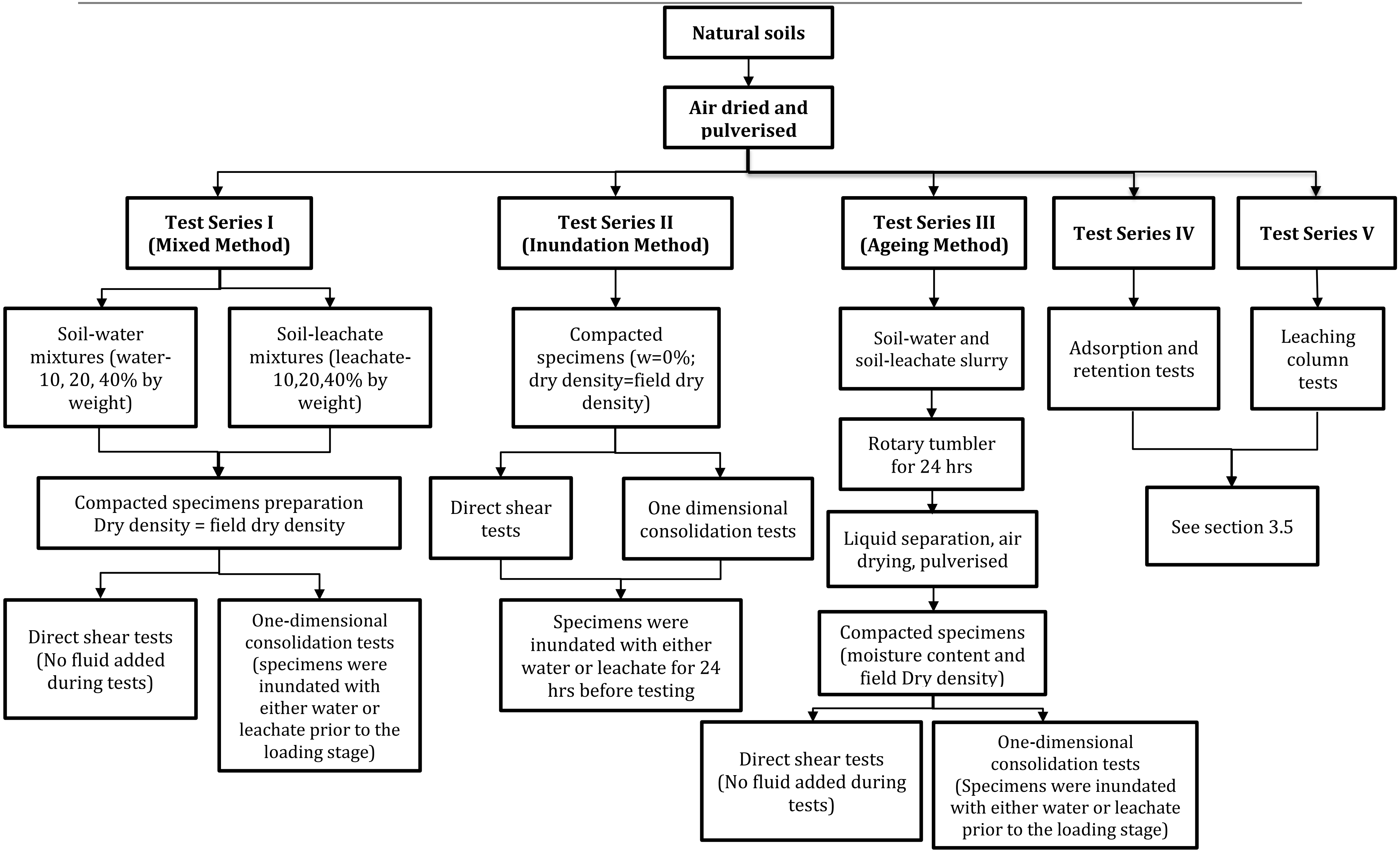


**Figure 3.5: Overview of the experimental program**

## 3.4.2 Specimen Preparation

### 3.4.2.1 Soil-Water and Soil-Contaminated Leachate Mixtures Preparation

Two soils were collected from the field (silty sand and clayey sand). The soils were first air dried and then pulverised to pass through 4.75 mm sieve following ASTM D421 (2007a). Prior to preparing soil specimens for the laboratory tests (direct shear and oedometer), predetermined percentages of either water or contaminated leachate were added to the air dried soils. The percentages of water or contaminated leachate considered were 10, 20, 30 and 40% (by dry mass of the soils).

### 3.4.2.2 Preparation of Inundation Specimens

The preparation was conducted for both soils, silty sand and clayey sand. The dried soils were remoulded to the field density in test apparatus. The specimens were then assembled in the apparatus. The specimens were then and inundated with leachate/water for a period of 24 hours to reach moisture/chemical equilibrium before conducted the test.

### 3.4.2.3 Preparation of Aged Specimens

The dried soil samples soaked in the leachate/water were kept in bottles and mixed using a rotary tumbler for 24 hours to reach equilibrium phase. The soil specimens were taken out of the solution and directly placed in containers for air drying. The specimens were then stored in sealed polyethylene bags to use later in this study.

### 3.4.3 Direct Shear Tests

Direct shear tests were carried out following the ASTM D3080 (2011a) on several compacted specimens of both soils. The specimens were prepared by compacting soil-water and soil-contaminated leachate mixtures directly within direct shear specimen box (diameter = 63 mm and height = 20.6 mm). The dry density of all specimens corresponds to the field dry density of the soils. For both soils, the measured insitu dry density remained between 1.798 and 1.802 $Mg/m^3$. Therefore, the compaction dry density of all specimens tested in this investigation was 1.8 $Mg/m^3$.

The specimens in the direct shear mould were prepared in four layers. The specimens were then covered and left for fluid equilibration (i.e., curing) for 24 hours. For each water content or leachate content, three specimens with similar compaction conditions were tested. The specimens were subjected to one of the normal stress of 31.5, 62.9, and 125.9 kPa. The specimens were then sheared at a strain rate 0.35 mm/min. The horizontal deformation, vertical deformation and the applied shear force were recorded by the software system (ELE DS7) connected to the apparatus. The maximum shear stresses corresponding to various applied normal stresses were considered for determining the shear strength parameters (c and $\phi$).

### 3.4.4 One–Dimensional Consolidation Tests

One dimensional consolidation tests were carried out following ASTM D2435 (2011b) several specimens of the two selected soils (see Figure 3.5). Compacted soil specimens were prepared directly within oedometer specimen rings (diameter = 75 mm and height = 18 mm) at different preparation condition described in section 3.3.2. The specimens were covered and stored for 24 hours for liquid equilibration. The specimens with specimen rings were assembled in oedometers. Filter papers were used at top and bottom of the specimens. For the loading stage, the specimens were firstly subjected a seating pressure of 5 kPa. Further, the specimens were inundated with either water or leachate solutions. The inundation fluid was water for the specimens that were prepared with water, whereas the inundation fluid was leachate solution for the specimens that were prepared with leachate solution in test series I.

A total of six vertical pressure increments were considered for all specimens, such as 12, 25, 50, 100, 200, 400 kPa. At the end of maximum loading step, the specimens were unloaded in a step-wise manner. The time-deformation data were analysed based on square root of time method (ASTM D 2435 Clause 12.3.2) for determining the values of coefficient of consolidation ($C_v$). The compression index ($C_c$) and the swelling index ($C_s$) were determined from the corresponding void ratio-log (pressure) plots of the specimens.

## 3.5 Adsorption and Retention Tests

### 3.5.1 Adsorption Isotherms

Adsorption isotherms were used to determine the interaction between the leachate and soil. The protocol of the United States Environmental Protection Agency (USEPA, 2010) was followed.

The soils were air dried for at least 24 hours, then broken up using a mortar and pestle and passed through a 2.0mm sieve. Several heavy metal solutions (copper, arsenic, nickel and chromium), each about 500 mL and with designated concentration were procured. Seven ratios of soil : solution (1:4, 1:10, 1:40, 1:60, 1:100, 1:200 and 1:400) were considered for each selected heavy metal solution, and were kept in closed-lid polyethylene bottles. The selection of solutions was based on the high concentration of the heavy metals in the leachate. The initial concentrations of the heavy metals are shown in the Table 3.1.

**Table 3.1: Initial solute concentration**

| Solute | Concentration (μg/l) |
|---|---|
| Copper | 129.57 |
| Arsenic | 351.26 |
| Nickel | 164.74 |
| Chromium | 292.53 |

A control solution (i.e., the stock solution) was prepared for each case to determine the initial solute concentration. The mass of the adsorbent specimens were calculated based on the corresponding oven-dried equivalent weights. The specimens were then mixed by using a rotary tumbler at 30 rpm for 24 hours. A 0.45 μm pore–size membrane filter was used to separate the solution and soil. To determine the solute concentration using ICP-OES apparatus, 2.0mL of each sample was taken.

The linear Langmuir equation and Freundlich equation were used to construct the adsorption isotherms curves. The linear Langmuir equation can be expressed as (USEPA, 2010):

$$\frac{x}{m} = \left[\frac{K_L\,MC}{1+K_L C}\right] \qquad (3.1)$$

where x is the concentration of the solute adsorbed, m is the mass of the soil adsorbed, C is the equilibrium concentration of the solute and $K_L$ and M are constants evaluated from the slope and intercept of linear equation.

The linear Freundlich equation can be expressed as (USEPA, 2010);

$$\frac{x}{m} = K_f x\, C^{1/n} \qquad (3.2)$$

where x is the concentration of the solute adsorbed, m is the mass of the adsorbent (i.e., the oven-dried soil), C is the equilibrium concentration of the solute and $K_f$ and 1/n are constants evaluated from the slope and intercept of linear equation.

### 3.5.2 Leaching Column Tests

The leaching column tests were carried out to generate the breakthrough curves to and to extract specimens for use in the shear and consolidation tests. The leaching column tests were used to study the contamination fate and transport through soils from the Al-Jahra site.

#### 3.5.2.1 Materials Used

The uncontaminated soils were prepared as detailed in section 3.4.1 and the leachate used was from Al-Qurain landfill as described in section 3.3.

#### 3.5.2.2 Preparation of Column Cell

The leaching column tests were carried out following ASTM D4874 (2006b). A Plexiglas cylinder of 99.5 mm diameter and 145.0 mm height was used as the leaching column cell. The soils used (a silty sand and a clayey sand) were obtained from the Al-Jahra site. The soils were then pulverized to pass through 4.75 mm sieve. The soils were remoulded to the field dry density (1.8 $Mg/m^3$ for both soils) and moisture content (2.9% and 3.4% for the silty sand and the clayey sand, respectively). The soils were compacted in four equal layers in the cell. The cell was line marked to four equal layers to ensure that each layer was compacted at the same dry density and to keep the sample homogeneous. The surface of each compacted layer was scratched with knife to prevent separation between consecutive layers that could lead to horizontal movement of leachate.

For a test, a compacted specimen was placed in the column cell. A photograph of the leaching column apparatus used is shown in Figure 3.6. Rubber O-rings were placed at both top and bottom plates to avoid leakage of fluid. The porous stones were placed at top and bottom of the cell. The end plates were screwed tightly.

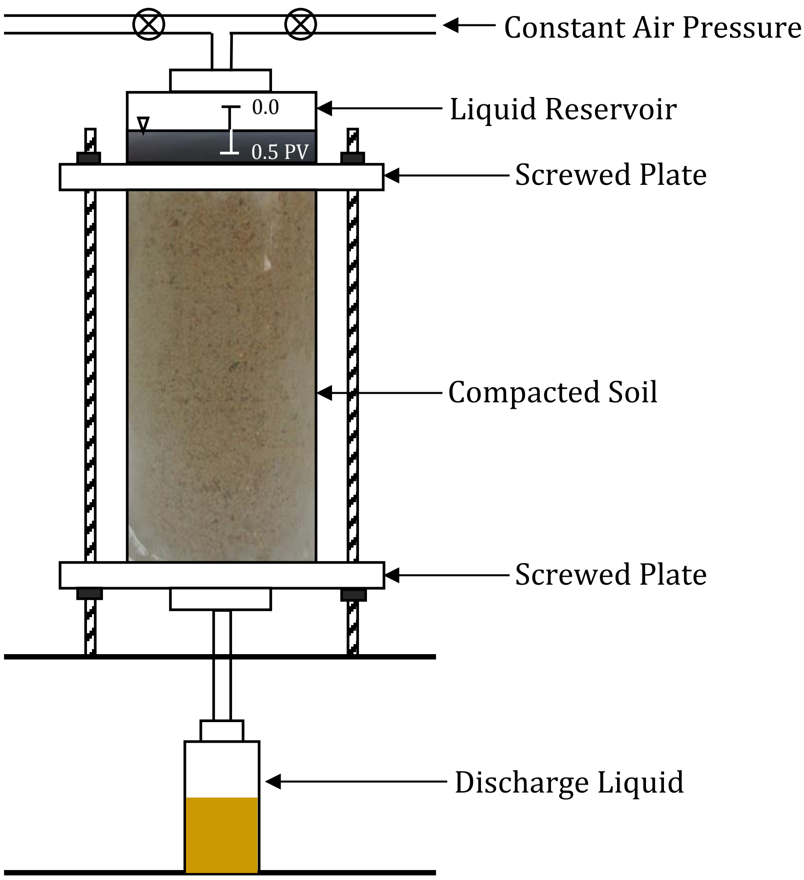


**Figure 3.6: Schematic diagram of leaching column test**

Each column test was conducted with a predetermined constant air pressure to prevent any change in the volume. The air pressure on a soil specimen was applied through the supply tubes and the magnitude of air pressure was controlled using a valve and a gauge system that allowed each cell to be controlled independently. The column tests on silty sand were conducted under a low constant air pressure of 6.9

kPa to allow the leachate to flow downward due to gravity, which was possible in the case of high permeability soil.

The column tests on specimens of the clayey sand were conducted under a constant air pressure of 34 kPa, which was required due to the low permeability of the clayey soil. The pressure rates were specified by ASTM D4874 (2006b). The wall effect in the leaching column test was negligible; the column diameter should be 20 times greater than the particle diameter (Korkisch 1989).

The soil specimens in columns tests were firstly leached with distilled water for up to 2 pore volumes (PVs). Further, the leachate was supplied for up to 5 pore volumes. The discharged liquid was collected by polyethylene bottles for every 0.5PV and kept in a refrigerator at 4°C for analysis.

After the 5 pore volumes was completed for both sets the compacted soils in the column cell was then extracted into six equal slices (22 mm each slice) and placed into a labeled container, oven-dry at 50°C and making it ready for analysis.

#### 3.5.2.3 Specimen Preparation Following Column Tests (Test Series V)

After the second set of column tests were completed, the specimens were extracted from the column cell. The sharp cutting edge of the specimen cutter (63mm diameter) was pushed into the center of column cell gently. The soil was loosened around the ring to pull out it easily as shown in Figure 3.7.


**Figure 3.7: Extraction of the specimen**

The ring was then placed on the levelled surface and the upper part of the soil was levelled, as shown in Figure 3.8.


**Figure 3.8: Levelling of the specimen**

The small nooks were filled with the same material. The specimen cutter was handled carefully to minimize the disturbance and distortion and pushed gently in the shear box or consolidation cell by using extrusion tool as shown in Figure 3.9.


**Figure 3.9: Inserting of the specimen**

### 3.5.2.4 Analysis of Discharge Liquid

By using an ICP-OES, the discharged liquid was collected at every 0.5 PV, and then analyzed. Before analyzing, the specimen was filtered through less than 0.2 μm pores–size membrane filter to remove impurities. The major heavy metals were analysed (Cu, Cr, As, Ni) and the pH value was also measured. The acid digestion method was used to extract the heavy metals from the soil slices, and the retention of heavy metals was measured by using ICP-OES.

#### 3.5.2.5 Acid Digestion Method

The acid digestion method guidelines were followed using USEPA (1996). The heavy metals were determined as per Mg/l in the ICP-OES after the leachate was refluxed and heated at 95°C.

Table 3.2 shows the testing matrix adopted for studying the geotechnical and geoenvironmental properties of the selected soils.

**Table 3.2 Geotechnical and geoenvironmental properties testing matrix**

| **Geotechnical Properties** | | | | | |
|---|---|---|---|---|---|
| Test Name | | Direct Shear Test | | Compression Test | |
| Soil Type | | Silty Sand | Clayey Sand | Silty Sand | Clayey Sand |
| Test Method | Moisture Type | Number of Samples | | Number of Samples | |
| Mixing | - | - | - | - | - |
| 0% | | 2 | 2 | 2 | 2 |
| 10% | Water | 2 | 2 | 2 | 2 |
| | Leachate | 2 | 2 | 2 | 2 |
| 20% | Water | 2 | 2 | 2 | 2 |
| | Leachate | 2 | 2 | 2 | 2 |
| 40% | Water | 2 | 2 | 2 | 2 |
| | Leachate | 2 | 2 | 2 | 2 |
| Inundation | Water | 2 | 2 | 2 | 2 |
| | Leachate | 2 | 2 | 2 | 2 |
| Ageing | Water | 2 | 2 | 2 | 2 |
| | Leachate | 2 | 2 | 2 | 2 |
| Extraction | Leachate | 1 | 1 | 1 | 1 |
| **Geoenvironmental Properties** | | | | | |
| Test Name | | Column test | | Adsorption Isotherms | |
| Soil Type | | Silty Sand | Clayey Sand | Silty Sand | Clayey Sand |
| Contamination Name | | Number of Samples | | Number of Samples | |
| Leachate | | 1 | 1 | - | - |
| Copper | | - | - | 7 | 7 |
| Arsenic | | - | - | 7 | 7 |
| Nickel | | - | - | 7 | 7 |
| Chromium | | - | - | 7 | 7 |

## 3.6 Concluding Remarks

In this chapter, the procedures adopted for determining the basic physical properties of soils, such as the particle size distribution, the liquid limit, the plastic limit, the compaction characteristics, the field density, the natural moisture content and the specific gravity are described. The procedures adopted for determining the chemical properties of soils, such as the pH and the organic matter are described. Similarly, the procedures adopted for determining the chemical properties of the leachate, such as the pH, the total dissolved solid, the chemical oxygen demand, the biological oxygen demand, the total organic carbon, the electrical conductivity, the chloride, the alkalinity and the heavy metals are presented in detail.

The specimen preparation conditions and experimental methods for various tests are explained in detail. The geotechnical (direct shear and one dimensional consolidation tests) and the geoenvironmental (adsorption isotherms and leaching column tests) properties as well as the procedures adopted for specimen preparation and the test methods are presented.

# Chapter 4

# GEOTECHNICAL PROPERTIES

## 4.1 Introduction

This chapter presents the results of the tests that were carried out to study the impact of the leachate on the physical properties of the soils. The results from the shear strength and compressibility tests are used to understand the behaviour of soil – leachate systems.

## 4.2 Soil Properties

The soils used in this investigation were natural soils from Kuwait. The soils were obtained from test pits of 0.5 to 3 m deep, taken from locations that were 1 to 3 meters away from the Al-Jahra landfill boundary.

### 4.2.1 Particle Size Distribution

The particle size distribution of the Al-Jahra soils is shown in Figure 4.1. The collected soils were mainly composed of sand without any gravel. The grain size distribution curves indicate the percentage of the fine particles (passed through a 63μm sieve) in the soils are about 10% and 26% for soils S1 and S2, respectively. The fine particles below 75μm were not measured due to unavailability of the necessary facilities at the Kuwait university laboratory. The particles size distributions for the soils are summarized in Table 4.1.

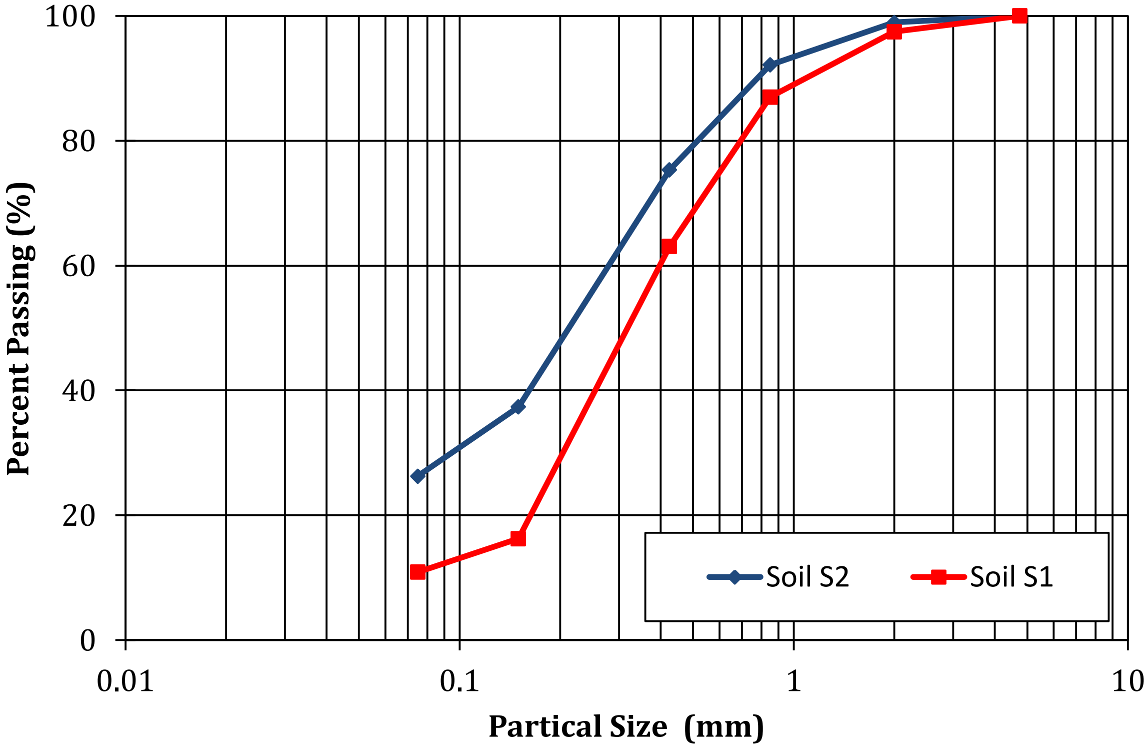


**Figure 4.1: Particle size distribution of the chosen Al-Jahra soils**

**Table 4.1: The grain size distribution of the soils**

| Soil | Percent Passing | | | | | | Soil Group | | |
|---|---|---|---|---|---|---|---|---|---|
| | Sieve Openings (mm) | | | | | | Gravel | Sand | Silt and Clay |
| | 4.75 | 2 | 0.85 | 0.425 | 0.150 | 0.075 | (%) | | |
| **S1** | **100** | **97.47** | **87** | **63.07** | **16.27** | **10.89** | **0** | **89.11** | **10.89** |
| **S2** | **100** | **98.94** | **92.16** | **75.33** | **37.36** | **26.27** | **0** | **73.73** | **26.27** |

### 4.2.2 Atterberg Limits

The results of the Atterberg limit tests for soil S2 are shown in Figure 4.2. The methods of obtaining the results are detailed in section 3.2.3 of Chapter 3. It can be noticed that the liquid limit for all samples is below 30%, representing the low plasticity and compressibility of the soils (Head 1981; Mitchel 1993).

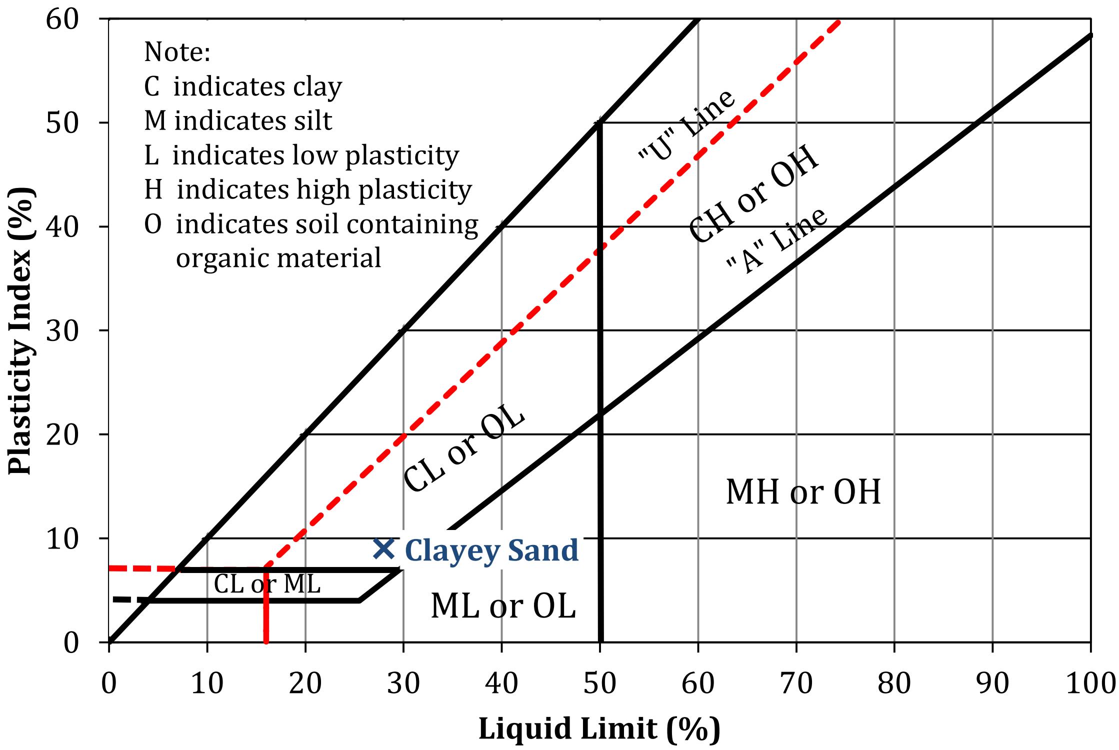


**Figure 4.2: Plasticity chart**

The plasticity index of the S2 soil sample results is plotted below the U-line and upper A-line in Figure 4.2. ASTM D2487 (2006) uses the A-line to separate the more claylike materials from silty materials, and the organics from the inorganics. However the U-line has been empirically determined to be the approximate upper limit for the general soil. The soil S1 is mostly silt, and can be clearly seen in the plasticity index to equal 0%.

### 4.2.3 Soil classification

The soils are classified according to the Unified Soil Classification System (USCS) as recommended by the ASTM D2487 (2006). The classifications are based on Atterberg limits and particle size distribution. Soil classification is based on the fine contents percentage, coefficient of uniformity (Cu), and the coefficient of curvature (Cc).

The calculation of the Cu and Cc values and the classification results of the soil samples are summarized in Table 4.2. The parameters of Cc and Cu were not calculated for the soil S2 if the fine particles were greater than 12%, as recommend by UCCS.

**Table 4.2: The soil classification**

| Soil | $F_{200}$ (%) | $D_{60}$ | $D_{30}$ | $D_{10}$ | $C_u$ | $C_c$ | Atterberg limits | | | Soil Classification |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | LL | PL | PI | |
| S1 | 10.89 | 0.4 | 0.21 | 0.075 | 5.3 | 1.3 | Non - Plastic | | | SP-SM |
| S2 | 26.27 | - | - | - | - | - | 28 | 19 | 9 | SC |

From Table 4.2, the soil S1 can be classified as poorly graded silty sand. The soil S2 can be classified as clayey sand. These are in general agreement with findings of Jeragh (2009, 2012).

### 4.2.4 Compaction

The compaction characteristics of the soils are presented in Figure 4.3. In the case of silty sand the maximum dry density of 2.03 Mg/m$^3$ is observed at the optimum moisture content of 8.5%, while for the clayey sand the maximum dry density is 2.06 Mg/m$^3$ at the optimum moisture content of about 10%.

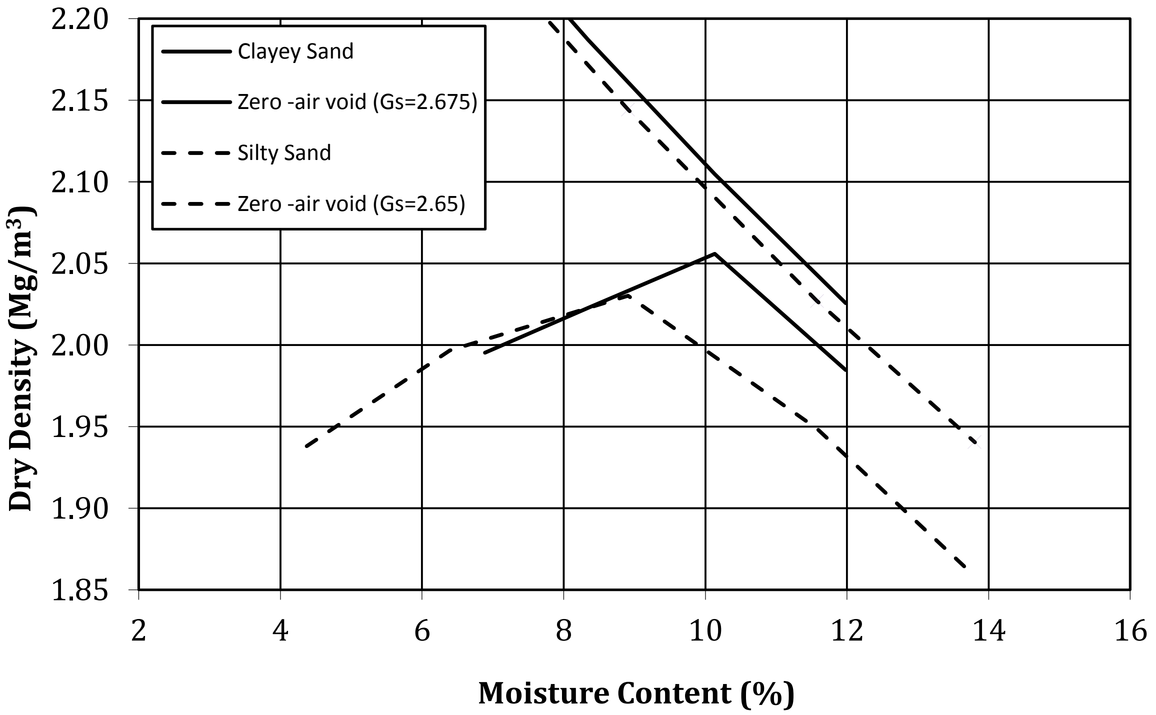


**Figure 4.3: Compaction curves of the soil used**

It can be seen that the compaction curves for silty sand and clayey sand are clearly defined single peak compaction curves. The maximum dry density for the silty sand and clayey sand showed no significant different.

### 4.2.5 Field Density

The field densities of the natural soil samples were measured as 1.8 $Mg/m^3$ using the method detailed in section 3.2.4. The field density refers to the actual density of the soil at the site. In this research the field density results was used for preparing soil specimens in order to mimic the field conditions which stands out as the key consideration of the study.

### 4.2.6 Natural Moisture Content

The natural moisture contents of the silty sand and the clayey sand were calculated as 2.9% and 3.4%, respectively. The natural moisture contents were determined using the method detailed in section 3.2.5. The natural moisture contents were used to achieve the field conditions in the prepared soil specimens.

### 4.2.7 Specific Gravity

The specific gravity ($G_s$) of the silty sand and the clayey sand were determined as 2.65 and 2.67 respectively, using the method detailed in section 3.2.6.

### 4.2.8 Chemical Characterisation

The basic chemical characterisation of the silty sand and the clayey sand was obtained from (Al-Fares 2009; Jeragh 2009), as shown in the Table 4.3.

The pH values of the soils are strongly alkaline which can be attributed to high calcium carbonate content present in the soils (Ismael et al. 1986). The total organic content of the soils are very low; less than 1%. Caravaca and Albaladejo (1999) and Ismael et al. (1986) reported that the semiarid climatologic characteristics (low rainfall and high temperature) could be reducing the input of the organic matter.

**Table 4.3: Chemical characterization of Al-Jahra soil (Al-Fares 2009; Jeragh 2009)**

| Soil Type | pH | Calcium Carbonate (%) | Organic Matter (%) |
|---|---|---|---|
| Silty sand | 8.49 | 8.37 | 0.027 |
| Clayey sand | 9.58 | 7.16 | 0.039 |

## 4.3 Chemical Characterisation of the Leachate Used

The results of the chemical analysis of the leachate obtained from Al-Qurain landfill site which was used in this study, is listed in Table 4.4.

Table 4.4 shows that the pH value of the leachate is 8.37, which is alkalinity and can reduce the mobility of the heavy metals. The concentrations of chromium (Cr), copper (Cu), Nickel (Ni) and Arsenic (As) are significant indicating the severity of toxic metals in the leachate. This aspects forms the main issue of the investigation.

**Table 4.4: Chemical analysis of the leachate sample**

| Parameters | Results | Parameters | Results |
|---|---|---|---|
| pH | 8.37 | Phosphate ($PO_4^{3-}$) | 31.705 ppm |
| Electrical Conductivity (EC) | 14.63 ms/cm | Sulphate ($SO_2^{4-}$) | 35591 ppm |
| Total dissolved solids (TDS) | 11704 Mg/l | Boron (B) | 13421.7 µg/l |
| Chemical oxygen demand (COD) | 1670 Mg/l | Titanium (Ti) | 829.49 µg/l |
| Biochemical oxygen demand (BOD) | 780 Mg/l | Vanadium (V) | < 0.01 µg/l |
| Total organic carbon (TOC) | 530 Mg/l | Chromium (Cr) | 292.53 µg/l |
| Total chlorine (Cl) | 0.18 Mg/l | Cobalt (Co) | 26.144 µg/l |
| Alkalinity | 400 Mg/l | Nickel (Ni) | 164.74 µg/l |
| Chloride ($Cl^-$) | 1730 Mg/l | Copper (Cu) | 129.57 µg/l |
| Calcium (Ca) | 323.24 Mg/l | Zinc (Zn) | 132.76 µg/l |
| Iron (Fe) | 4.38 Mg/l | Germanium (Ge) | 15.012 µg/l |
| Potassium (K) | 449.52 Mg/l | Arsenic (As) | 351.26 µg/l |
| Magnesium (Mg) | 125.25 Mg/l | Silver (Ag) | 4.7504 µg/l |
| Manganese (Mn) | 0.1 Mg/l | Cadmium (Cd) | < 0.01 µg/l |
| Sodium (Na) | 3804.77 Mg/l | Mercury (Hg) | < 5 µg/l |
| Strontium (Sr) | 2.98 Mg/l | Lead (Pb) | 5.1828 µg/l |

## 4.4 Strength and Compressibility Behavior of Natural and Contaminated Soils

The literature review presented in chapter 2 discussed the findings of several investigations on the interaction of the landfill leachate and uncontaminated soil.

Most of these studies (i.e. Al-Fares 2011; Reddy et al. 2009; Sunil et al. 2009) were carried out to investigate the effect of the addition of landfill leachate on the strength and compressibility of natural soils.

The landfill leachate is generated as a consequence of water percolation through solid waste, as well as oxidation and corrosion of the waste discarded in poorly designed landfill sites, which allow the leachate to easily pass through the soil strata and cause severe risk to the surrounding soil, the groundwater and the health of the local community.

In this section, the results of the direct shear and one dimensional compression tests are presented.

### 4.4.1 Direct Shear Tests

The main parameters obtained from the direct shear test are the internal angle of friction ($\phi$) and cohesion (c). The methods used to determine these parameters are presented in sections 3.4.1.1 to 3.4.1.3 and 3.5.2.3

The shear stress versus horizontal displacement plots are drawn for each tested soils at each applied load and based on the test results of duplicate soil specimens. The stress–strain behaviour from these curves can be deliberated. The shear stress is considered to be the shear strength corresponding to the state of failure ($\tau_f$). The shear stresses, $\tau_f$, are then plotted against the corresponding values of normal stresses, $\sigma_n$. Such a plot generally approximates to a straight line and represents the Mohr-Coulomb envelope for each tested soil specimen. The inclination of this line to the horizontal axis is equal to the angle of friction of the soil ($\phi$) and where it intercepts the vertical axis is the cohesion (c).

The results of the direct shear tests for the natural soils mixed with water and leachate (test series I) are presented in Figures 4.4 to 4.15. Figures 4.16 to 4.23 show the results of leachate inundation tests (test series II). Figures 4.24 to 4.31 present the results of the tests in which the specimens were aged prior to testing them (test series III).

#### 4.4.1.1 Effect of Soil-Water and Soil- Leachate Mixtures (Test Series I)

It is useful to investigate the behaviour of natural soils mixed with different percentages of leachate. A total of fourteen direct shear tests for the silty sand and fourteen tests for the clay sand were carried out as detailed in section 3.4.1.1.

##### 4.4.1.1.1 Shear Stress versus Shear Displacement

Figures 4.4, 4.5 and 4.6 show the shear stress versus horizontal displacement curves for the specimens of silty sand that were tested under normal stresses of 31.5 kPa, 63 kPa, and 125.9 kPa. Figures 4.4, 4.5 and 4.6 show the results at each applied stress and at different percentages of the fluids considered (leachate and water).

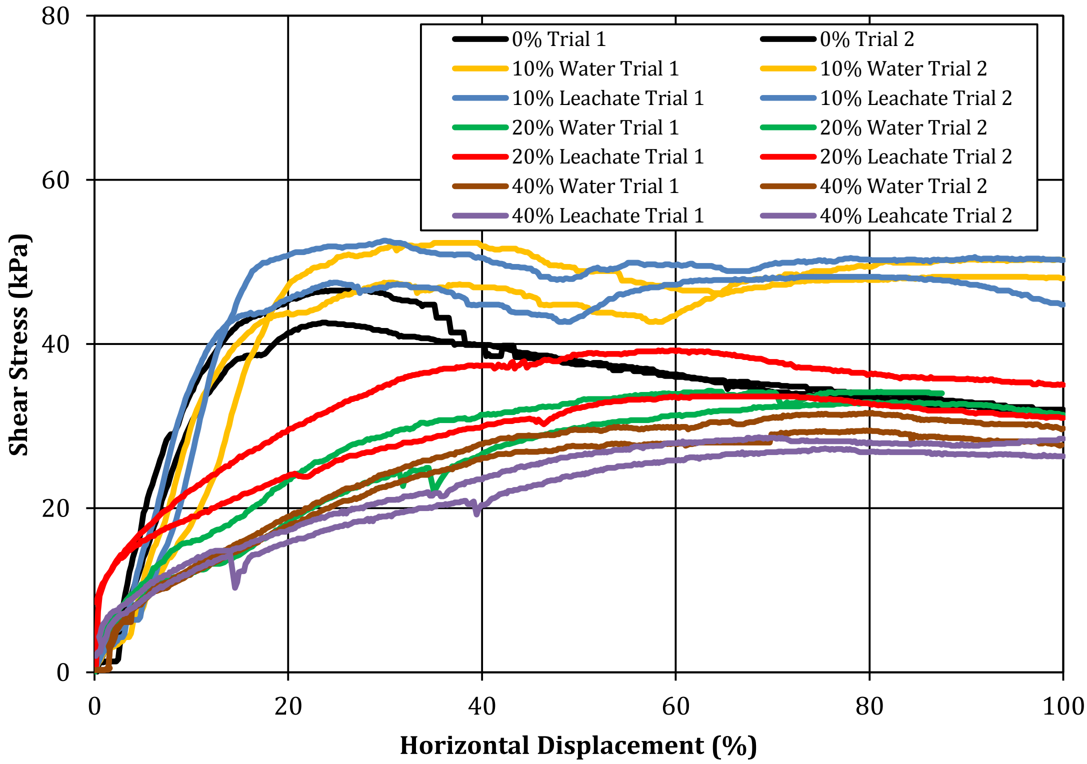


**Figure 4.4: Shear stress - horizontal displacement curves for silty sand at 31.5kPa normal stress**

Figures 4.4, 4.5 and 4.6 show the pre-failure portion of the shear stress versus horizontal shear displacement curves. The resulting peak shear stresses for leachate mixed with the silty sand varied for different applied vertical stresses. Figure 4.4 shows the peak shear stress at a normal stress of 31.5 kPa for the soil specimens mixed with leachate and water. It can be noticed that at 10% of water or leachate the test results are similar. The soil specimen mixed with leachate content of 20% shows a slight increase in the shear stress by about 3 kPa as compared to the specimen with water. However, a negligible reduction of the peak shear stress was noted for the soil specimen mixed with 40% of leachate content.

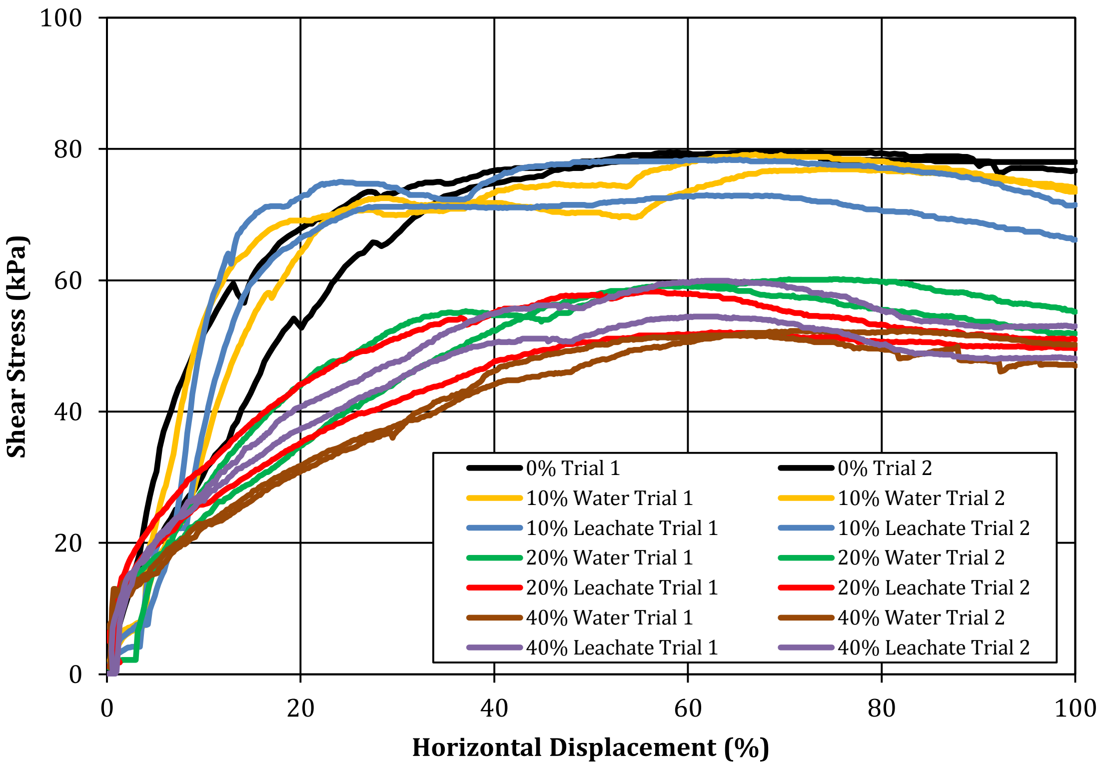


**Figure 4.5: Shear stress - horizontal displacement curves for silty sand at 63kPa normal stress**

A similar trend can be noticed for the silty sand at a normal stress of 63kPa in Figure 4.5. The soils at 0% moisture show the highest shear stress as compared to the others. This can be attributed to the lack of cohesion that leads to a reduction of sliding between particles, and an increase in friction (Kemper and Rosenau 1984).

Figure 4.6 shows the peak shear stresses at a normal stress of 125.9 kPa for the mixed samples. It can be seen that there is no effect at different percentages as the stress increases. This can be due to the fact that the sandy soil behaviour is mainly influenced by relative density, void ratio and gradation rather than moisture content (Holtz and Kovacs 1981).

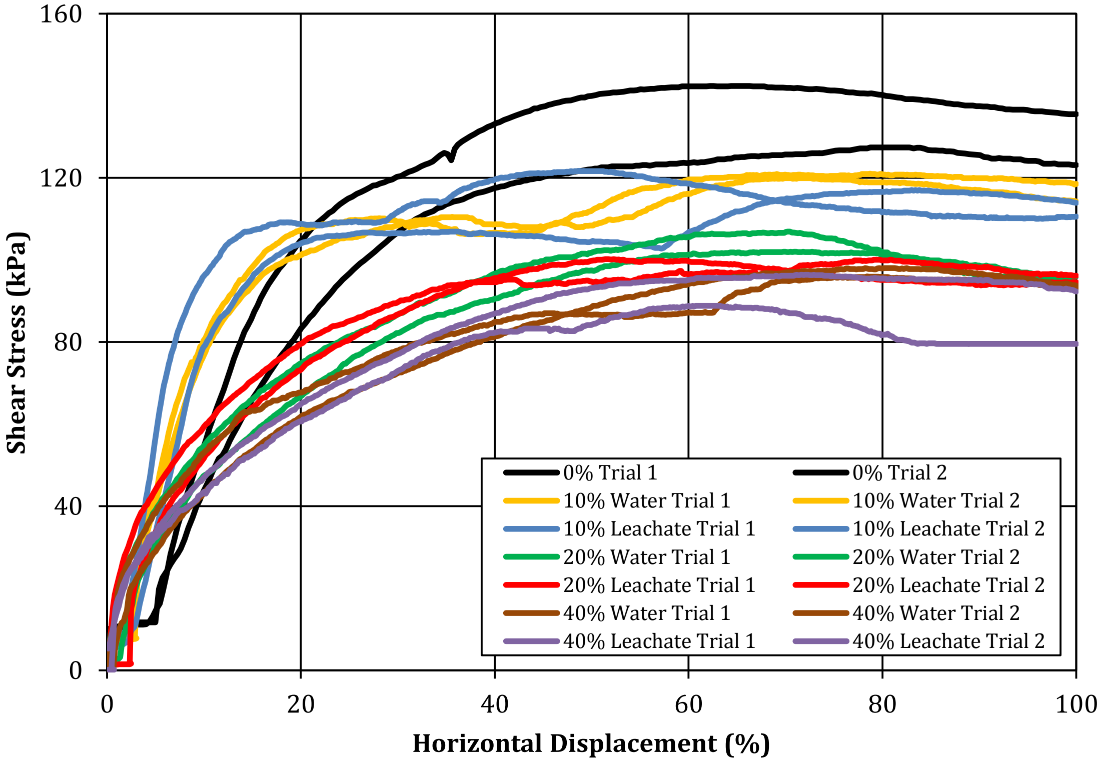


**Figure 4.6: Shear stress - horizontal displacement curves for silty sand at 125.9kPa normal stress**

Figures 4.7, 4.8 and 4.9 show the test results for the clayey sand specimens. The test results show that at low moisture content the peak shear stress of the soil mixed with leachate or water increased while as fluid content increased, the peak shear stress decreased. This trend may be due to the fact that, at low fluid content the suction is greater which holds the moisture more tightly to grains that reduces the lubrication between the particles which increases the friction between the soil particles (Bowders and Daniel 1987).

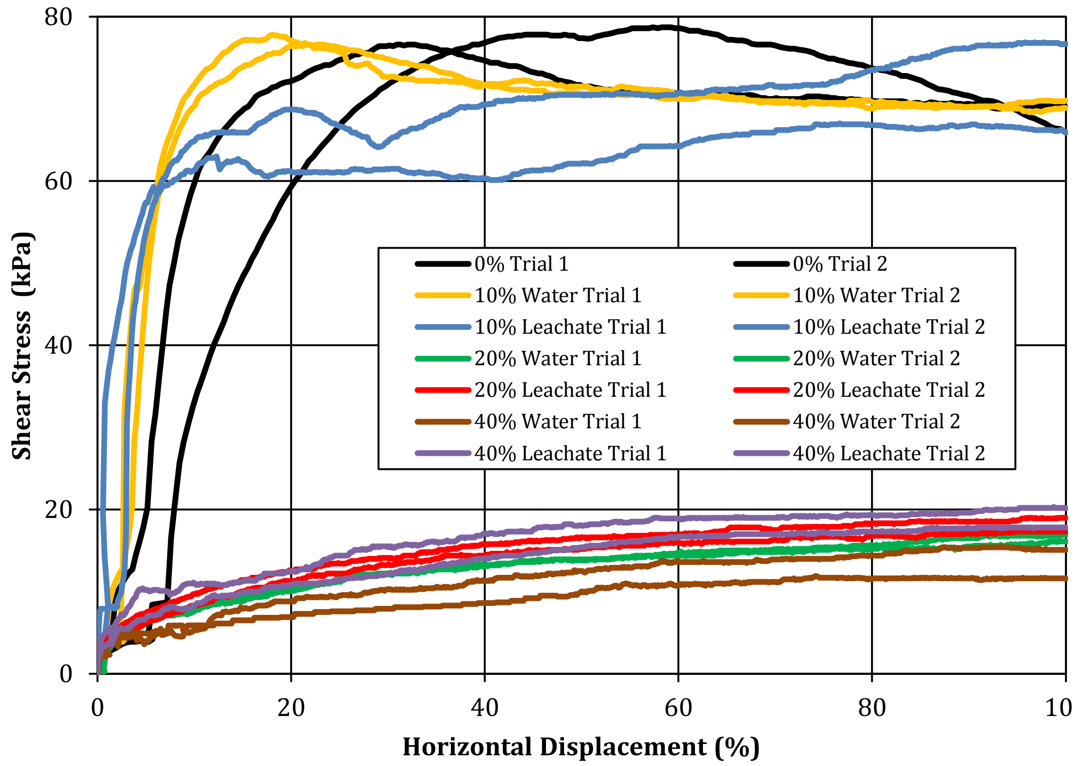


**Figure 4.7: Shear stress - horizontal displacement curves for clayey sand at 31.5kPa normal stress**

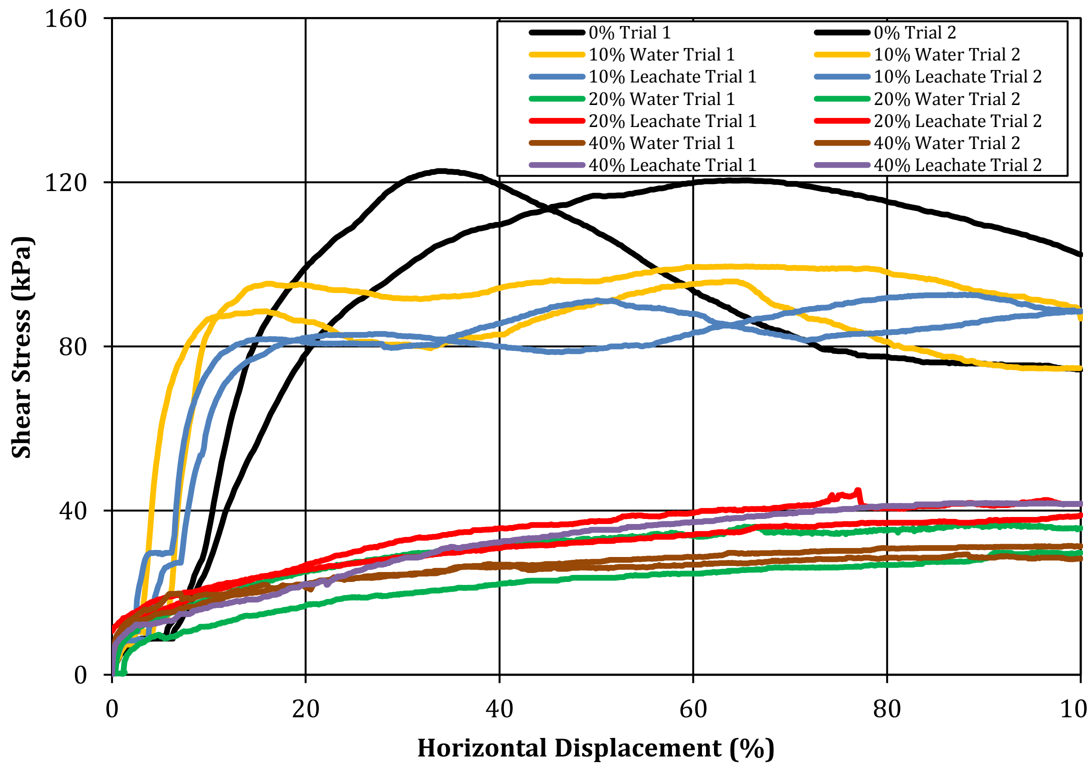


**Figure 4.8: Shear stress - horizontal displacement curves for clayey sand at 63kPa normal stress**

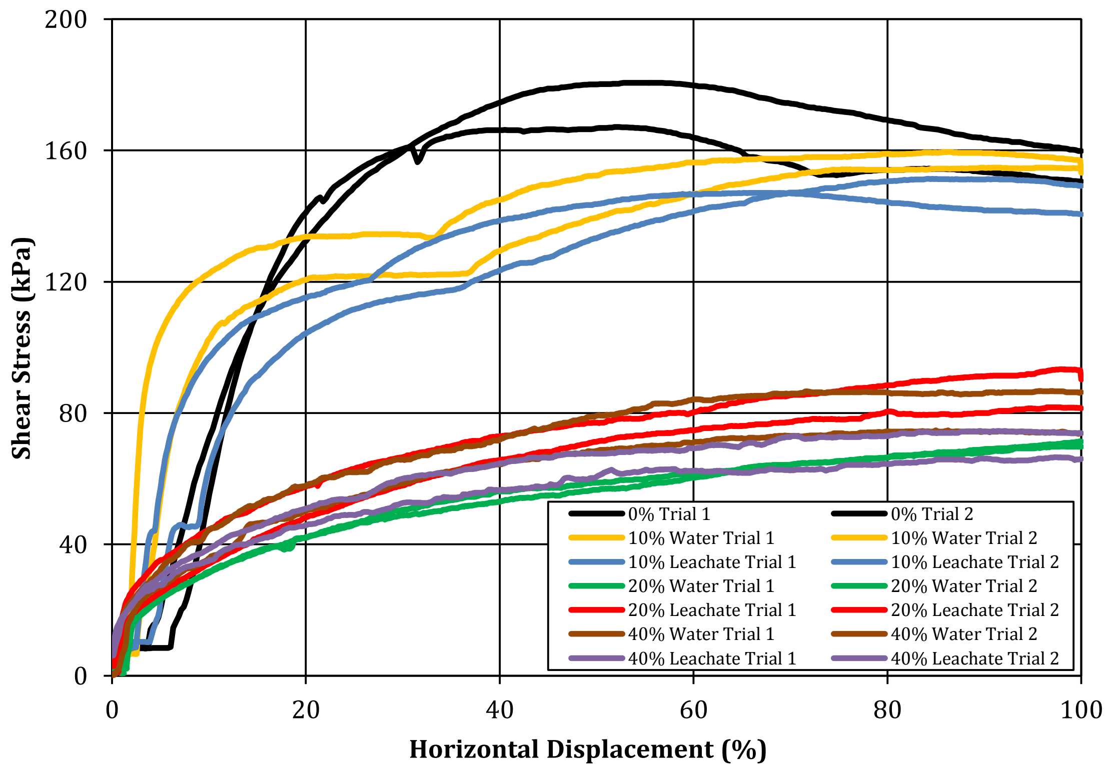


**Figure 4.9: Shear stress - horizontal displacement curves for clayey sand at 125.9kPa normal stress**

### 4.4.1.1.2 Peak Shear Stress versus Normal Stress

Figures 4.10 and 4.11 show the relationship between shear stress and normal stress for the natural soils mixed with various percentages of leachate and water (0%, 10%, 20% and 40%).

Figure 4.10 shows that at any percentage of the fluids, the slopes of the failure envelopes for the silty sand remains unchanged. This clearly shows that the sandy soil is not sensitive to the changes in the moisture content. The shear strength of the sandy soil is mainly dependent upon the relative density, the void ratio and the gradation (Holtz and Kovacs 1981).

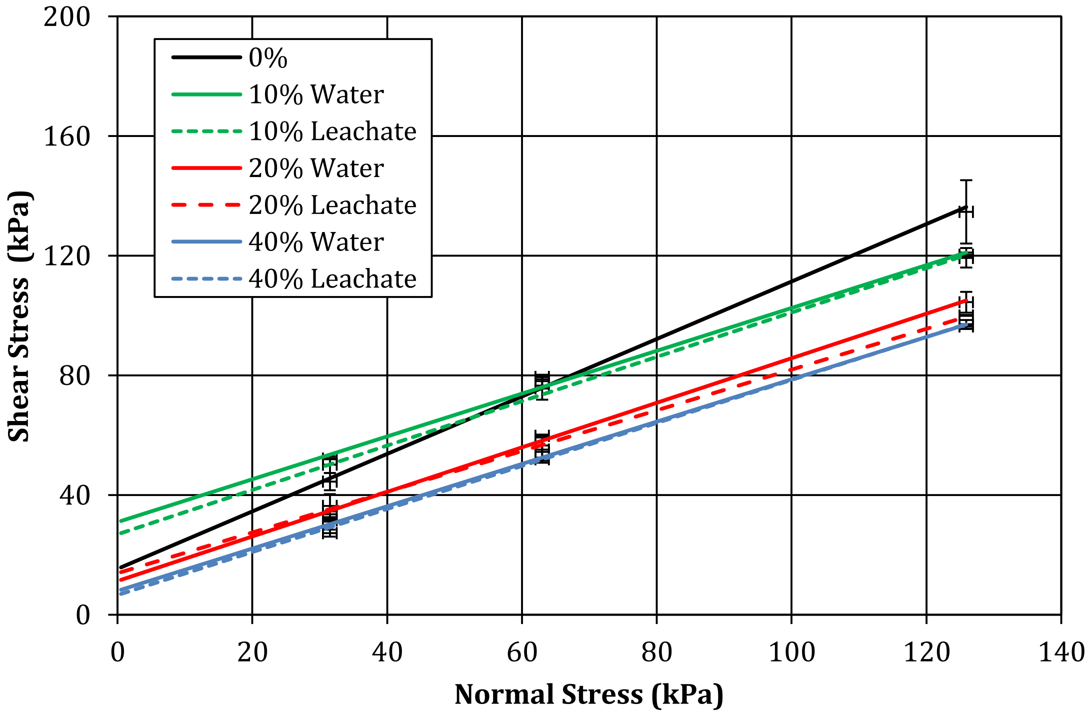


**Figure 4.10: Failure envelopes for silty sand mixed with water/leachate (Test Series I)**

Figure 4.11 shows the slopes of the failure envelopes for the clayey sand specimens for different percentages of the fluids. It can be observed that there is an increase in the angle of friction of the specimens with leachate than that for specimens with water at fluid contents of 10%, 20% and 40%. The behaviour may be attributed due to the various cations, such as Ca, Mg, K, Mn etc. in the leachate that lead to a reduction in the diffuse double layer thickness, allowing the soil particles to become closer to each other. This in turn leads to a decrease in the lubrication between the clay platelets (Farouk et al. 2004).

The apparent cohesion increased at 10% of leachate and water as compared to the dry specimen, but it decreased as the moistures content increased. This is due to the loss of soil suction caused by an increase in the moisture, which leads to a decrease in bonding between soil particles (Kamper and Rosenau 1984).

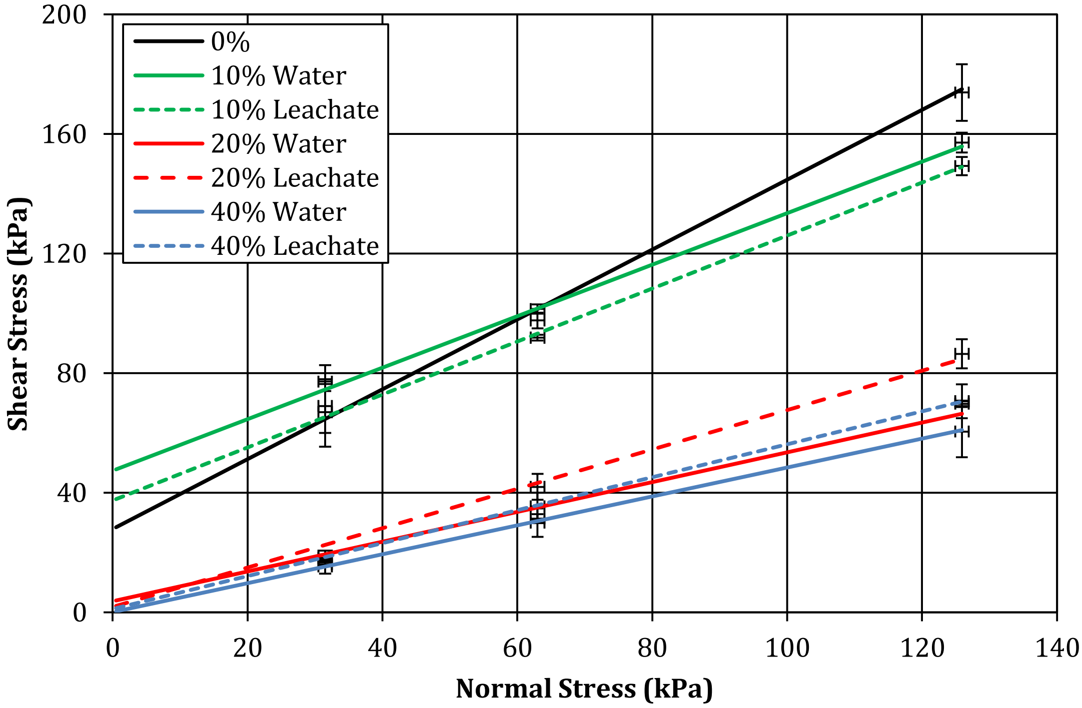


**Figure 4.11: Failure envelopes for clayey sand mixed with water/leachate (Test Series I)**

Table 4.5 summarizes the angle of friction and cohesion results for the soils in test series I (mixed method). The measured angle of friction values remain between 34° to 38° for the silty sand mixed with water and leachate. However, the apparent cohesion decreased with an increase in the percentage fluids. For any given percentage of the fluids, a variation of the apparent cohesion was insignificant indicating that, interaction of the silty sand with leachate does not affect the shear strength of the soil. For the clayey sand, both the angle of friction and the apparent cohesion decreased with an increase in the fluid content. Additionally a decrease in the apparent cohesion and an increase in the angle of friction were distinct at all leachate contents as compared to the water saturated specimens.

**Table 4.5: Angle of friction and cohesion for the interaction of natural soil and leachate/water**

| Test Series | Soil Type | | Silty Sand | | Clayey Sand | |
|---|---|---|---|---|---|---|
| | Method | Moisture Type | ϕ (Degree) | c (kPa) | ϕ (Degree) | c (kPa) |
| I | 0% | - | 44 | 15 | 52 | 28 |
| | 10% | Water | 35 | 31 | 41 | 47 |
| | | Leachate | 36 | 27 | 41 | 37 |
| | 20% | Water | 36 | 11 | 25 | 4 |
| | | Leachate | 34 | 14 | 32 | 2 |
| | 40% | Water | 35 | 8 | 26 | 0 |
| | | Leachate | 35 | 6 | 29 | 1 |
| II | Inundation | Water | 34 | 7 | 24 | 46 |
| | | Leachate | 34 | 5 | 35 | 10 |
| III | Ageing | Water | 38 | 21 | 17 | 12 |
| | | Leachate | 36 | 10 | 15 | 8 |
| V | Extracted | Leachate | 38 | 9 | 36 | 2 |

The variation of the angle of friction of the specimens at different moisture contents are shown in Figures 4.12 and 4.13 for the silty sand and the clayey sand, respectively. It can be noted from Figure 4.12 that the silty sand has a negligible effect in the angle of friction with leachate addition as compared to that of the specimens mixed with water.

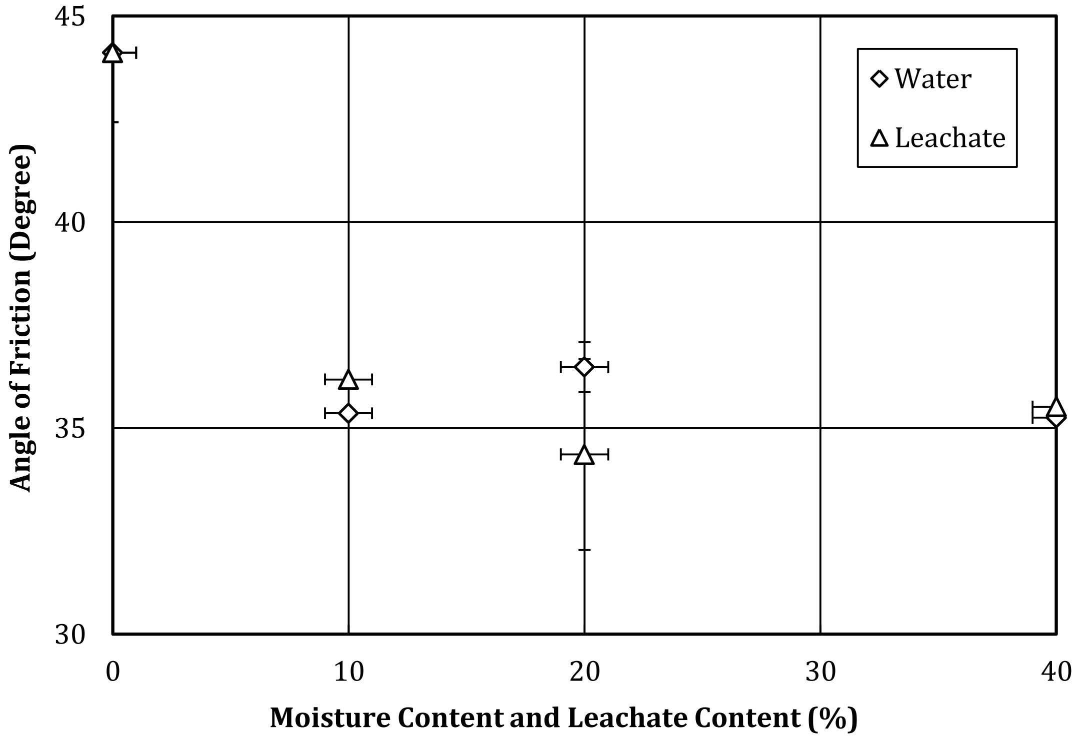


**Figure 4.12: Variation in angle of friction with leachate/water content for silty sand (Test Series I)**

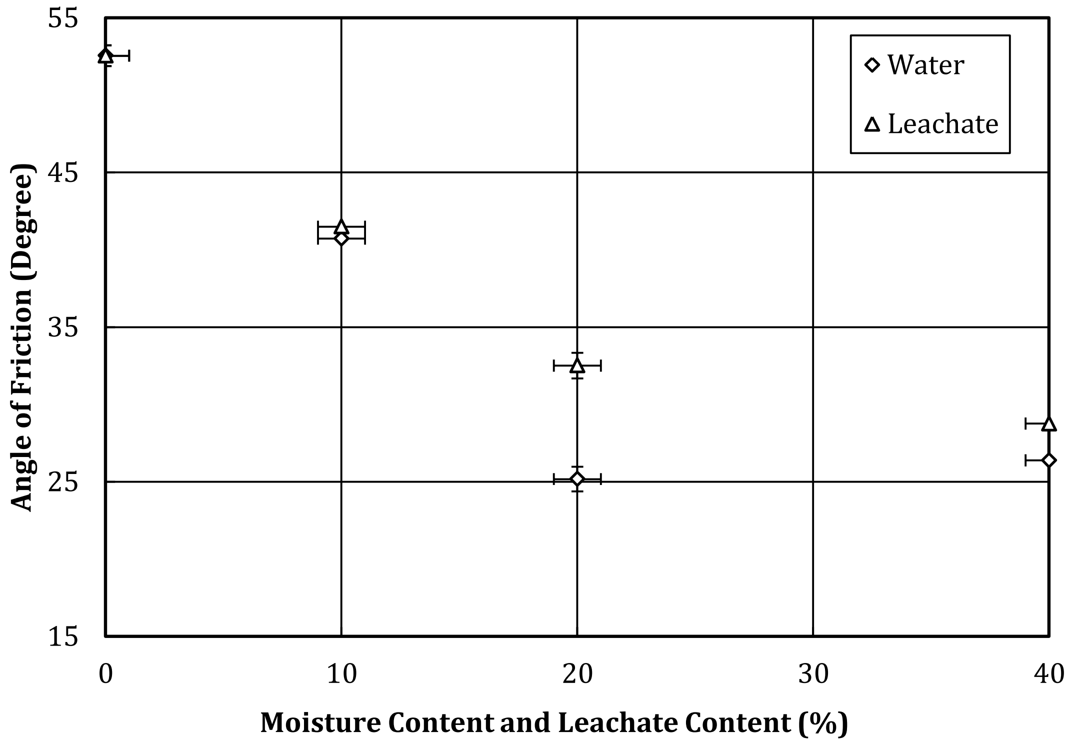


**Figure 4.13: Variation in angle of friction with leachate/water content for clayey sand (Test Series I)**

Figure 4.13 clearly shows how the effect of the leachate is distinct for the clayey sand. The negative charge on the surfaces of the clay particles attract the cations present in the leachate. This process allows the clay particles to move closer together, which leads to an increase in the friction between the particles due to a decrease in the electric double layer thickness (Bowders and Daniel 1987).

Figures 4.14 and 4.15 show the variation of cohesion at various fluid contents for the silty sand and the clayey sand, respectively. Figure 4.14 shows variations of cohesion for the silty sand. The specimens with water show higher cohesion as compared to the specimens with leachate at 10%, whereas no significant change occurred at 20% and 40%. This can be due to the matric suction at low moisture content that allows the soil particles to hold more tightly due to the capillary action (Alhassan 2012).

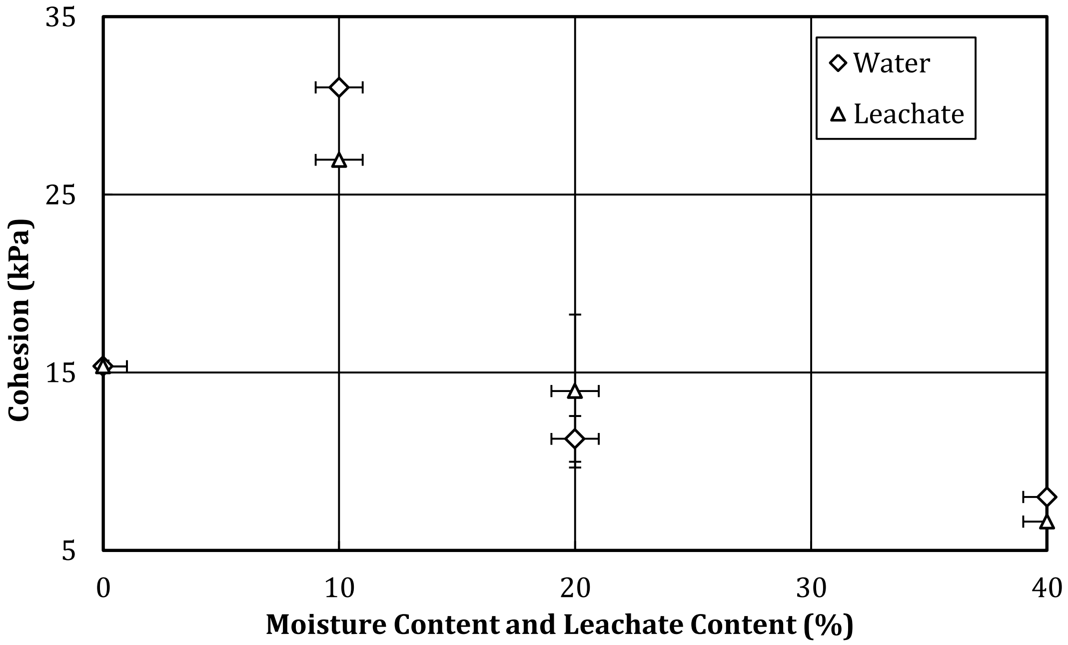


**Figure 4.14: Variation in cohesion with leachate/water content for silty sand (Test Series I)**

It can be clearly seen in Figure 4.15 that there is a reduction in the cohesion of the clayey sand soil mixed with leachate as compared to the specimens of the soil mixed with water at 10%, whereas no significant change occurred at 20% and 40%. This can be attributed to the matric suction at low moisture content that allows the soil particles to hold more tightly due to the capillary action (Alhassan 2012).

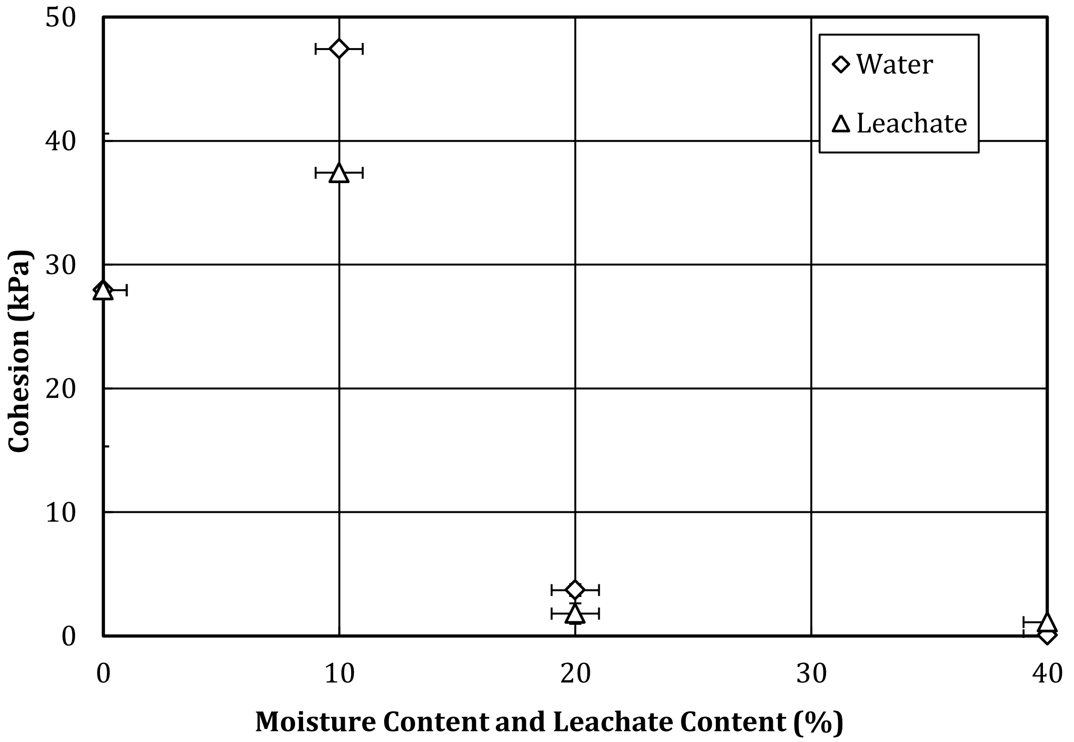


**Figure 4.15: Variation in cohesion with leachate/water content for clayey sand (Test Series I)**

### 4.4.1.2 Effect of Inundation (with Leachate/Water) on shear strength (Test Series II)

The inundation method was used in this research to mimic the flow of the leachate or water in a landfill site. A total of three direct shear tests for the silty sand and three tests for the clayey sand were carried out as detailed in sections 3.4.2.2 and 3.5.2.3.

#### 4.4.1.2.1 Shear Stress versus Shear Displacement

To better understand the interaction of the leachate with the soils under inundation test conditions, the results from test series II were compared with the results of specimens in test series I (mixed method) and test series V. The test results of specimens in series II test with fluid content of 40% were considered for comparison.

Figures 4.16, 4.17 and 4.18 show the results of the silty sand specimens inundated with leachate and water under normal stress of 31.5 kPa, 63 kPa, and 125.9 kPa. The results of specimens in test series I and V are shown for comparison.

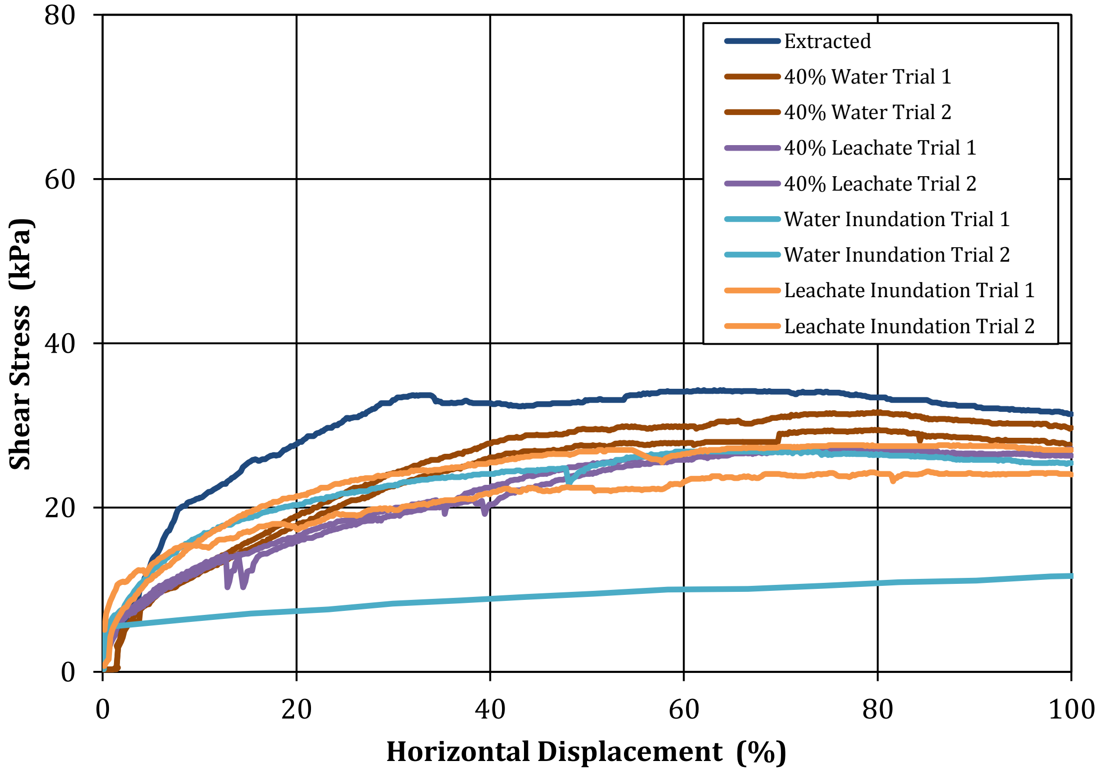


**Figure 4.16: Shear stress - horizontal displacement curves for silty sand at 31.5kPa normal stress**

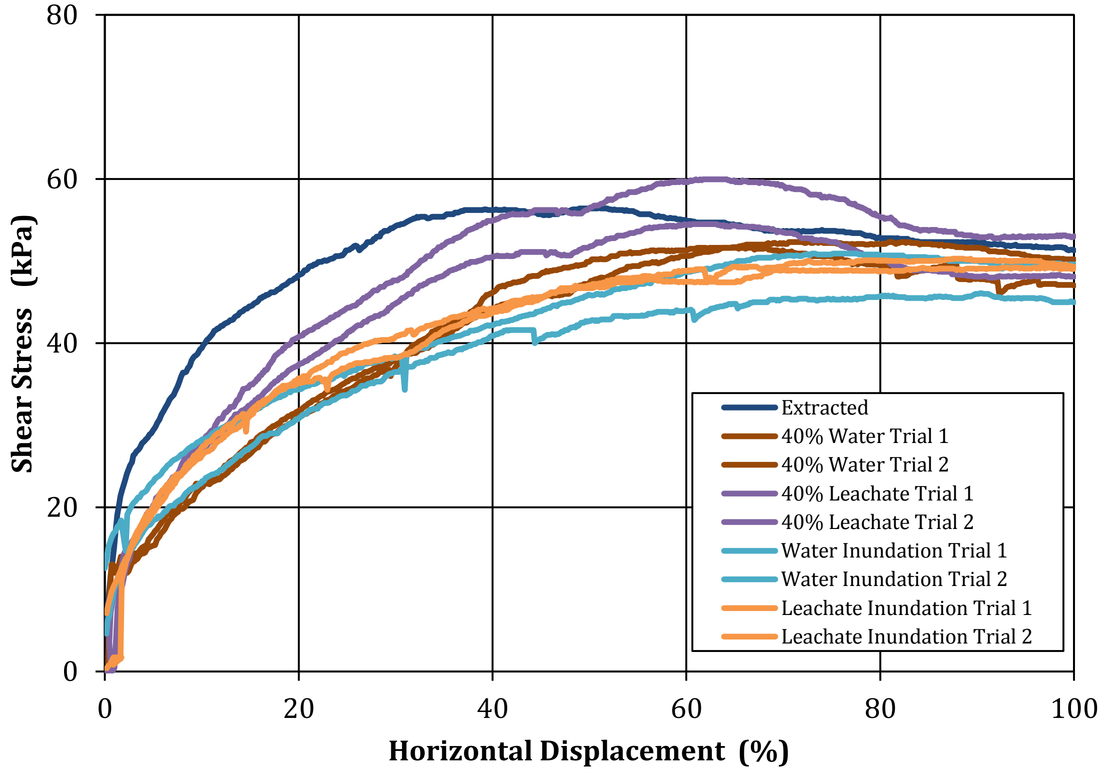


**Figure 4.17: Shear stress - horizontal displacement curves for silty sand at 63kPa normal stress**

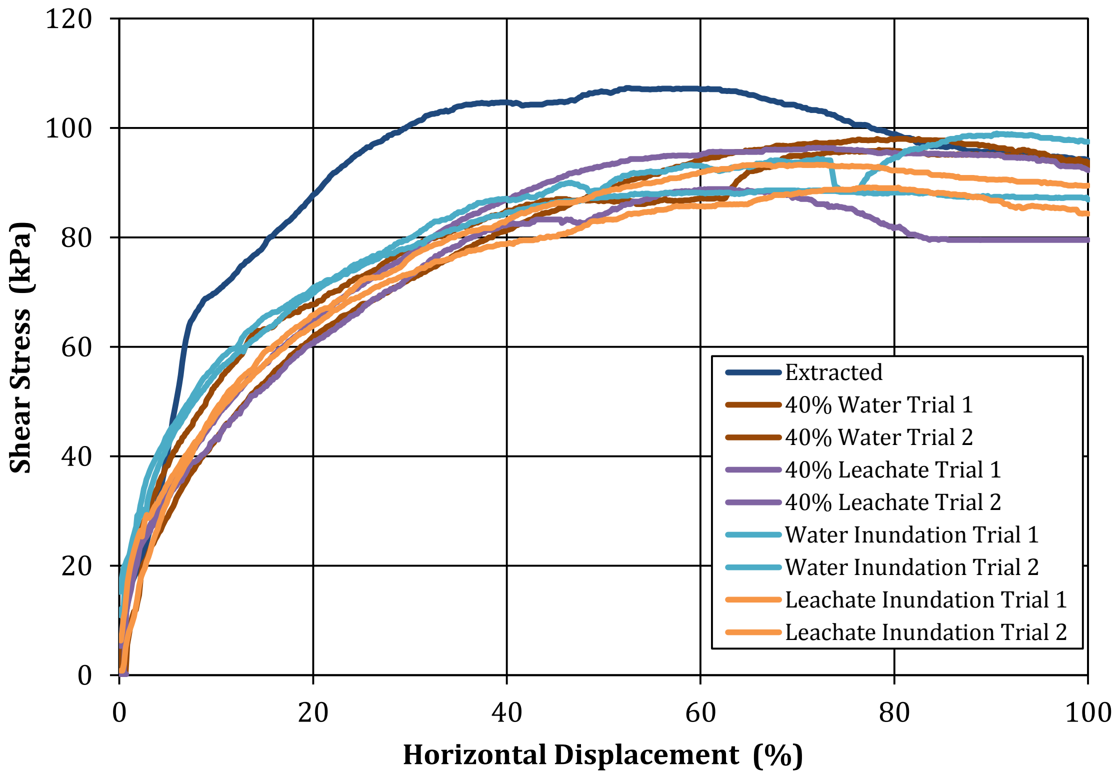


**Figure 4.18: Shear stress - horizontal displacement curves for silty sand at 125.9kPa normal stress**

The peak stresses under different normal stresses for the specimens of silty sand inundated with water and leachate (Figures 4.16 to 4.18) are found to be similar. However, the extracted specimen from the column shows a higher peak stress which can be attributed due to a rearrangement of the soil particles during the leaching column test resulting in a reduction in the void ratio, making the soil denser.

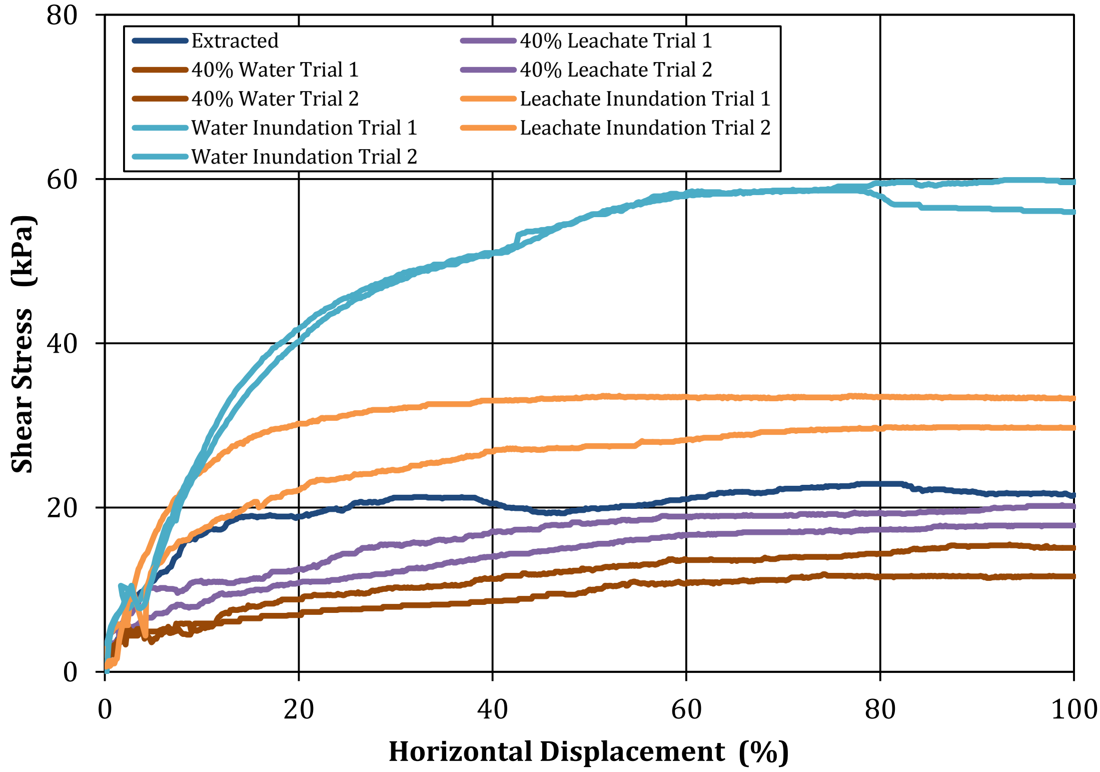


**Figure 4.19: Shear stress - horizontal displacement curves for clayey sand at 31.5kPa normal stress**

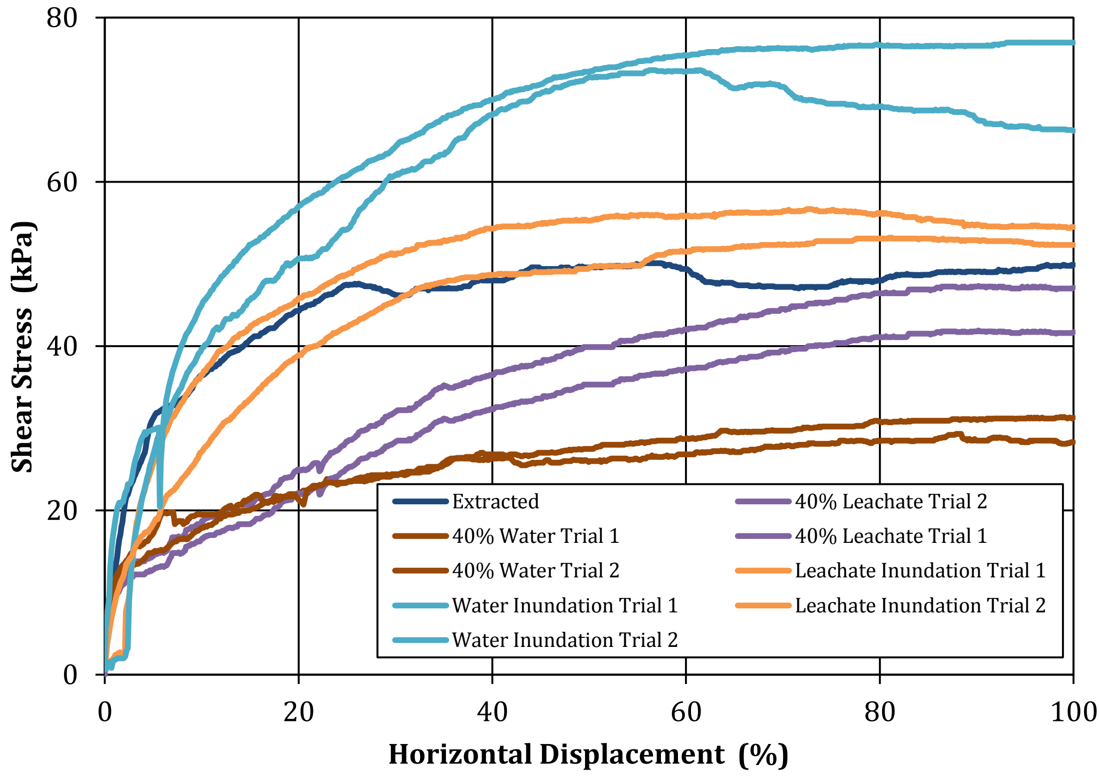


**Figure 4.20: Shear stress - horizontal displacement curves for clayey sand at 63kPa normal stress**

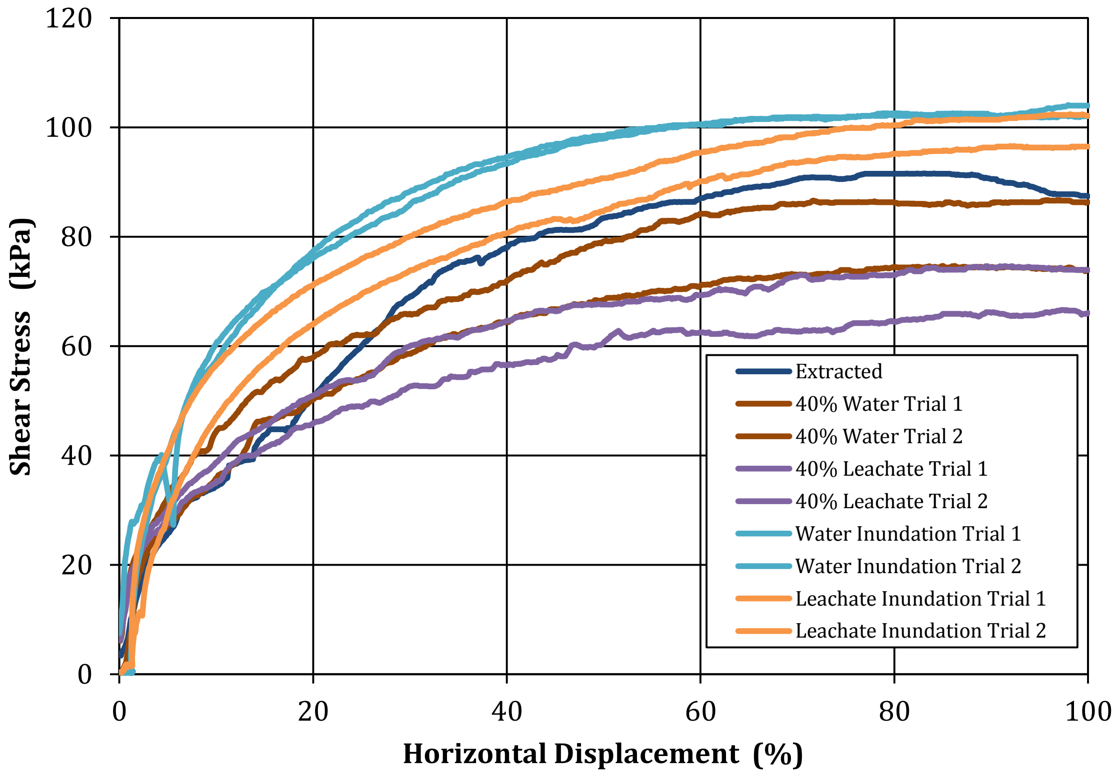


**Figure 4.21: Shear stress - horizontal displacement curves for clayey sand at 125.9kPa normal stress**

Figures 4.19, 4.20 and 4.21 show the test results of clayey sand specimens. The peak stresses of the soil inundated with leachate or water at different normal stresses showed an increase in the peak stress as compared to the extracted specimens and the soils mixed with water or leachate. This can be attributed to the test conditions, since the clayey sand has a low permeability that delays a reduction in the soil suction which increases the resistance force between the soil particles (Bowders and Daniel 1987).

#### 4.4.1.2.2 Peak Shear Stress versus Normal Stress

The peak shear stress versus the normal stress at failure for the inundation specimens, mixed specimens at 40%, and extracted specimens from the column tests for the natural silty sand are shown in Figure 4.22. Figure 4.22 shows that the fluid type has no significant impact on the shear strength of the soil.

Figure 4.23 shows the test results of the clayey sand under different conditions. It can be noted that the angle of friction increases for specimens that interacted with the leachate. The reduction of the apparent cohesion may be attributed due to the loss of the soil suction as the fluid content is increased.

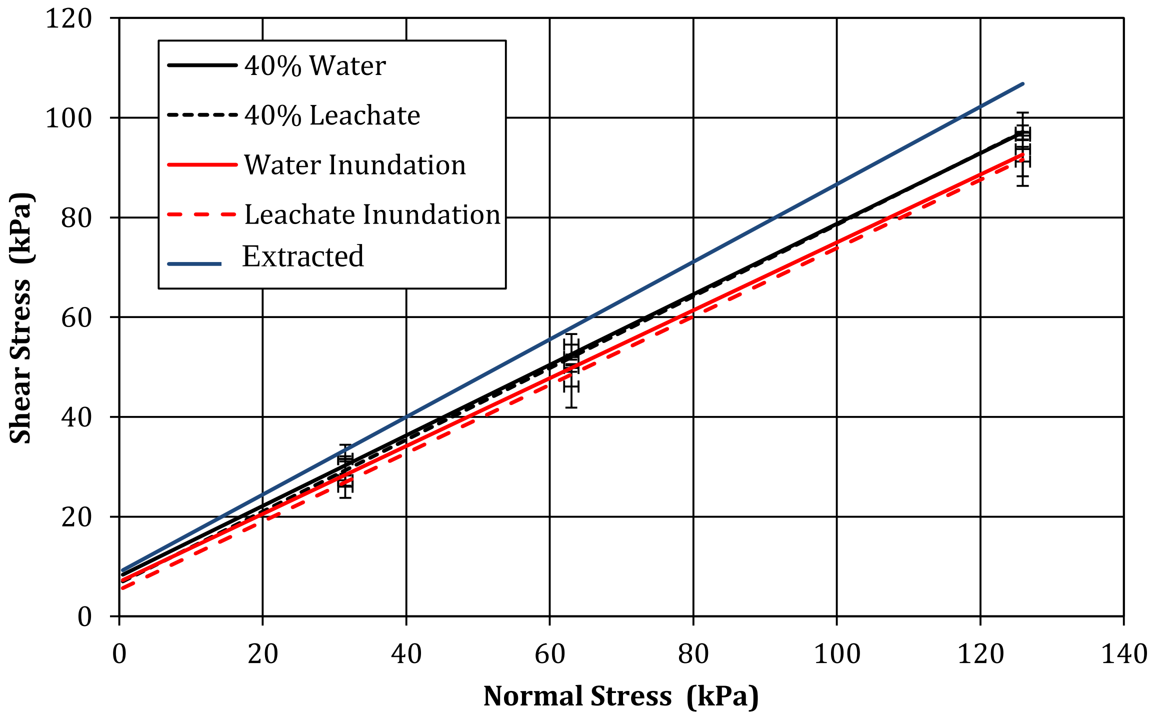


**Figure 4.22: Failure envelopes for silty sand (Test Series II)**

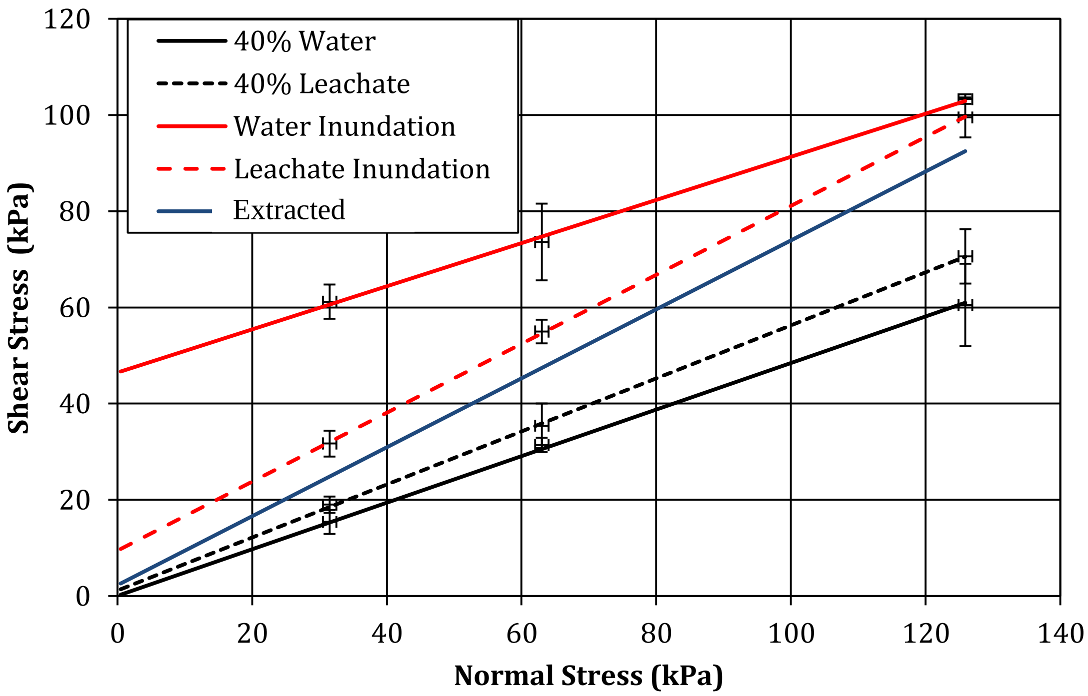


**Figure 4.23: Failure envelopes for clayey sand (Test Series II)**

#### 4.4.1.3 Effect of ageing (with Leachate/Water) on shear strength (Test Series III)

As previously described in this chapter, the ageing stage recreates the effect of the passage of leachate or water through the soil after rainfall or flooding, followed by gradual loss of moisture. This aspect was explored via two direct shear tests on the silty sand specimens and two direct shear tests on the clay sand specimens. The specimen preparation and testing details are described in section 3.4.2.3.

##### 4.4.1.3.1 Shear Stress versus Shear Displacement

Figures 4.24, 4.25 and 4.26 illustrate the shear stress versus horizontal displacement curves for the aged silty sand with leachate and water under normal stresses of 31.5 kPa, 63 kPa and 125.9 kPa. The test results presented in Figures 4.24 to 4.26 show no significant effect of fluid type on the silty sand. As explained in earlier sections, the sandy soil is mainly influenced by the relative density, the void ratio and the gradation rather than fluid type.

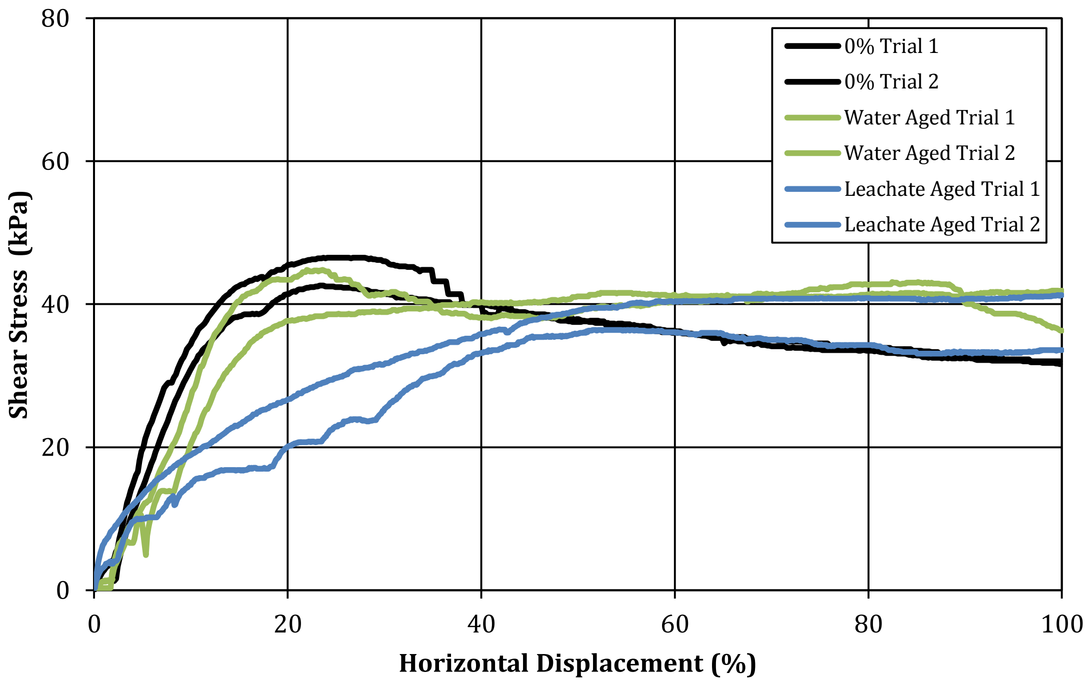


**Figure 4.24: Shear stress - horizontal displacement curves for silty sand at 31.5kPa normal stress**

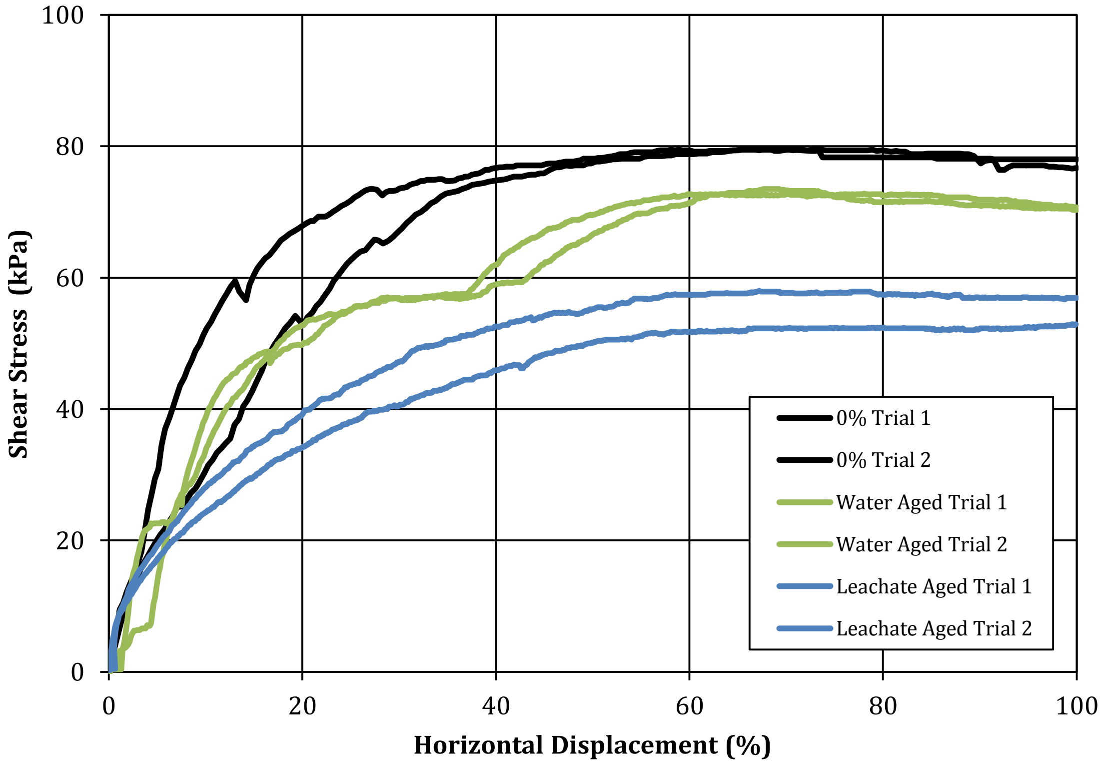


**Figure 4.25: Shear stress - horizontal displacement curves for silty sand at 63kPa normal stress**

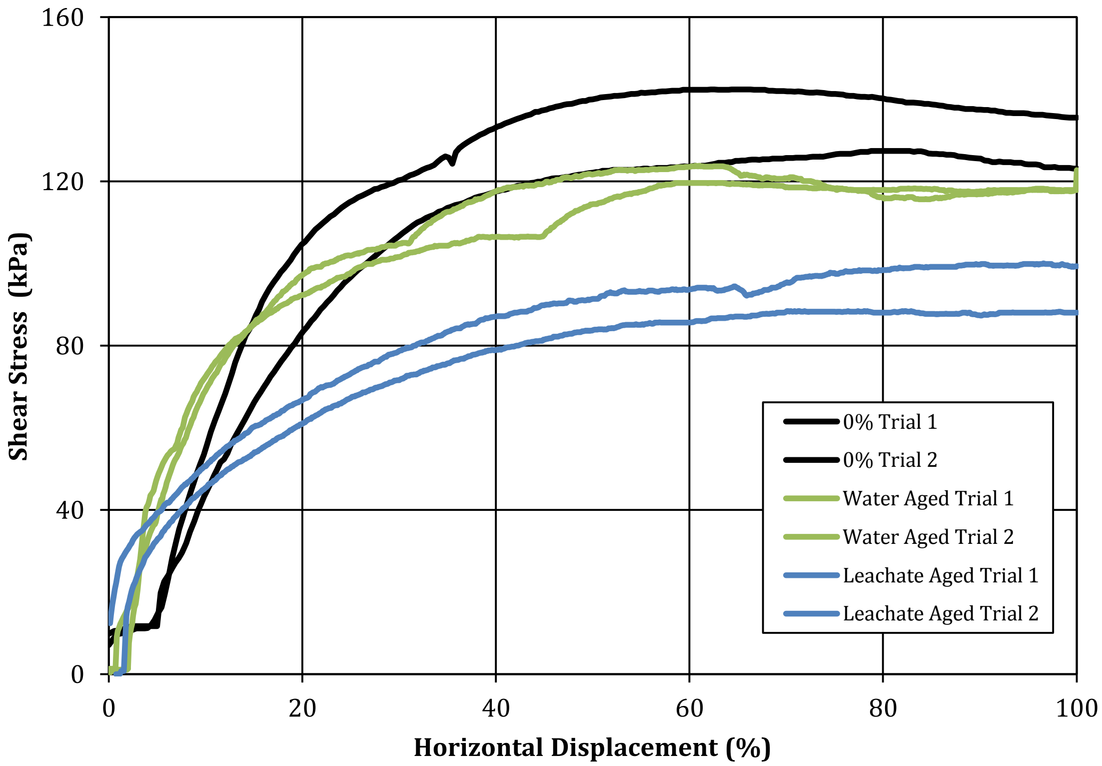


**Figure 4.26: Shear stress - horizontal displacement curves for silty sand at 125.9kPa normal stress**

Figures 4.27, 4.28 and 4.29 present the results for clayey sand specimens. It is apparent that aged specimens with leachate and water show a reduction in the peak stress as compared to the dry specimen, which can be attributed due to a delay in the reduction of soil suction. The aged specimens had moisture content more than 15% which lead to a better lubrication between the soil particles as compared to the dry specimen.

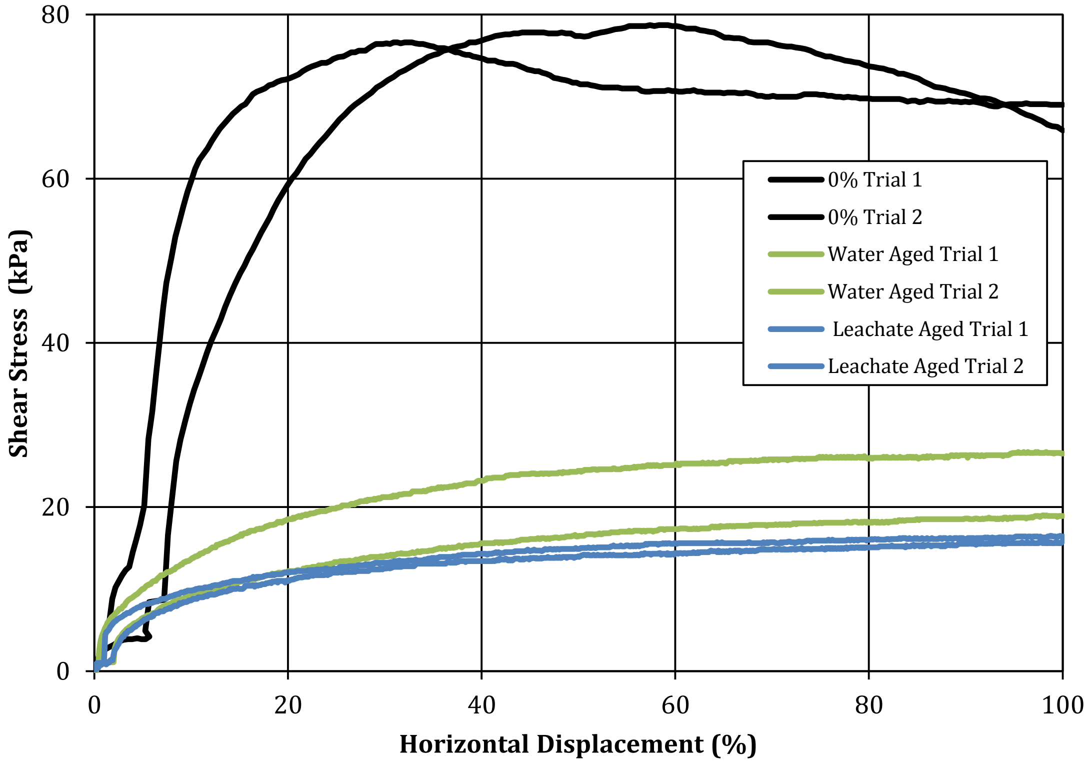


**Figure 4.27: Shear stress - horizontal displacement curves for clayey sand at 31.5kPa normal stress**

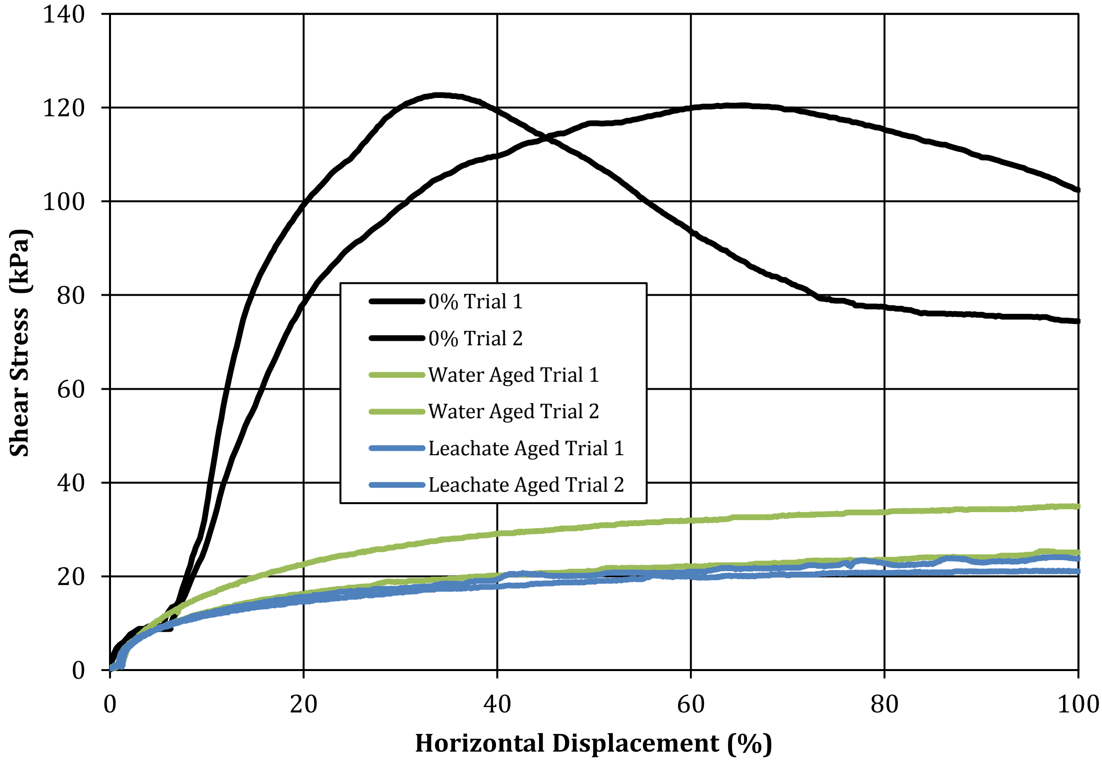


**Figure 4.28: Shear stress - horizontal displacement curves for clayey sand at 63kPa normal stress**

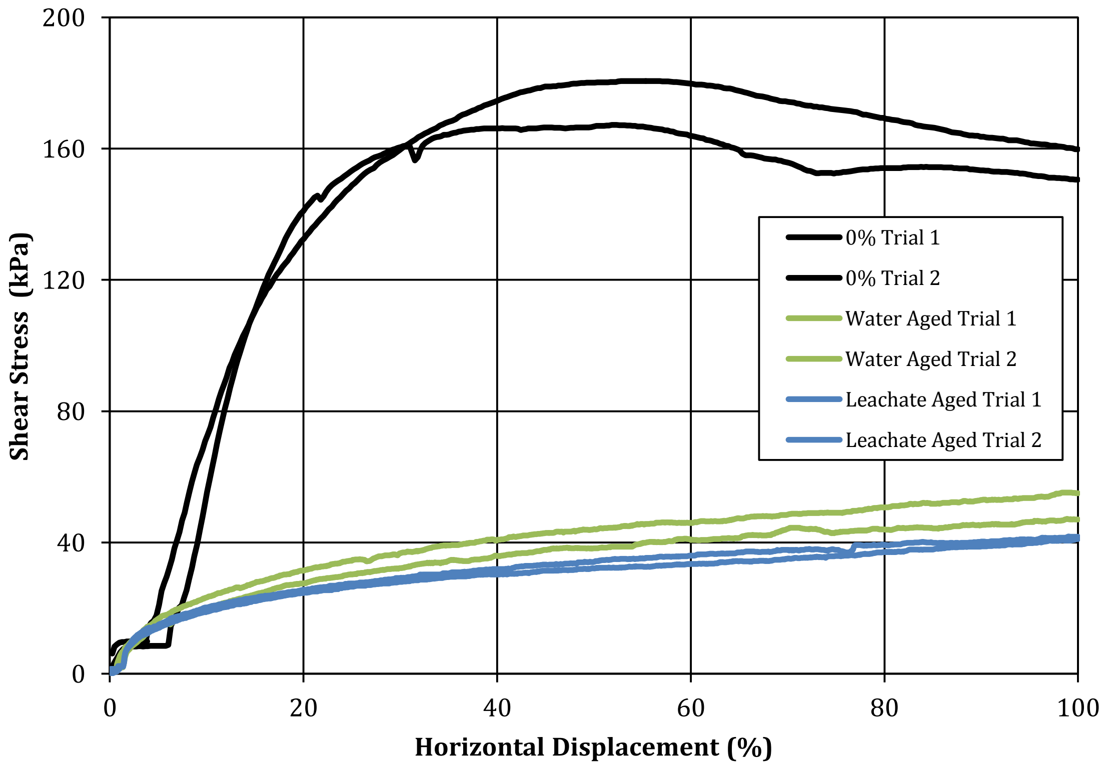


**Figure 4.29: Shear stress - horizontal displacement curves for clayey sand at 125.9kPa normal stress**

#### 4.4.1.3.2 Peak Shear Stress versus Normal Stress

Figure 4.30 shows the relationships between shear stress and vertical stress for the specimens of silty sand with 0% moisture and the aged specimens. Figure 4.30 shows a reduction in the angle of friction of the aged specimens as compared to the dry specimen. The effect of leachate on the shear strength of silty sand is insignificant due to a relatively high permeability and the soil is chemically inert. Similar behaviour can be noted for the specimens of clayey sand (see Fig. 4.31).

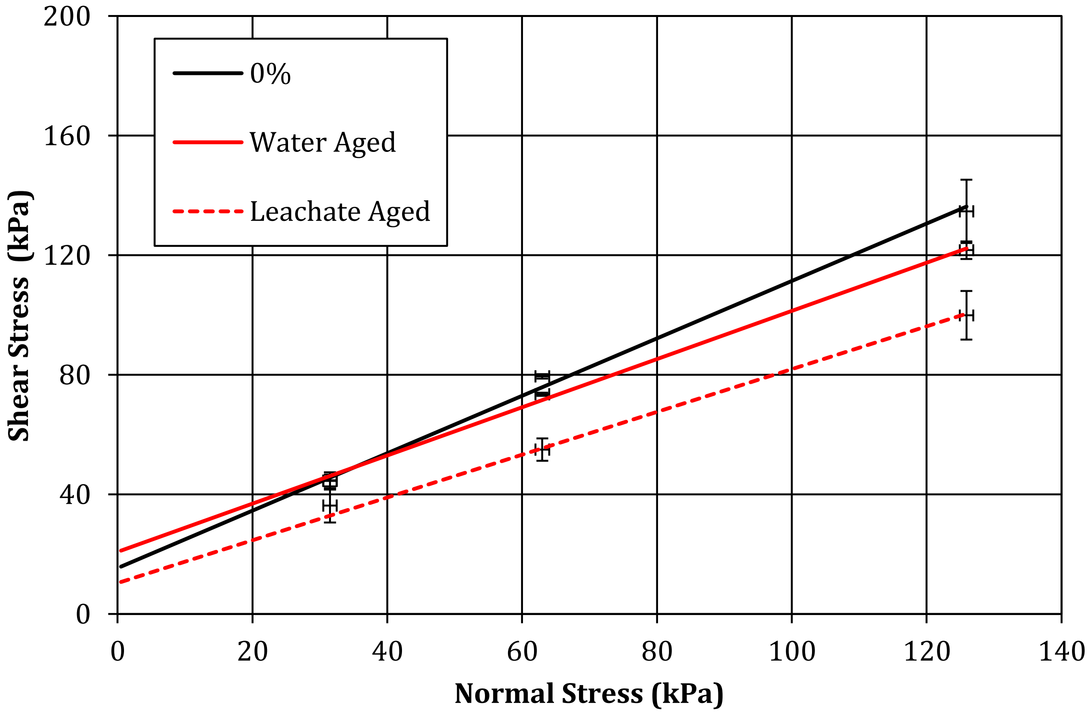


**Figure 4.30: Failure envelopes for silty sand (Test Series III)**

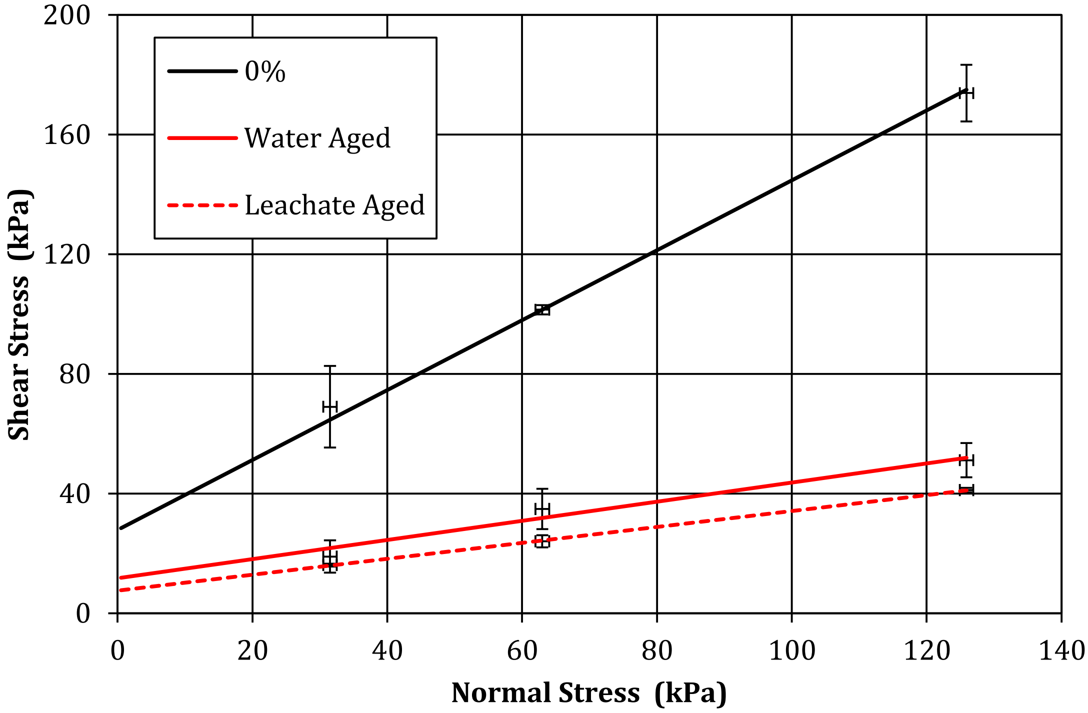


**Figure 4.31: Failure envelopes for clayey sand (Test Series III)**

The angle of friction and the apparent cohesion values from the direct shear tests in test series II, III and V are summarised in Table 5.4. The effect of test conditions (test series I, II, III and V) on the shear strength parameters of the soils follow some distinct trends. For the silty sand, the friction angle is less influenced by the test conditions and the fluid type, whereas the apparent cohesion is significantly influenced by the test conditions. Additionally, the presence of leachate in the soil caused a decrease in the apparent cohesion. For the clayey sand, the test conditions significantly influenced the shear strength parameters. In general, the presence of leachate in the soil caused an increase in the friction angle, whereas the apparent cohesion decreased.

### 4.4.2 One – Dimensional Consolidation Tests

A Study of the effect of landfill leachate on the compressibility and swelling behavior of natural soil is important. The leachate component has many chemical properties as details in section 4.2, and these chemicals can cause excessive settlements and lead to serious consequence. In the literature review (chapter 2), many studies alert us to the effect of the unlined landfill and the compressibility of soils.

Table 4.6 summarizes the compression index ($C_c^*$) and swelling index ($C_s^*$) of the soils tested in various test series. The following sections present the stress (σ) – void ratio (e) relationships of the soils.

**Table 4.6: Compression and swelling indices for interaction of natural soil and leachate/water**

| Test Series | Soil Type | | Silty Sand | | Clayey Sand | |
|---|---|---|---|---|---|---|
| | Method | Moisture Type | $C_c^*$ | $C_s^*$ | $C_c^*$ | $C_s^*$ |
| I | 0% | - | 0.06 | 0.007 | 0.13 | 0.01 |
| | 10% | Water | 0.02 | 0.008 | 0.05 | 0.009 |
| | | Leachate | 0.02 | 0.007 | 0.09 | 0.008 |
| | 20% | Water | 0.03 | 0.007 | 0.17 | 0.008 |
| | | Leachate | 0.03 | 0.006 | 0.15 | 0.008 |
| | 40% | Water | 0.04 | 0.008 | 0.12 | 0.008 |
| | | Leachate | 0.04 | 0.008 | 0.14 | 0.007 |
| II | Inundation | Water | 0.06 | 0.007 | 0.12 | 0.009 |
| | | Leachate | 0.06 | 0.008 | 0.13 | 0.009 |
| III | Ageing | Water | 0.02 | 0.008 | 0.11 | 0.008 |
| | | Leachate | 0.06 | 0.006 | 0.13 | 0.007 |
| V | Extracted | Leachate | 0.05 | 0.008 | 0.12 | 0.009 |

Figures 4.32 to 4.37 show the test results of the soils mixed with leachate and water. Figures 4.38 to 4.39 show the test results for inundation conditions. Figures 4.40 to 4.41 present the results of the aged specimens.

### 4.4.2.1 Effective Stress versus Void Ratio – Mixed Method (Test Series I)

A total of fourteen consolidation tests on the silty sand and fourteen tests on the clayey sand were carried out (section 3.4.2.1). The e – log σ curves of the soils tested under vertical pressures of 25, 50, 100, 200 and 400 kPa are presented in this section.

Consolidation test results for the silty sand mixed with water and leachate are presented in Figure 4.32. The e – log σ curves are for specimens at fluid contents of 0%, 10%, 20% and 40%. At an initial stress, the void ratio of the soil mixed with either leachate or water decreased as the fluid content increased, which can be attributed due to a decrease in suction. At any vertical pressure, the volume change behaviour of specimens with water and leachate are found to be similar.

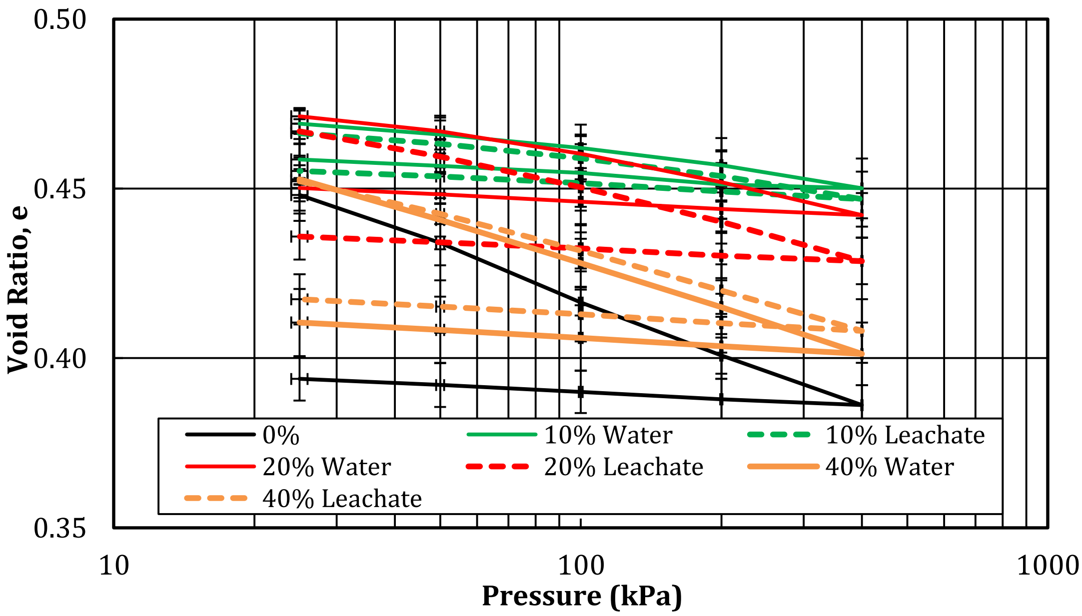


**Figure 4.32: e – log $\sigma$ curve for silty sand mixed with water/leachate (Test Series I)**

Figure 4.33 shows the e – log σ plots for the clayey sand specimens. At an initial stress, the void ratio of the soil mixed with either leachate or water decreased as the fluid content increased. At low moisture the capillary surface tension increases, which holds the moisture more tightly to grains and prevents changes in the void ratio (Vanapalli et al. 1996). However, the soil specimen with a leachate content of 20% exhibited a reduction in the void ratio, which can be attributed to a decrease of the electrical double layer surrounding the clay particles (Arasan 2010).

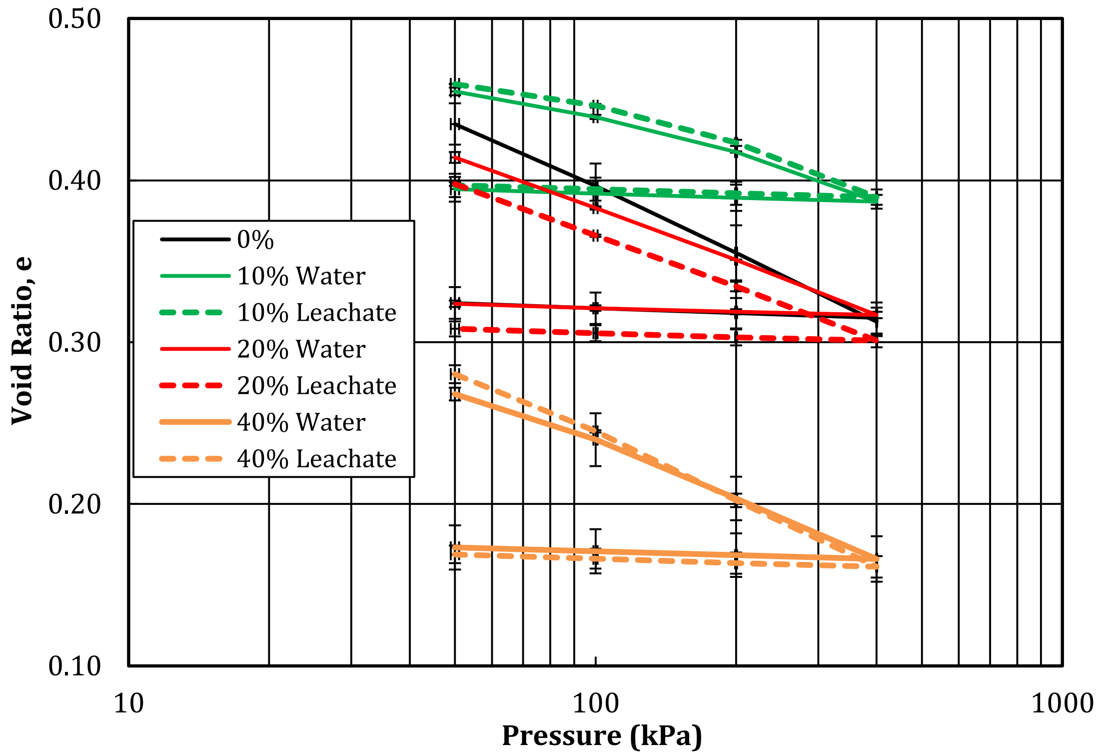


**Figure 4.33: e – log *σ* curve for clayey sand mixed with water/leachate (Test Series I)**

The compression indices of the soils as affected by the fluid type are shown in Figures 4.34 and 4.35. Figure 4.34 shows that the effect of fluid type on the compression index of silty sand is insignificant. This is attributed due to a high permeability of the soil and which is chemically inert. Figure 4.35 shows the leachate specimens compressed more than water specimens that can be attributed to the presence of clay minerals in the clayey sand.

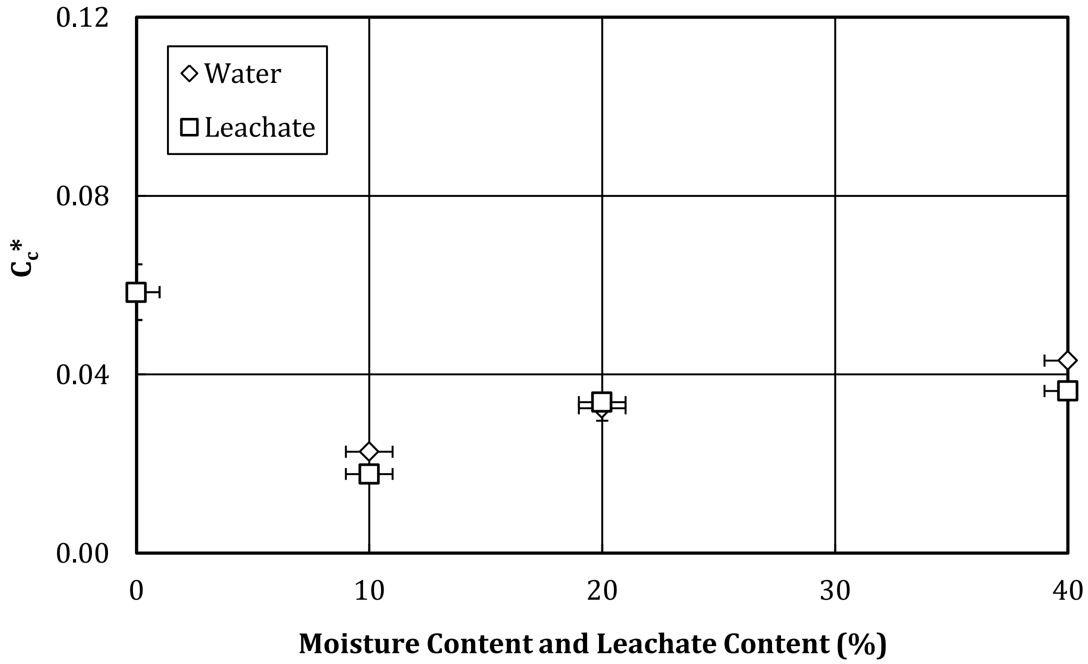


**Figure 4.34: Variation in compression index with leachate/water content for silty sand**

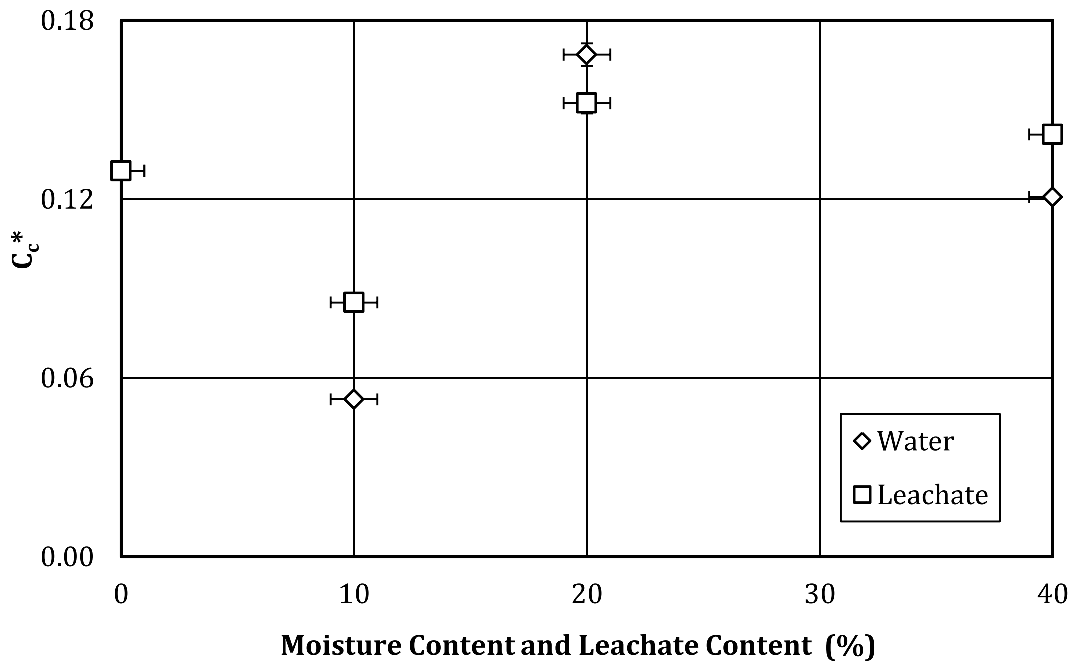


**Figure 4.35: Variation in compression index with leachate/water content for clayey sand**

Figures 4.36 and 4.37 show the variation of swelling index at different fluid percentages, for the silty sand and the clayey sand respectively. The results show the swelling indices of the soils are insignificant because the Kuwait soils are usually classified as non-expansive soils (Ismael et al. 1986).

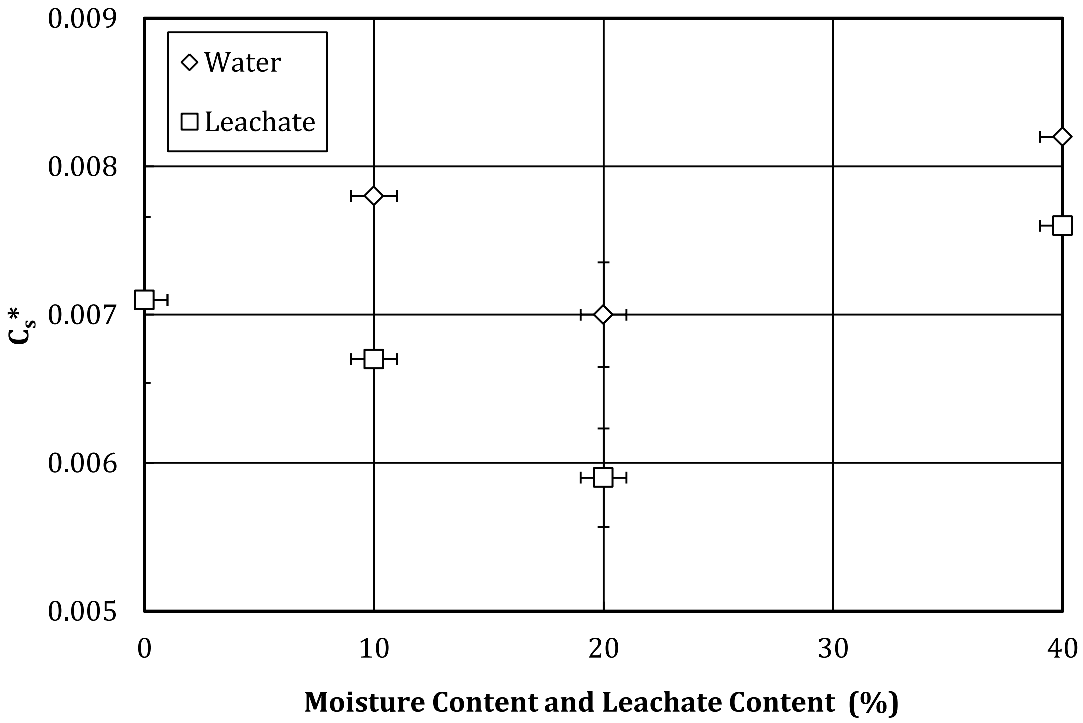


**Figure 4.36: Variation in swelling index with leachate/water content for silty sand**

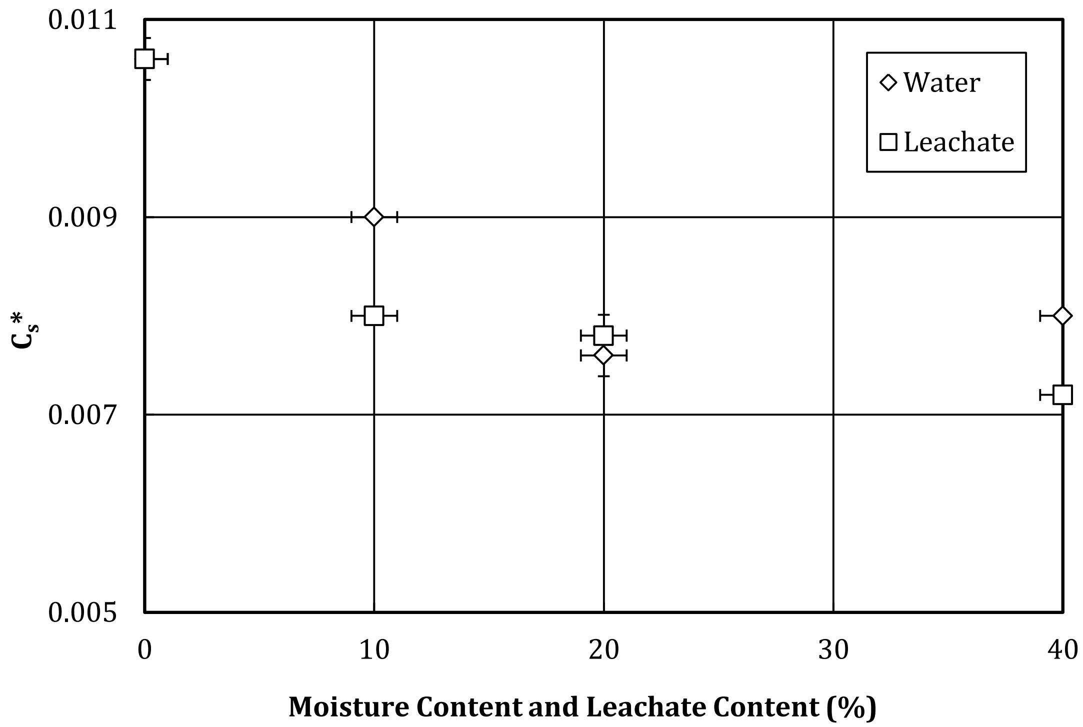


**Figure 4.37: Variation in swelling index with leachate/water content for clayey sand**

#### 4.4.2.2 Effective Stress versus Void Ratio – Inundation Method (Test Series II)

A total of three consolidation tests on the silty sand and three tests on the clayey sand were carried out using the method described in sections 3.4.2.2 and 3.5.2.3. Figures 4.38 and 4.39 show the e – log σ plots of the specimens tested. The results from test series I and V are presented for comparisons for both soils.

Figure 4.38 shows that there is no significant difference between the compressibility behaviour of specimens tested in mixed and inundation methods. However, the extracted specimen remains at higher void ratio which can be attributed due to a low moisture content of the specimen as compared to others. In this case, a higher suction of the specimen prevented a change in the void ratio.

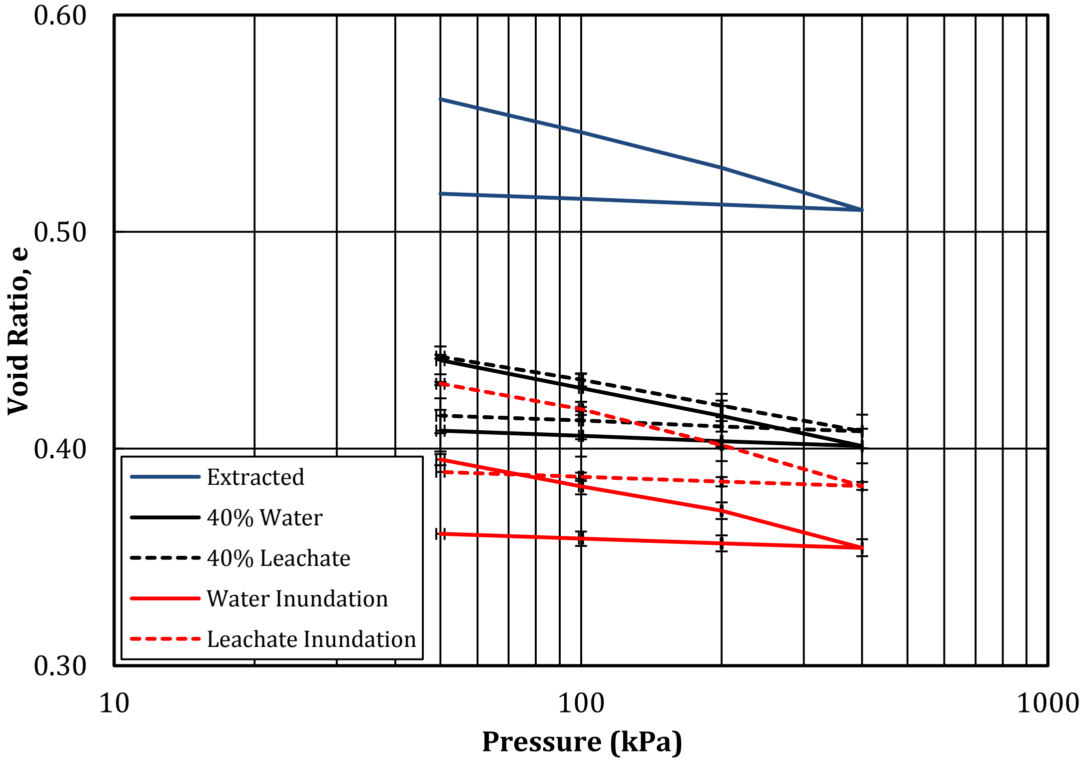


**Figure 4.38: e – log $\sigma$ curve for silty sand (Test Series II)**

Figure 4.39 shows the consolidation test results for the clayey sand specimens. It can be seen that the inundated specimen had higher void ratios as compared to the specimen with 40% fluid content. This can be attributed to the test conditions. A reduction in suction during inundation, fabric and structure of the specimens, and low permeability of the soil contributed to the differences in the void ratios of the specimens.

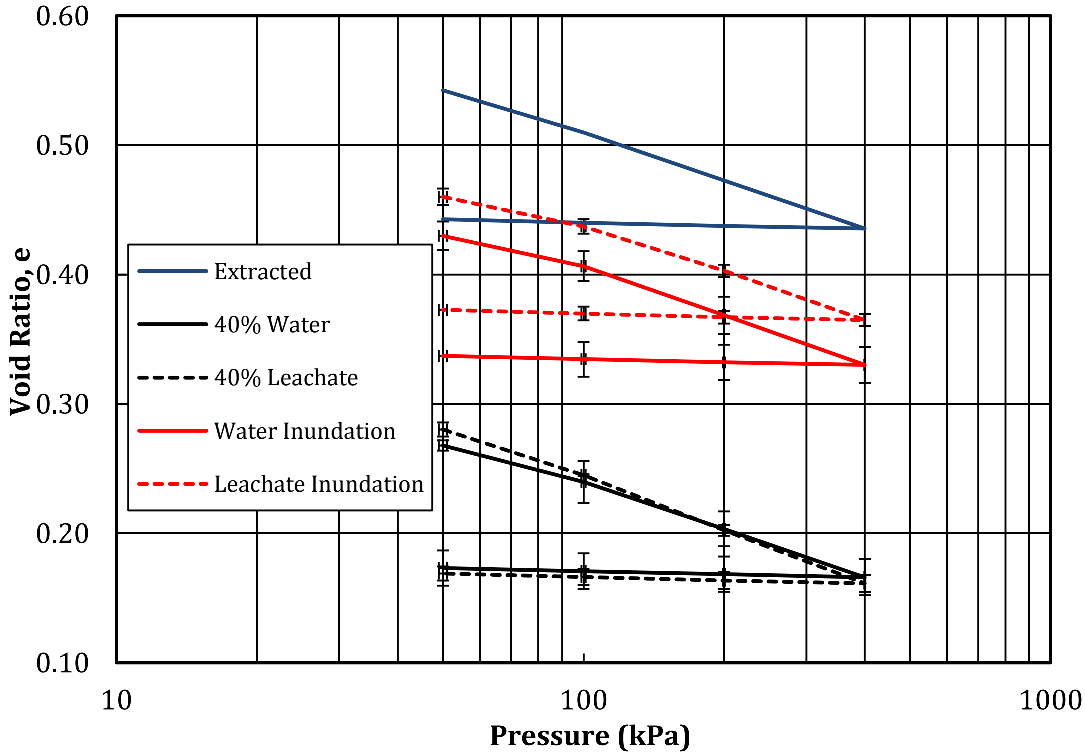


**Figure 4.39: e – log *σ* curve for clayey sand (Test Series II)**

### 4.4.2.3 Effective Stress versus Void Ratio –Ageing Method (Test Series III)

A total of two consolidation tests on the silty sand and two tests on the clayey sand were carried out as described in section 3.4.2.3.

Figure 4.40 illustrates the e – log σ curves of aged silty sand with leachate and water. The test results show that the aged specimen with leachate shows a greater reduction in the void ratio as compared to the soil specimen that was aged with water. The difference in the compressibility behaviour of water – aged and leachate – aged specimens can attributed due to a difference in the initial fluid content; the leachate – aged specimen had higher leachate content (about 5% higher) than the water – aged specimen.

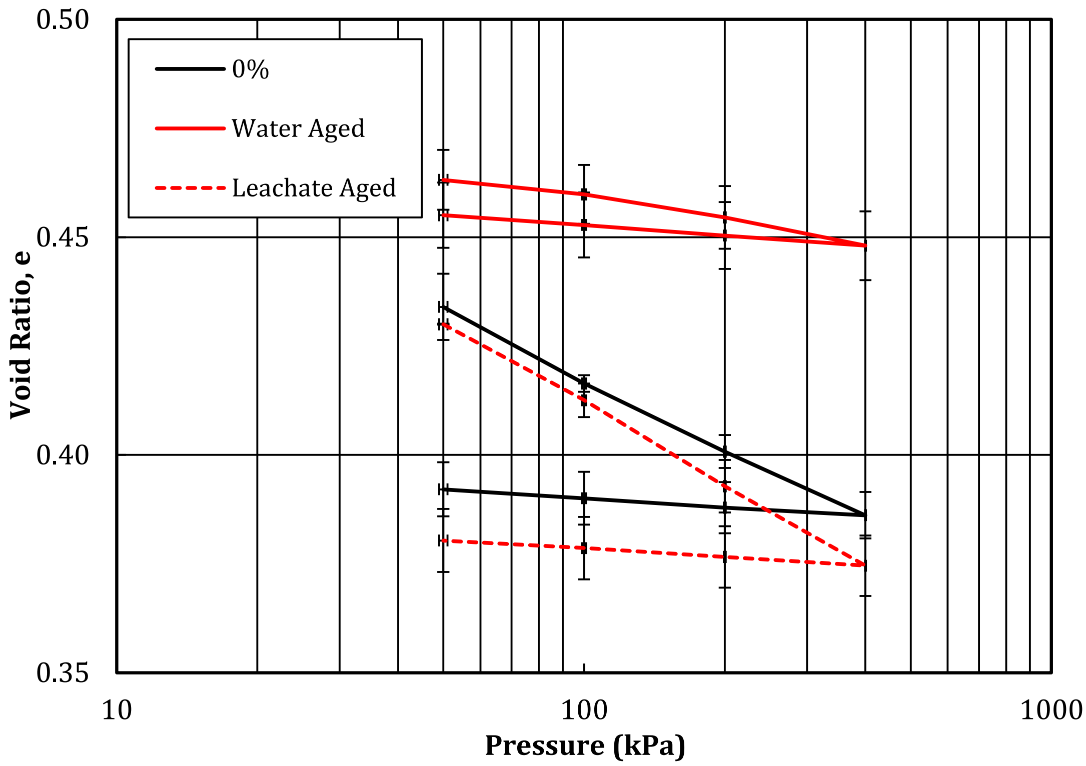


**Figure 4.40: e – log $\sigma$ curve for silty sand (Test Series III)**

Figure 4.41 shows the results of the clayey sand specimens. The leachate – aged specimen compressed more than water – aged specimen. A difference in the compressibility behaviour of the leachate – aged and water – aged specimens can be attributed due to the differences in the initial fluid content and fabric and structure of the specimens.

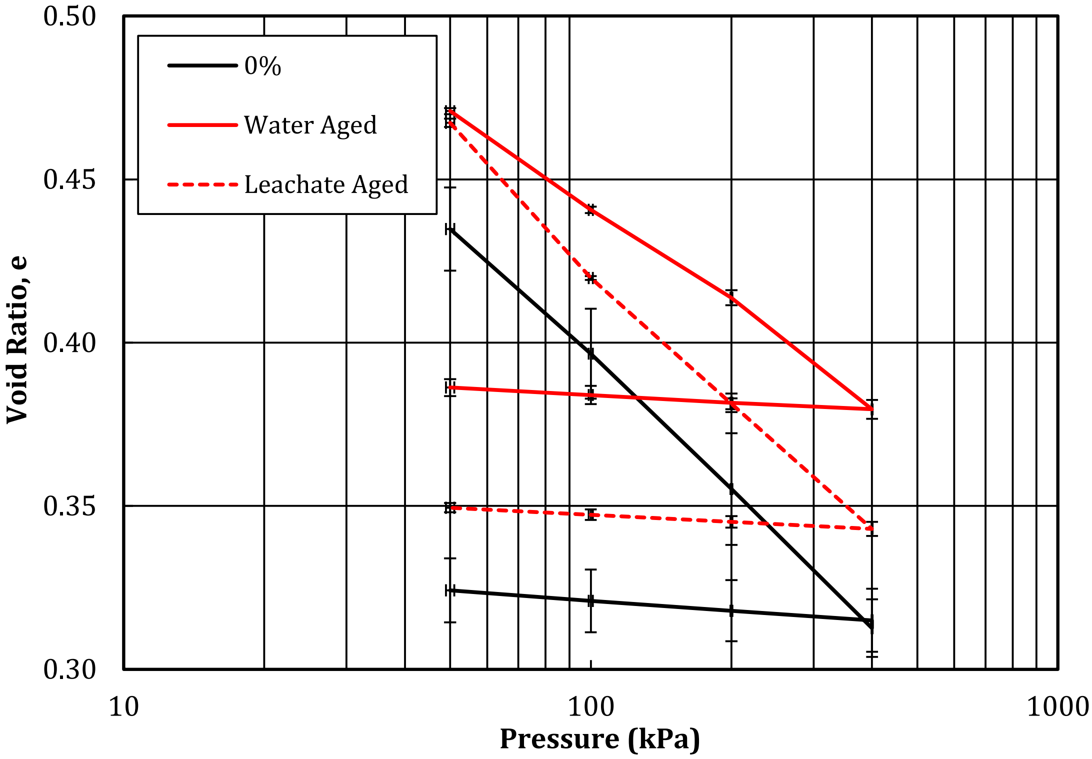


**Figure 4.41: e – log $\sigma$ curve for clayey sand (Test Series III)**

## 4.5 Concluding Remarks

Shear strength and compressibility tests were carried out to study the impact of the landfill leachate on the behaviour of a natural silty sand and a clayey sand. The main observation from this chapter can be summarized as follows:

1. The test results from the investigation provide an insight into the behaviour of natural soils of Kuwait, in the context of landfills.

2. The silty sand has relatively a high permeability and is relatively chemically inert. The leachate has similar effects on the geotechnical properties as that of the water for this soil.

3. The leachate has a significant impact on the geotechnical properties of the clayey sand due to a low permeability and the presence of clay minerals in the soil.

4. Suction effects are present in both soils at low moisture content, yielding apparent cohesion effects.

# Chapter 5

# GEOENVIRONMENTAL PROPERTIES

## 5.1 Introduction

The impact of landfill leachate on the physical and mechanical properties of the soils are presented in chapters 3 and 4. This chapter presents the chemical behaviour of the soils. The interaction between the leachate and the natural soils were studied by focusing on the adsorption and retention properties of the soils. The results presented in this chapter are based on the batch adsorption isotherms and leaching column tests.

## 5.2 Batch Adsorption Isotherms Tests

The batch adsorption tests were carried out to demonstrate the amount of heavy metals that are adsorbed by the soil for different soil solution ratios. The experimental methods which were followed to obtain the results are presented in section 3.5.1. The adsorption data can be fitted using the adsorption equation to investigate whether or not the processes follow Langmuir or Fredlundich isotherms.

Figure 5.1 shows the metal concentration in solution versus the amount of metal adsorbed in the silty sand. From Figure 5.1 it can be observed that the adsorption of heavy metals follow similar trends in that, as the metal concentration in the solution increased, the amount of adsorption increased. The amount of adsorption of Cr is higher than other metals at the early stages of the test at low metal concentrations in solution. The adsorption of Ni is less as compared to the Cr, whereas the adsorption of Cu and As were negligible. The high amount of adsorption of the Cr mainly depends upon the pH of the soil since Cr dissolves well in acid and alkaline soils (Wyszkowska 2001).

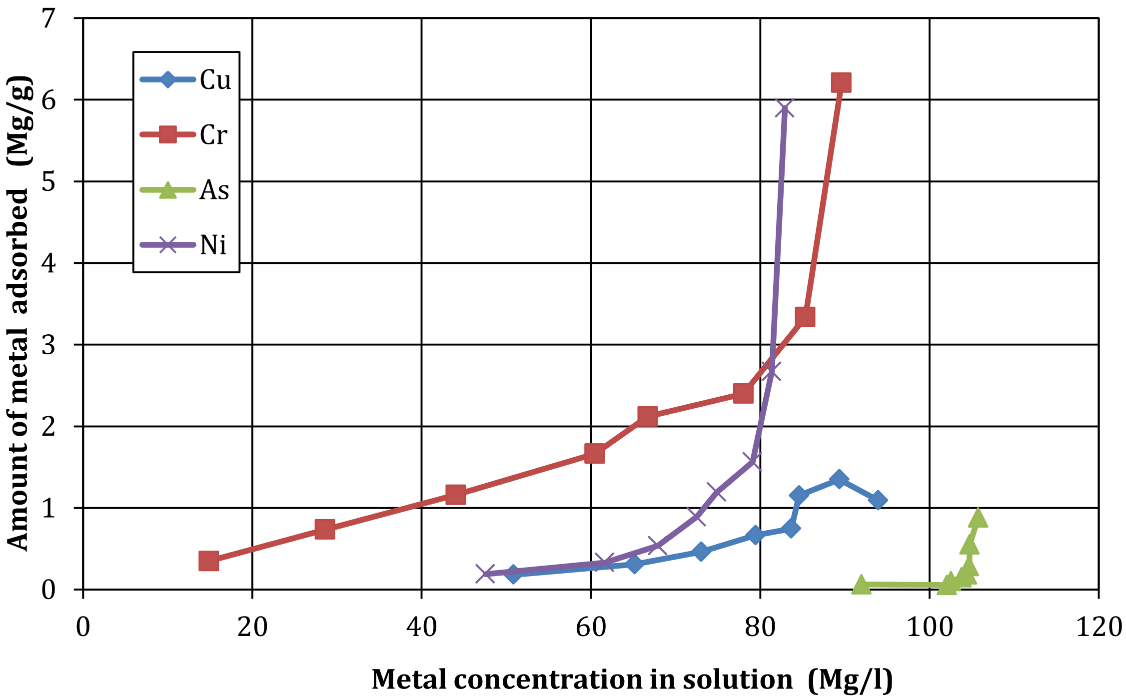


**Figure 5.1: Amount of heavy metals adsorbed in silty sand soil**

The amount of heavy metals adsorption in the clayey sand are shown in Figure 5.2. As the metal concentration in the solution increased the amount of adsorption of the heavy metals increased. About 99% of Cu and Cr in solution were adsorbed at the initial concentration, whereas the amount of Ni and As adsorbed are 68.94% respectively. The clayey sand showed higher levels of metal adsorption as compared to the silty sand. It is apparent that complete adsorption of Cr and Cu occurs at low concentration, which can be attributed to the clay particles tending to disperse at low concentration due to full development of the diffuse double layer, which maximizes the contact between the surface of the clay particles and the solution (Mohammed et al. 1992).

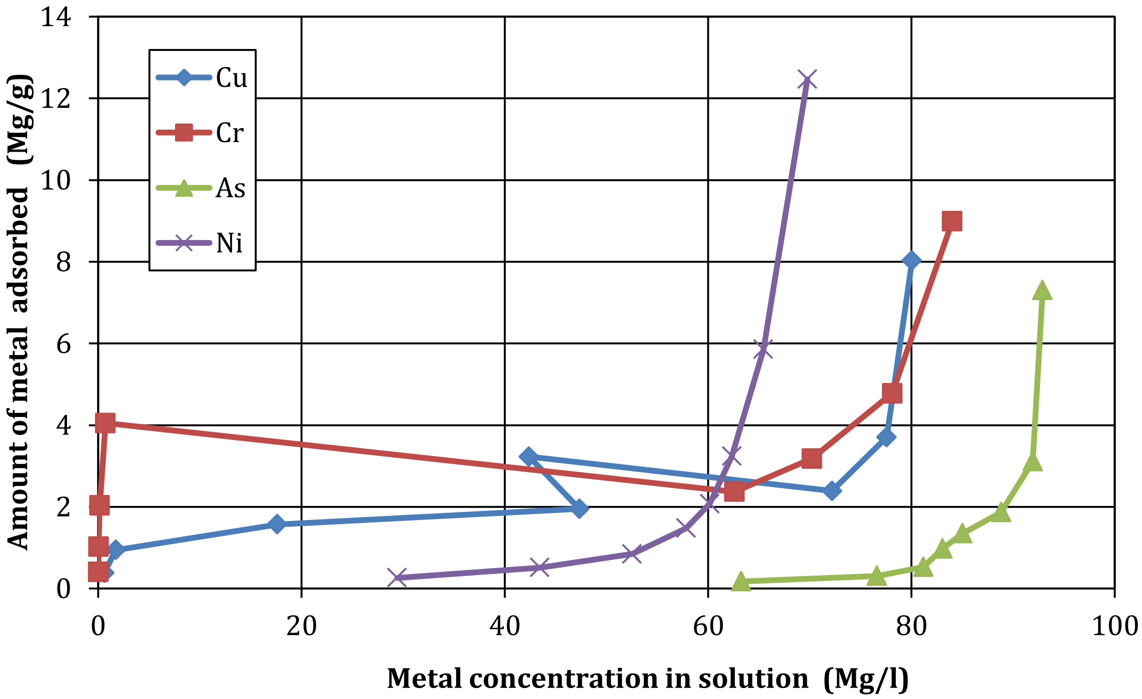


**Figure 5.2: Amount of heavy metals adsorbed in clayey sand soil**

The relationship between the solution concentration and adsorption can be explained by using Langmuir and Freundlich equations (see section 3.5.1). The parameters in Langmuir equation can be obtained by plotting the concentration of the solute adsorbed (x) and the mass of the soil adsorbed (m) as a function of the equilibrium concentration of the solute (C), while the parameters in Freundlich equation can be determined by plotting log (x/m) against log (C). The Freundlich constant parameters ($K_f$, n) can be evaluated from the slope and intercept of the linear equation due to a lack absence of independent evidence concerning the actual retention mechanism (Buchter et al. 1989).

The Langmuir constant parameters (b, K) were obtained from the slope, where b is the maximum adsorption and K is the bonding energy of the adsorption to the adsorbent. The Langmuir isotherm was established based on the equilibrium thermodynamics. It is widely used due to its simplicity and ability to fit a wide range of adsorption data. The model makes a number of assumptions, however, such as equivalent adsorption sites (which means the adsorption sites are equal) and a monolayer of adsorbents (the model suggests a maximum of one layer of adsorption, but the in case of clayey soil more than one is possible). The linear regression ($R^2$) values are used as an indicator that the adsorption data fitted very well.

Figures 5.3 and 5.4 show the plot of the Langmuir and Freundlich linear for the silty sand specimens. Figures 5.5 and 5.6 show the results for the clayey sand specimens.

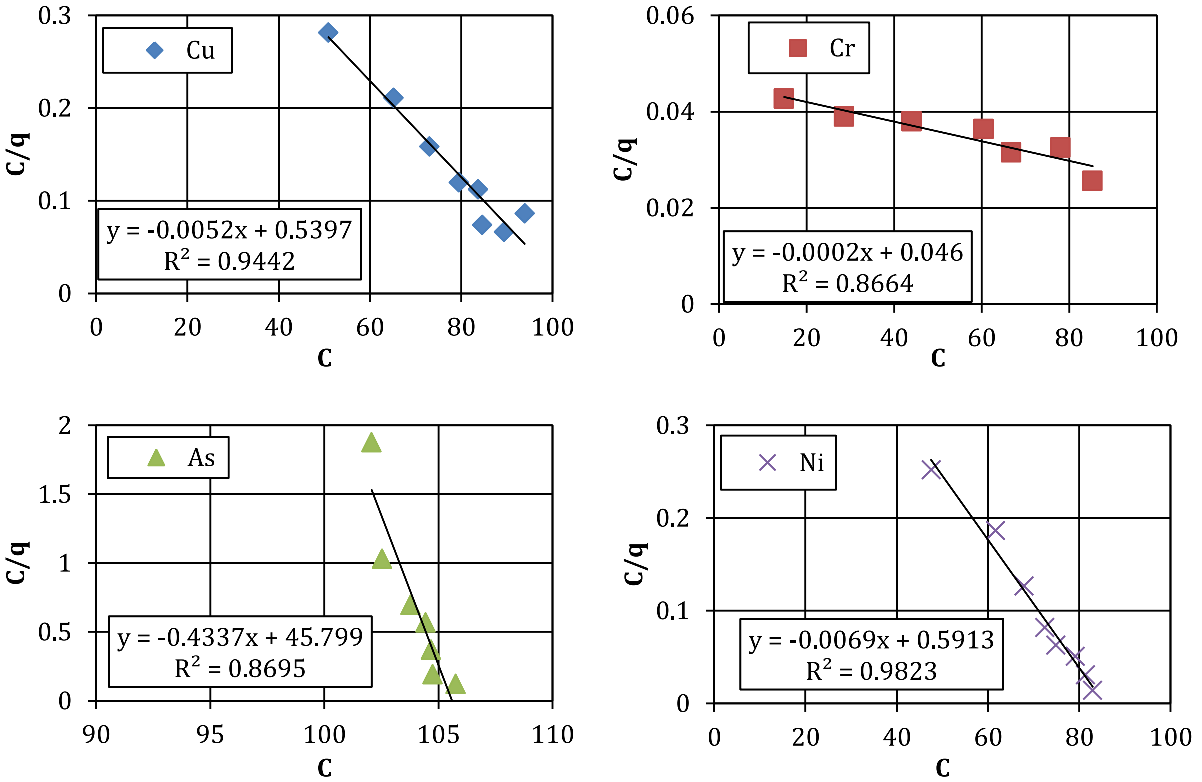


**Figure 5.3: Langmuir plots for silty sand soil**

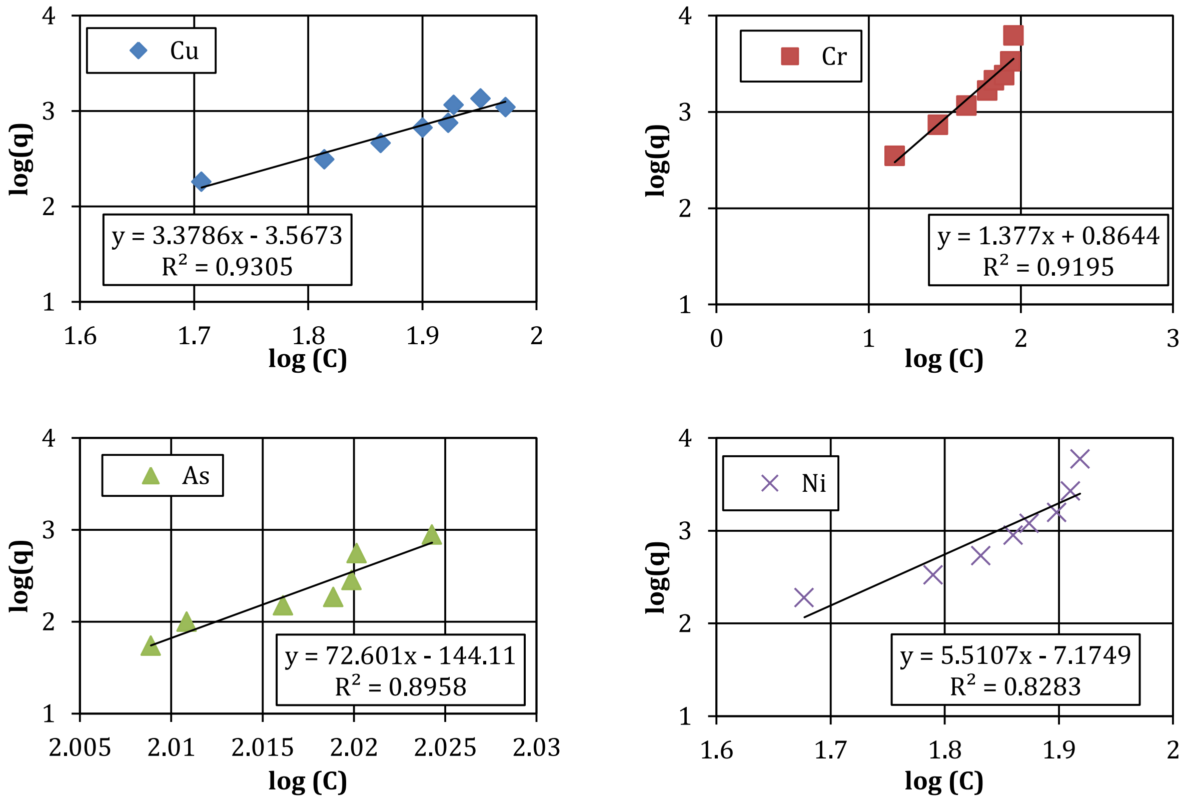


**Figure 5.4: Freundlich plots for silty sand soil**

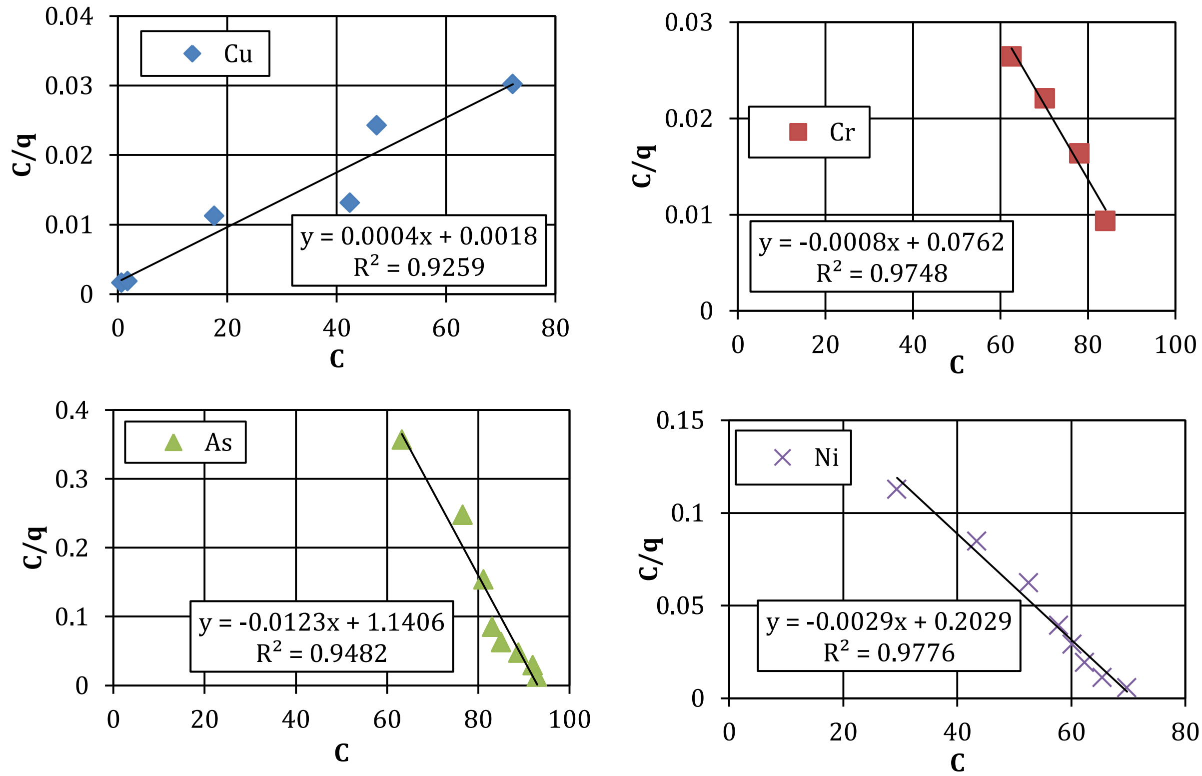


**Figure 5.5: Langmuir plots for clayey sand soil**

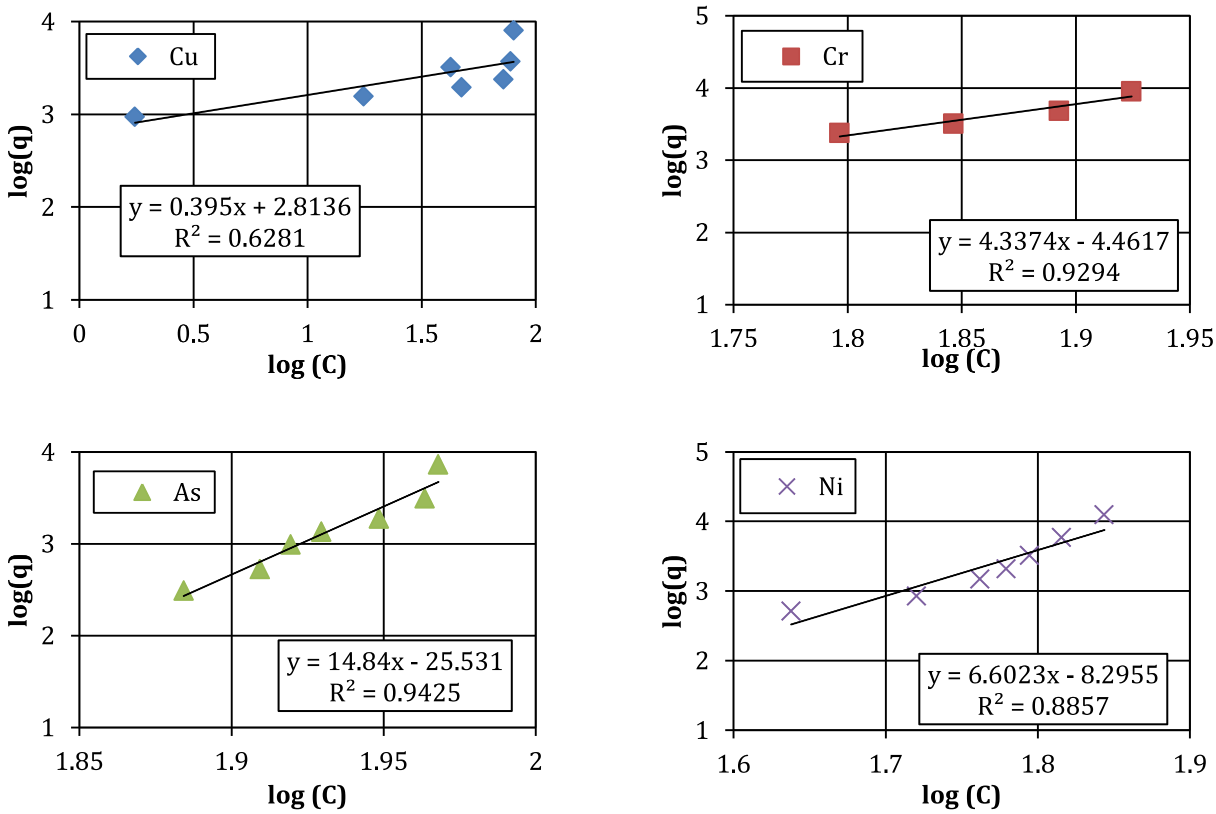


**Figure 5.6: Freundlich plots for clayey sand soil**

The values of linear regression derived from Freundlich and Langmuir model are summarized in Table 5.1. It can be noticed that the linear regression values from Freundlich and Langmuir models fit very well for both soils. The $R^2$ values for all samples were between 0.82 and 0.97, expect for the Cu for the clayey sand soil in the Freundlich model, which was 0.62.

**Table 5.1: The linear regression obtained from Freundlich and Langmuir equation for both soils.**

| Samples | Freundlich Equation | | | | Langmuir Equation | | | |
|---|---|---|---|---|---|---|---|---|
| | Cu | Cr | As | Ni | Cu | Cr | As | Ni |
| | $R^2$ | $R^2$ | $R^2$ | $R^2$ | $R^2$ | $R^2$ | $R^2$ | $R^2$ |
| Silty Sand | 0.931 | 0.920 | 0.896 | 0.828 | 0.949 | 0.866 | 0.870 | 0.982 |
| Clayey Sand | 0.628 | 0.929 | 0.943 | 0.886 | 0.926 | 0.975 | 0.948 | 0.978 |

Table 5.2 lists the adsorption parameters from the Freundlich equation. These consist of the capacity of the adsorbents ($K_f$) and (n). The values for both soils show very low retention capability for heavy metals. Table 5.3 lists the Langmuir equation parameters, namely the maximum adsorption (b) and the bonding energy of the adsorption. The silty sand sample show negligible adsorption and bonding energy for all metals tested, which can be attributed to fact that the particles in the silty sand possess a neutral electrical charge and have insignificant cation exchange capacity. The adsorption of Cr and Cu in the clayey sand are significant. The cations competing with heavy metals for adsorption are primarily Ca and Mg, possibly from the dissolution of soil carbonates in the soil suspension (Udo et al. 1970). There is

no significant bonding energy of the adsorption. The soils with a high pH value are those which contain amorphous oxide content, clay content and carbonate content, and are expected to retain more cations (Buchter et al. 1989).

The Cr showed the highest capacity of adsorbent for the silty sand samples with a value of $K_f$ of 7.32, while the Cu, As and Ni have no capacity of adsorption. Cu and Cr showed the highest value of $K_f$ (541.3 and 1930 respectively) for the clayey sand sample.

**Table 5.2: The parameters of Freundlich equation for both soils**

| Samples | Silty Sand | | Clayey Sand | |
|---|---|---|---|---|
| Parameter | $K_f$ | n | $K_f$ | n |
| Cu | -3.56 | 0.30 | 2.18 | 2.53 |
| Cr | 0.86 | 0.73 | -4.46 | 0.23 |
| As | -144 | -2.3 | -25.50 | 0.07 |
| Ni | -7.17 | 0.18 | -8.30 | 0.15 |

**Table 5.3: The parameters of Langmuir equation for both soils**

| Samples | Silty Sand | | Clayey Sand | |
|---|---|---|---|---|
| Parameter | K | b | K | b |
| Cu | -0.001 | -192 | 0.11 | 5000 |
| Cr | -0.106 | -3333 | 0.003 | 1250 |
| As | -0.001 | -2.3 | -25.50 | -81.3 |
| Ni | -0.012 | -144 | -0.014 | -344 |

## 5.3 Leachate Column Tests

Leachate column tests were carried out to study the attenuation of the leachate within an intact compacted soil column. Four column tests were carried out following the methods described in section 3.5.2. Two column tests (one for the silty sand and one for the clayey sand) were used to investigate the pH of the effluent, permeability values, breakthrough curves and retention profiles, while the other two column tests were used to extract specimens for the direct shear and compression tests presented in chapter 4.

### 5.3.1 The pH and Buffering Capacity of Soils

The pH value of the effluent was measured after every 0.5 PV to evidence the buffering of the various soils on the leachate, which is important to impede the movement of the contamination through the soil columns. The buffering capacity of a soil is the soil's ability to maintain its natural pH against the effects of the leachate. Both soil samples (i.e. silty sand and clayey sand) showed a slightly decreasing trend in the pH value, due to an increase in the pore volume during the leaching cycles.

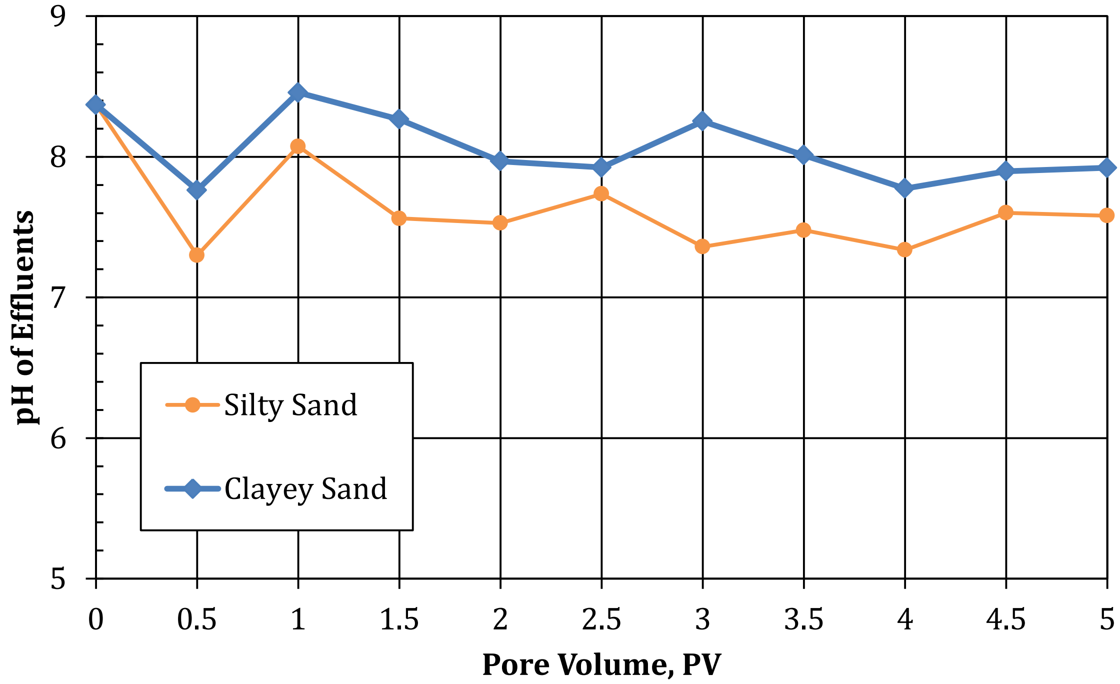


**Figure 5.7: pH value of effluents for soils**

It is interesting to note that the pH value in the effluents for both soils decreased as compared to the influent values, which can be attributed to the dissolution of carbonate in the soils which leads to a decrease in the pH value (Yaacob 2000).

## 5.3.2 Permeability

The permeabilities of the soils with water was first determined during the saturation stage at every 0.5PV up to 2PV, while the permeability of the soil with the leachate was measured after the saturation stage was completed at every 0.5PV up to 5PV as per the method presented in section 3.5.2.4.

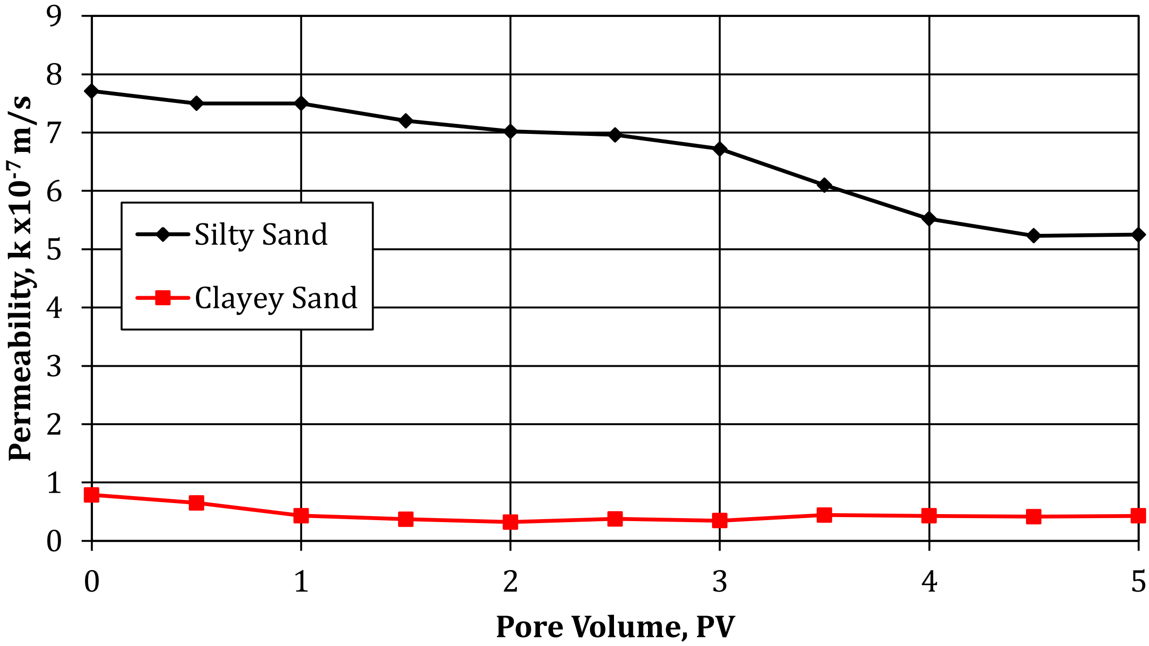


**Figure 5.8: Permeability of the soils from column tests**

Figure 5.8 shows the permeability of the samples of silty sand and clayey sand. The permeability values from 0PV to 2PV are obtained during the saturation stage with water, whereas after 2PV the results are with the leachate. The permeability of the silty sand sample slightly decreased as the pore volume increased, whereas the permeability of the clayey sand sample dropped slightly during the saturation stage (between 0PV and 1PV). After that, the value remained constant as the pore volume increased.

Table 5.4 summarizes the permeability results for the saturation stage (up to 2PV) and leachate inflow stage (up to 5PV) for both soils. A minor decrease of the permeability can be attributed due to a reduction of the void ratio of samples during the fluid flow (Badv and Omidi 2007).

**Table 5.4: Permeability of soils in leaching column tests (with water and leachate)**

| Soil Type | Permeability ($k \times 10^{-7}$ m/s) | |
|---|---|---|
| | with water | with leachate |
| Silty Sand | 7.71 | 5.25 |
| Clayey Sand | 0.79 | 0.43 |

## 5.3.3 Retention of Heavy Metals in Soil Columns

The retention of heavy metals in a column test can be explained by the breakthrough curves of the contamination obtained from the effluent. The heavy metals movement was measured using the acid digestion method described in section 3.5.2.6, as a function of depth of the soil column.

### 5.3.3.1 Breakthrough Curves

The breakthrough curves can be defined as the plot of the concentration of contaminate in the effluent ($C_e$) to the input test leachate concentration ($C_o$) at a point in the column versus time.

Figure 5.9 shows the breakthrough curves of the heavy metals Arsenic, Chromium, Copper and Nickel during the leachate flow stage up to 5 PV for the silty sand. For Cr and Cu the $C_e/C_o$ values increased and it becomes nearly constant after 2PV, whereas the $C_e/C_o$ values of Ni showed a rapid increase as the pore volume increased. The results show that the silty sand possesses a less ability to attenuate the contamination components, which can be explained by the absence of ion exchange in the soil (Bright et al. 1993). The value of $C_e/C_o$ for As is found to be about 2.

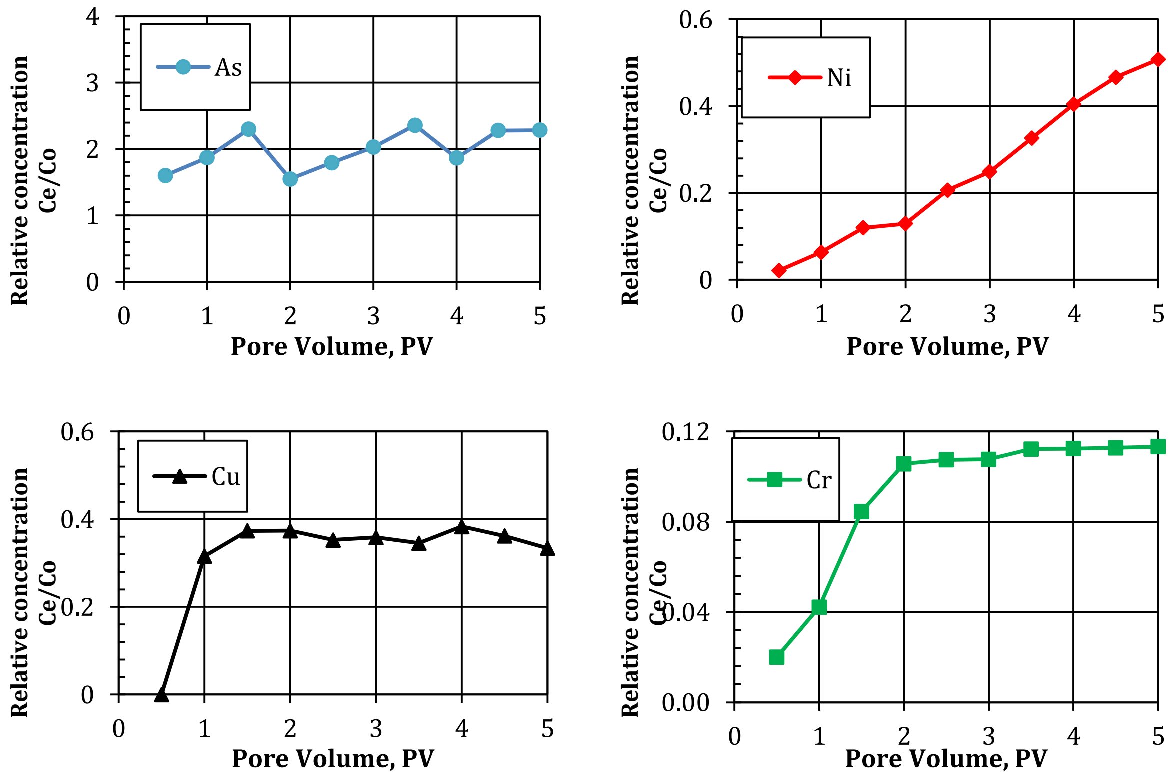


**Figure 5.9: Breakthrough curves for the heavy metals of silty sand soil**

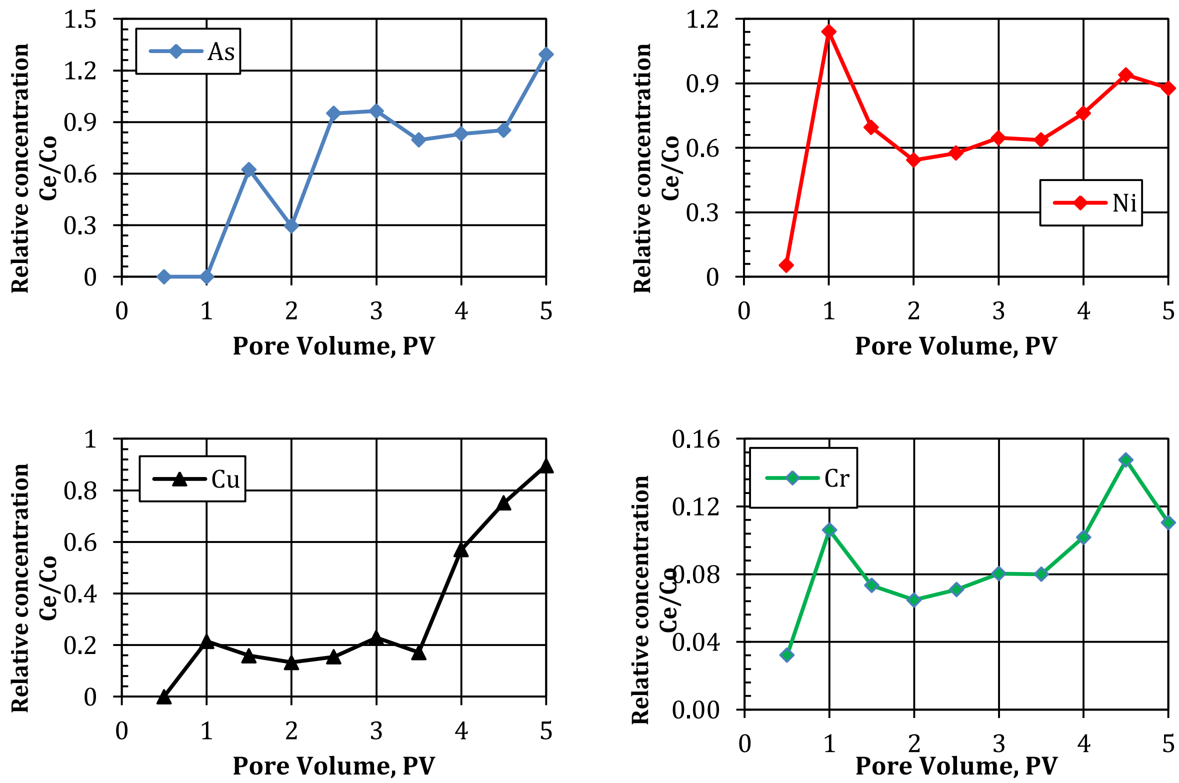


**Figure 5.10: Breakthrough curves for the heavy metals of clayey sand soil**

The breakthrough curves of heavy metals in clayey sand sample are shown in Figure 5.10. The values of $C_e/C_o$ of Cr and Ni gently varied as the pore volume increased. The ability of the clayey sand to attenuate the contamination is shown to be better than the silty sand, which is due to the attenuation of heavy metals from cations exchange and the replacement of the Cr and Ni over other cations types. However the $C_e/C_o$ values of As after 2.5PV and Cr after 0.5PV are found be greater than 1.

#### 5.3.3.2 Heavy Metals Retention Profiles

The retention profiles of heavy metals were determined from the slices of the soil columns after completion of the leaching tests. Acid digestion method was used for this purpose.

The retention of heavy metals with depth for the silty sand is shown in Figure 5.11. It can be observed from Figure 5.1 that the retention decreased with depth of the soil column until a depth of 72 mm. The retention of heavy metals appears to be limited, which can be explained by a lack of an ionic exchange mechanism on the surface of the silt and sand particles (Buchter et al. 1989). However, Figure 5.12 shows that the retention of heavy metals by the clayey sample occurred at the top of the soil column, which can be attributed due to the presence of clay minerals that adsorbed heavy metals from the solution (Mohammed et al. 1992).

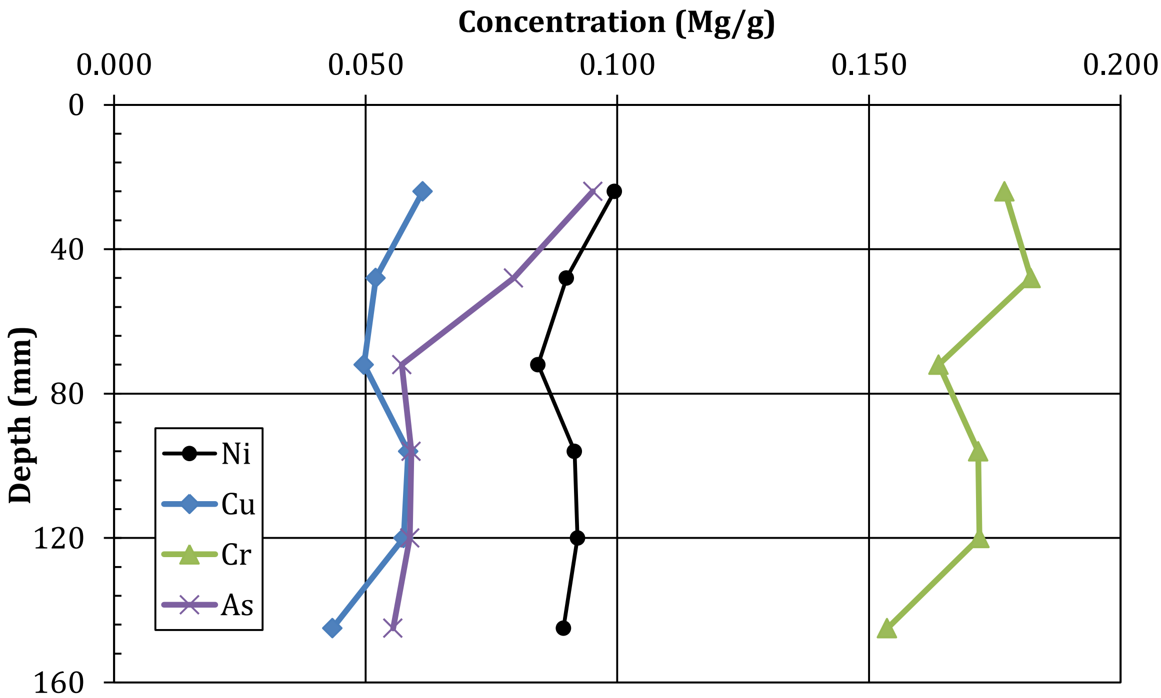


**Figure 5.11: The retention of heavy metals with depth for silty sand column**

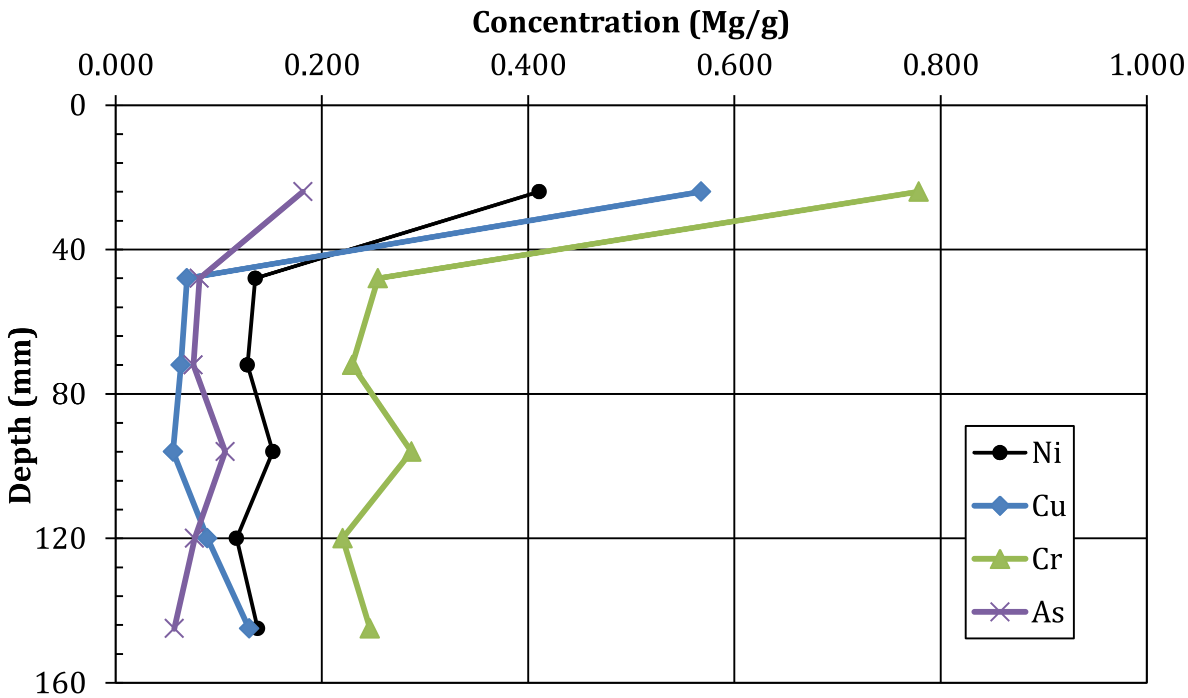


**Figure 5.12: The retention of heavy metals with depth for clayey sand column**

#### 5.3.3.3 Mass Balance Calculation on Heavy Metals from Column Tests

Mass balance calculations were used to verify the balance between the mass input of heavy metals in the leachate after five pore volumes and the mass of heavy metals leached out. The total mass retained was quantified using the acid digestion method described in section 3.5.2.5. The sum of the mass retained and the mass of the effluents are compared to the mass of the influents, which provides a quality check on the experimental data.

The mass balance is based on the classical concept in that the total mass of a system remains unchanged. Mass balance shows the amount of contamination entering a system should be equal to the amount of the contamination leaving, retained or changed within the system (Yaacob 2000). The mass balance was calculated for certain heavy metals, such as Cr, Cu, As and Ni. It is recommended by Yaacob (2000) that the quality of the data used should be checked with a mass balance calculation prior to leachate movement modeling.

The calculation of the input and output mass of the heavy metals after 5PV from the column test for each soil are shown in the Table 5.5. It can be seen from Table 5.5 that the mass of each metal per 0.5PV for each soil calculated separately based on the final concentration of the metal obtained from the ICE and the volume of the effluent as presented in section 3.5.2.4. The sum of each 0.5PV is presented as the mass of the metal/5PV which can be defined as the total effluents output. The total effluents output was used in the mass balance calculation.

**Table 5.5: Summary of input and output of the heavy metals from column tests**

| Soil | Silty Sand | | | | | | Clayey Sand | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Metal Name | Input Mass of metal / 5PV (Mg) | PV | Final Conc. (Mg/l) | Volume of effluent (l) | Mg of metal /0.5PV (Mg) | Mg of metal /5PV (Mg) | Input Mass of metal / 5PV (Mg) | PV | Final Conc. (Mg/l) | Volume of effluent (l) | Mg of metal /0.5PV (Mg) | Mg of metal /5PV (Mg) |
| Cu | 0.236 | 0.5 | 0.0000 | 0.2239 | 0.0000 | 0.0700 | 0.236 | 0.5 | 0.0000 | 0.1848 | 0.0000 | 0.0769 |
| | | 1 | 0.0409 | 0.1750 | 0.0072 | | | 1 | 0.0279 | 0.1830 | 0.0051 | |
| | | 1.5 | 0.0484 | 0.1859 | 0.0090 | | | 1.5 | 0.0206 | 0.1819 | 0.0037 | |
| | | 2 | 0.0484 | 0.1817 | 0.0088 | | | 2 | 0.0172 | 0.1748 | 0.0030 | |
| | | 2.5 | 0.0457 | 0.1614 | 0.0074 | | | 2.5 | 0.0200 | 0.1958 | 0.0039 | |
| | | 3 | 0.0465 | 0.1757 | 0.0082 | | | 3 | 0.0297 | 0.1874 | 0.0056 | |
| | | 3.5 | 0.0448 | 0.1628 | 0.0073 | | | 3.5 | 0.0222 | 0.1711 | 0.0038 | |
| | | 4 | 0.0497 | 0.1516 | 0.0075 | | | 4 | 0.0739 | 0.1879 | 0.0139 | |
| | | 4.5 | 0.0469 | 0.1570 | 0.0074 | | | 4.5 | 0.0974 | 0.1688 | 0.0164 | |
| | | 5 | 0.0433 | 0.1694 | 0.0073 | | | 5 | 0.1161 | 0.1848 | 0.0215 | |
| Cr | 0.532 | 0.5 | 0.0059 | 0.2239 | 0.0013 | 0.0454 | 0.532 | 0.5 | 0.0094 | 0.1848 | 0.0017 | 0.0459 |
| | | 1 | 0.0123 | 0.1750 | 0.0022 | | | 1 | 0.0310 | 0.1830 | 0.0057 | |
| | | 1.5 | 0.0247 | 0.1859 | 0.0046 | | | 1.5 | 0.0214 | 0.1819 | 0.0039 | |
| | | 2 | 0.0309 | 0.1817 | 0.0056 | | | 2 | 0.0189 | 0.1748 | 0.0033 | |
| | | 2.5 | 0.0314 | 0.1614 | 0.0051 | | | 2.5 | 0.0207 | 0.1958 | 0.0041 | |
| | | 3 | 0.0315 | 0.1757 | 0.0055 | | | 3 | 0.0235 | 0.1874 | 0.0044 | |
| | | 3.5 | 0.0328 | 0.1628 | 0.0053 | | | 3.5 | 0.0234 | 0.1711 | 0.0040 | |
| | | 4 | 0.0329 | 0.1516 | 0.0050 | | | 4 | 0.0298 | 0.1879 | 0.0056 | |
| | | 4.5 | 0.0330 | 0.1570 | 0.0052 | | | 4.5 | 0.0431 | 0.1688 | 0.0073 | |
| | | 5 | 0.0331 | 0.1694 | 0.0056 | | | 5 | 0.0323 | 0.1848 | 0.0060 | |
| As | 0.639 | 0.5 | 0.0563 | 0.2239 | 0.0126 | 0.1213 | 0.639 | 0.5 | 0.0000 | 0.1848 | 0.0000 | 0.4240 |
| | | 1 | 0.0657 | 0.1750 | 0.0115 | | | 1 | 0.0000 | 0.1830 | 0.0000 | |
| | | 1.5 | 0.0808 | 0.1859 | 0.0150 | | | 1.5 | 0.2191 | 0.1819 | 0.0398 | |
| | | 2 | 0.0545 | 0.1817 | 0.0099 | | | 2 | 0.1038 | 0.1748 | 0.0182 | |
| | | 2.5 | 0.0630 | 0.1614 | 0.0102 | | | 2.5 | 0.3338 | 0.1958 | 0.0653 | |
| | | 3 | 0.0713 | 0.1757 | 0.0125 | | | 3 | 0.3386 | 0.1874 | 0.0634 | |
| | | 3.5 | 0.0829 | 0.1628 | 0.0135 | | | 3.5 | 0.2796 | 0.1711 | 0.0478 | |
| | | 4 | 0.0655 | 0.1516 | 0.0099 | | | 4 | 0.2921 | 0.1879 | 0.0549 | |
| | | 4.5 | 0.0801 | 0.1570 | 0.0126 | | | 4.5 | 0.2997 | 0.1688 | 0.0506 | |
| | | 5 | 0.0803 | 0.1694 | 0.0136 | | | 5 | 0.4541 | 0.1848 | 0.0839 | |
| Ni | 0.300 | 0.5 | 0.0035 | 0.2239 | 0.0008 | 0.0680 | 0.300 | 0.5 | 0.0088 | 0.1848 | 0.0016 | 0.2054 |
| | | 1 | 0.0104 | 0.1750 | 0.0018 | | | 1 | 0.1879 | 0.1830 | 0.0344 | |
| | | 1.5 | 0.0197 | 0.1859 | 0.0037 | | | 1.5 | 0.1146 | 0.1819 | 0.0208 | |
| | | 2 | 0.0214 | 0.1817 | 0.0039 | | | 2 | 0.0894 | 0.1748 | 0.0156 | |
| | | 2.5 | 0.0340 | 0.1614 | 0.0055 | | | 2.5 | 0.0949 | 0.1958 | 0.0186 | |
| | | 3 | 0.0410 | 0.1757 | 0.0072 | | | 3 | 0.1065 | 0.1874 | 0.0200 | |
| | | 3.5 | 0.0538 | 0.1628 | 0.0088 | | | 3.5 | 0.1049 | 0.1711 | 0.0180 | |
| | | 4 | 0.0667 | 0.1516 | 0.0101 | | | 4 | 0.1254 | 0.1879 | 0.0236 | |
| | | 4.5 | 0.0769 | 0.1570 | 0.0121 | | | 4.5 | 0.1548 | 0.1688 | 0.0261 | |
| | | 5 | 0.0836 | 0.1694 | 0.0142 | | | 5 | 0.1445 | 0.1848 | 0.0267 | |

Table 5.6 summarizes the values of the input mass from the column tests ($C_o$) as the input mass of metal/5PV, and the mass of the output effluent ($C_e$) as the output Mg of metal/5PV taken from Table 5.6. The values of mass retained ($C_r$) were measured from the acid digestion test. It can be theoretically expected (Yaacob 2000) that the sum of the retained mass ($C_r$) and the effluent mass ($C_e$) are equal to the influent mass ($C_o$).

**Table 5.6: The mass balance calculation**

| Results | | Column Test | | Acid Digestion | | Δ |
|---|---|---|---|---|---|---|
| Sample | Heavy metals | Input ($C_o$) (Mg) | Output ($C_e$) (Mg) | Retained ($C_r$) (Mg) | $C_T= C_r+C_e$ (Mg) | $C_T/C_o$ (%) |
| Silty Sand | Cu | 0.236 | 0.070 | 0.126 | 0.196 | 83.2 |
| | Cr | 0.532 | 0.045 | 0.383 | 0.429 | 80.5 |
| | As | 0.639 | 0.121 | 0.166 | 0.288 | 45.0 |
| | Ni | 0.300 | 0.068 | 0.204 | 0.272 | 90.8 |
| Clayey Sand | Cu | 0.236 | 0.077 | 0.151 | 0.228 | 96.9 |
| | Cr | 0.532 | 0.046 | 0.481 | 0.527 | 99.0 |
| | As | 0.639 | 0.424 | 0.206 | 0.630 | 98.6 |
| | Ni | 0.300 | 0.205 | 0.268 | 0.473 | 157.8 |

It can be observed from Table 5.6 that for the silty sand the ratio of sum of the retained mass and the effluent mass to the influent mass for Cu, Cr and Ni are 83.2%, 80.5% and 90.8% respectively. For the clayey sand, the mass balance calculation for Cu, Cr and As are 96.9%, 99% and 98.6 respectively. This shows there is a good degree of consistency between the amounts of heavy metals determined from acid digestion with the amount of inputs and outputs of heavy metals in the column tests. However the amount of As in the silty sand and Ni in the clayey sand samples (45% and 157.8% respectively) show a lack of consistency.

## 5.4 Concluding Remarks

The batch adsorption and column tests were carried out to measure the adsorption and retention ability of the soils for heavy metals which will have an impact on the soil structure. The main observations from this chapter can be summarized as follows:

1. The results from the geoenvironmental tests are compatible with the results obtained for the geotechnical properties of the silty sand.

2. The presence of clay minerals plays an important role in the clayey sand and shows the importance of cations exchange in the soil properties

3. The results of heavy metal concentration in the soil column tests soils are in good agreement with those calculated from the mass balance.

# Chapter 6

# MODELLING OF AL-JAHRA SITE

## 6.1 Introduction

In this chapter, the geotechnical test results presented in chapter 4 were used to model the bearing capacity and settlement of the Al-Jahra landfill soil strata. The main intent of this chapter is to investigate the effect of leachate on the geotechnical properties of the soil under different conditions. The model of the bearing capacity for the shallow footing was based on the Terzaghi's theory and the model of settlement was based on one-dimensional primary consolidation. The geoenvironmental results in chapter 5 were used to calibrate and validate the HYDRUS 1D program. The HYDRUS 1D program numerically solves the Richard's equation for variably unsaturated water flow, as well as advection-dispersion type equations for solute transport (Simunek et al. 2009).

## 6.2 Modelling of Al-Jahra Site (Bearing Capacity)

Bearing capacity is a one of the main factors in the structural stability of soil. The ultimate bearing capacity is defined as the maximum foundation pressure the soil can support without occurrence of the shear failure. The calculation of the bearing capacity of shallow foundations is based on Terzaghi (1943)'s theory. The theory is used to calculate the ultimate bearing capacity for square shallow footings (Equation 6.1).

$$q_u = c' N_c + q_o (N_q - 1) + 0.4 \gamma' B N_\gamma \qquad (6.1)$$

where $q_u$ is the ultimate bearing capacity, c' is the effective cohesion of soil, γ' is the submerged unit weight of soil, $D_f$ is the depth of the footing from surface, B is the width of the footing, ($q_o = \gamma D_f$) is equal to the effective overburden stress and $N_c$, $N_q$, $N_\gamma$ are the bearing capacity factors. The bearing capacity factors are defined as non-dimensional parameters that are related to the angle of friction (Equations 6.2, 6.3 and 6.4).

$$N_q = \tan^2\left(45 + \frac{\phi}{2}\right) e^{\pi \tan\phi} \qquad (6.2)$$

$$N_c = \left(N_q - 1\right) \cot\phi \qquad (6.3)$$

$$N_\gamma = 2\left(N_q + 1\right) \tan\phi \qquad (6.4)$$

The common shape and type of foundation design in Kuwait is square or rectangular and shallow foundation (Ismael 1985). The shear strength parameters of the soil (cohesion and angle of friction) were measured with different conditions and moistures types, as described in chapters 3 and 4. The calculation of the allowable bearing capacity was based on the strata of the Al-Jahra landfill. The assumptions made in order to model the bearing capacity of the strata soil are as follows:

1- The first layer is the contaminated layer, and therefore will be excavated and filled with clean clayey or silty sand, with the footing then being placed at the top of the layer.

2- Three sizes of the footing are used to interpret the effect of the size on the bearing capacity; 1m by 1m, 2m by 2m and 3m by 3m.

3- The depth of footing, $D_f$ is 2m.

Figure 6.1 shows a schematic of the assumed footing location with the water table position at the Al-Jahra landfill site.

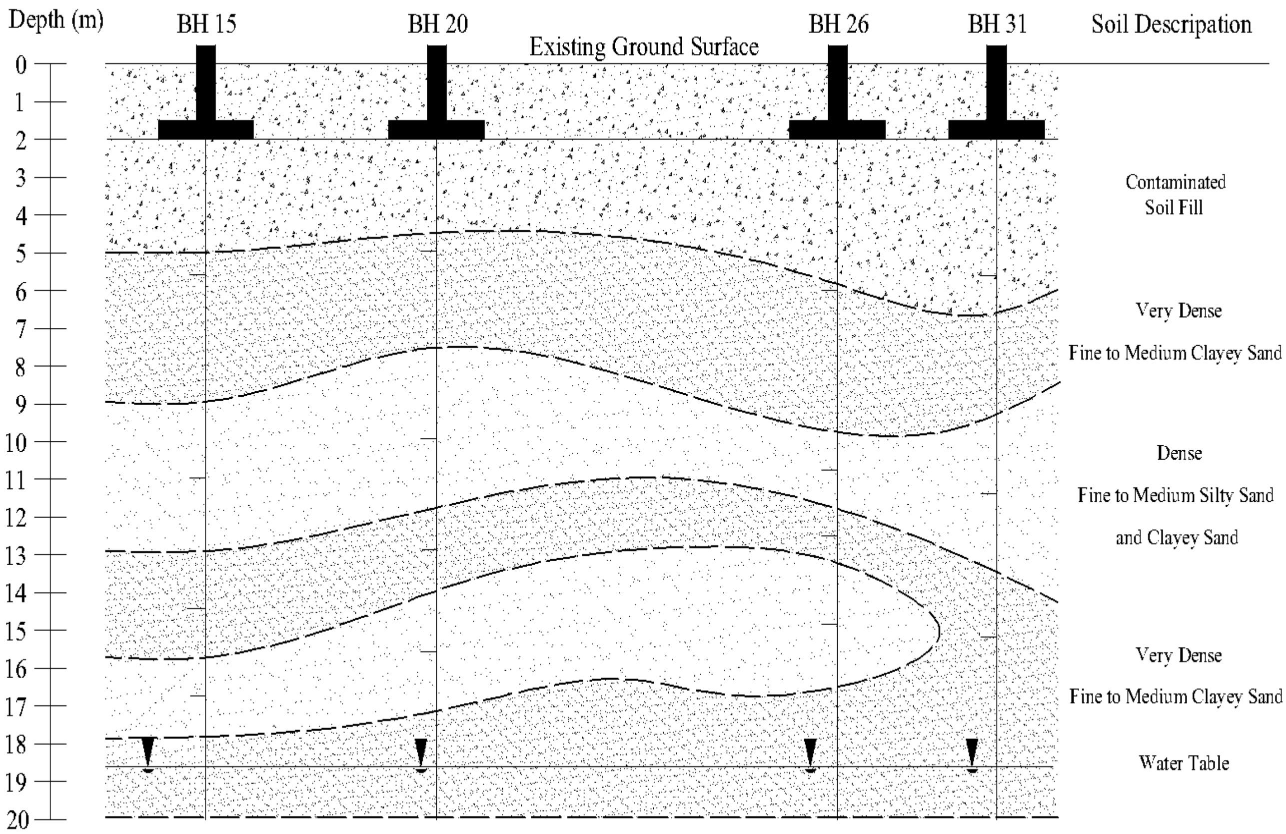


**Figure 6.1: Assumed footing location for bearing capacity calculation**

Tables 6.1 and 6.2 show the calculated ultimate bearing capacities for the clayey sand and the silty sand respectively. The calculated bearing capacity values for both soils at all conditions are found to be higher than the maximum recommended values for the ultimate bearing capacity for landfill site footing design(300kN/$m^2$ ) (Ismael 1985).

Since most soils in Kuwait possess sand fraction of more than 70%, the applied pressure is usually controlled by allowable settlement rather than the ultimate bearing capacity (Ismael 1985 & 1986), making the modelling of the settlement an important aspect of the design process.

**Table 6.1: Bearing capacity calculation for clayey sand**

| Test Series | Method | Moisture Type | Shear Strength Parameters $\phi$ (Degree) | c (kPa) | Bearing Capacity Factors $N_c$ | $N_q$ | $N_\gamma$ | Equivalent Surcharge q | Foundation Size (BxL) m 1 x 1 $q_u$ kN/m² | 2 x 2 $q_u$ | 3 x 3 $q_u$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| I | 0% | - | 52 | 28 | 347.5 | 415.1 | 1072.8 | 36 | 35291 | 43015 | 50739 |
| | 10% | Water | 41 | 47 | 103.7 | 90.3 | 133.5 | 36 | 10605 | 11566 | 12527 |
| | | Leachate | 41 | 37 | 113.2 | 101.3 | 156.3 | 36 | 10280 | 11405 | 12530 |
| | 20% | Water | 25 | 4 | 25.5 | 12.9 | 8.6 | 36 | 652 | 714 | 775 |
| | | Leachate | 32 | 2 | 46.1 | 30.4 | 29.4 | 36 | 1414 | 1626 | 1837 |
| | 40% | Water | 26 | 0 | 27.9 | 14.9 | 10.5 | 36 | 2295 | 2371 | 2447 |
| | | Leachate | 29 | 1 | 33.6 | 19.5 | 15.6 | 36 | 862 | 974 | 1086 |
| II | Inundation | Water | 24 | 46 | 23.6 | 11.6 | 7.3 | 36 | 1898 | 1950 | 2002 |
| | | Leachate | 35 | 10 | 61.2 | 44.9 | 50.8 | 36 | 2733 | 3099 | 3464 |
| III | Ageing | Water | 17 | 12 | 14.8 | 5.7 | 2.3 | 36 | 446 | 463 | 480 |
| | | Leachate | 15 | 8 | 12.8 | 4.4 | 1.5 | 36 | 297 | 308 | 319 |
| V | Extracted | Leachate | 36 | 2 | 61.5 | 45.1 | 51.1 | 36 | 2168 | 2537 | 2905 |

**Table 6.2: Bearing capacity calculation for silty sand**

| Test Series | Method | Moisture Type | Shear Strength Parameters: $\phi$ (Degree) | c (kPa) | Bearing Capacity Factors: $N_c$ | $N_q$ | $N_\gamma$ | Equivalent Surcharge q | Foundation Size (BxL) m: 1 x 1 $q_u$ kN/m² | 2 x 2 $q_u$ | 3 x 3 $q_u$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| I | 0% | - | 44 | 15 | 154.2 | 150.6 | 268.6 | 36 | 10431 | 12365 | 14299 |
| | 10% | Water | 35 | 31 | 59.8 | 43.5 | 48.6 | 36 | 4330 | 4680 | 5030 |
| | | Leachate | 36 | 27 | 64.7 | 48.4 | 56.3 | 36 | 4414 | 4820 | 5225 |
| | 20% | Water | 36 | 11 | 66.6 | 50.4 | 59.6 | 36 | 3218 | 3647 | 4076 |
| | | Leachate | 34 | 14 | 54.5 | 38.3 | 40.7 | 36 | 2660 | 2953 | 3246 |
| | 40% | Water | 35 | 8 | 59.2 | 42.9 | 47.7 | 36 | 2417 | 2761 | 3104 |
| | | Leachate | 35 | 6 | 60.8 | 44.4 | 50.1 | 36 | 2482 | 2843 | 3203 |
| II | Inundation | Water | 34 | 7 | 55.3 | 36.1 | 41.9 | 36 | 2096 | 2397 | 2699 |
| | | Leachate | 34 | 5 | 54.9 | 38.7 | 41.3 | 36 | 2067 | 2364 | 2662 |
| III | Ageing | Water | 38 | 21 | 83.3 | 67.7 | 89.8 | 36 | 5339 | 5986 | 6632 |
| | | Leachate | 36 | 10 | 61.7 | 45.4 | 51.6 | 36 | 2836 | 3208 | 3579 |
| V | Extracted | Leachate | 38 | 9 | 77.5 | 61.6 | 78.6 | 36 | 3673 | 4239 | 4805 |

## 6.3 Modelling of Al-Jahra Site (Settlement)

A study of the settlement behaviour is a key part of the investigation which will indicate the impact of underdesigned landfill sites on the settlement of soils. Sandy soils normally settle immediately under an applied load, whereas clayey soils take a longer time to settle.

Volume change in coarse grained soils occurs due primarily to the immediate settlement. The magnitude of immediate settlement can be assessed via elastic theories (Das 2007). Volume change in fine grained soils is accompanied by consolidation settlement. The magnitude of consolidation settlement can be assessed by the consolidation theory proposed by Terzaghi (1967). The soils used in this study were a natural soils comprised of sand, silt and clay and classified as silty sand and clayey sand according to Unified Soil Classification System USCS) as recommended by the ASTM D2487 (2006). The fine grained fractions in the soils were 10.89% and 26.27% for the silty sand and clayey sand respectively. Ismael and Jeragh (1986) reported that the consolidation settlement theory proposed by Terzaghi can be used in case of soils with fine fractions.

The settlement of the soils were calculated based on test results from chapter 4. The settlement can be calculated using Equation 6.5.

$$S = \sum_{i}^{n} \frac{C_{c(i)}}{1+e_{o(i)}} H_i \log\left(\frac{\sigma_{o(i)} + \Delta\sigma_{(i)}}{\sigma_{o(i)}}\right) \qquad (6.5)$$

where

$C_{c(i)}$ = compression index for sub layer *i*

$e_{o(i)}$ = void ratio for sub layer *i*

$H_i$ = thickness of sub layer *i*

$\sigma_{o(i)}$ = initial average effective overburden pressure for sub layer *i*

$\Delta\sigma_{(i)}$ = increases of vertical pressure for sub layer *i*

The compression indices for the sub layers were obtained from test results presented in chapter 4. The void ratios for the silty sand and the clayey sand soils layers are 0.477 and 0.486 respectively. The calculation of an increase in the stress below the footing area are based on the integration technique suggested by Boussinesq (Das 2007) (Equations 6.6 and 6.7).

$$\Delta\sigma_{(i)} = q_o I \qquad (6.6)$$

and

$$I = \frac{1}{4\pi}\left[\frac{2mn\sqrt{m^2+n^2+1}}{m^2+n^2+m^2n^2+1} x \frac{m^2+n^2+2}{m^2+n^2+1} + \tan^{-1}\left(\pi - \frac{2mn\sqrt{m^2+n^2+1}}{m^2+n^2+1-m^2n^2}\right)\right] \qquad (6.7)$$

where

$q_o$ = applied pressure on the footing

I = influence factor based on the m and n where m = B/z and n = L/z

z = the mid depth of the sub layer (*i*) measured from the base of the footing

The settlements of *in-situ* soil with 2m of contaminated soil surrounding the Al-Jahra landfill strata were calculated for various footing pressures. The assumed footing locations are shown in Figure 6.2.

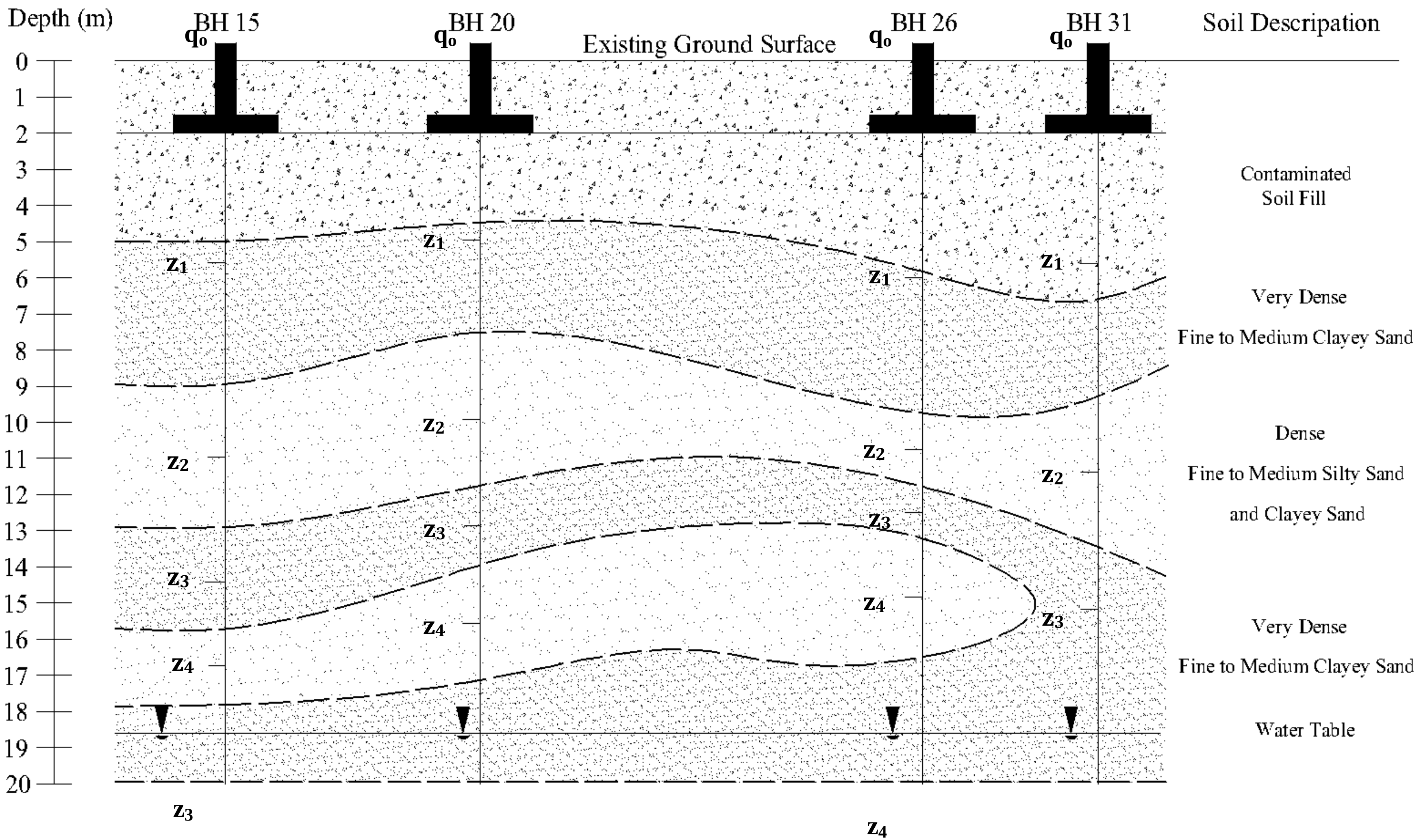


**Figure 6.2: Assumed footing locations for settlement calculation**

The assumptions made to enable the modelling of the settlement are as follows:

1- The settlement will be calculated based on the test results for inundation, aged and extraction conditions which are more realistic and representative of the *in-situ* conditions.

2- The settlement will be calculated up to a distance of 18m above the water table.

3- The footing will be square with 2m width and 2m length.

4- The footing will be placed at a depth of 2m.

5- The footing will be modelled in four positions at BH15, BH20, BH26 and BH31 to show the variation of the strata conditions and to be sure about the strata conditions that were obtained from the boreholes (Jergah 2009).

6- The variation of applied pressure on the footing ($q_o$) will be assumed to start at 50kN/m$^2$ increasing with increments of 25kN/m$^2$ up to 300kN/m$^2$.

Table 6.3 summaries the calculated settlements for BH15 and BH20 locations. Table 6.4 presents the results for BH26 and BH31 locations. Tables 6.3 and 6.4 present the settlements for applied pressure range from 50kN/m$^2$ to 300kN/m$^2$. The increase in the stress for each sub layer and the calculated total settlements are presented.

**Table 6.3: Settlement calculation of BH15 and BH20**

| **Footing Location** | | **BH15** | | | **Total Settlement (mm)** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Applied Pressure (kN/m²)** | **Stress for each sub layer (kN/m²)** | | | | **Inundation** | | **Aged** | | **Ext.** |
| **$\Delta\sigma_{oi}$** | **$\Delta\sigma_{z1}$** | **$\Delta\sigma_{z2}$** | **$\Delta\sigma_{z3}$** | **$\Delta\sigma_{z4}$** | **Water** | **Leachate** | **Water** | **Leachate** | **Leachate** |
| **50** | 6.9 | 1.2 | 0.8 | 0.6 | **17.4** | **17.8** | **14.9** | **17.8** | **16.3** |
| **75** | 10.3 | 1.8 | 1.1 | 0.9 | **25.7** | **26.3** | **22.1** | **26.3** | **24.0** |
| **100** | 13.8 | 2.4 | 1.5 | 1.2 | **33.8** | **34.6** | **29.0** | **34.5** | **31.6** |
| **125** | 17.2 | 3.0 | 1.9 | 1.5 | **41.6** | **42.6** | **35.7** | **42.5** | **38.9** |
| **150** | 20.7 | 3.6 | 2.3 | 1.8 | **49.2** | **50.4** | **42.2** | **50.3** | **46.0** |
| **175** | 24.1 | 4.2 | 2.6 | 2.1 | **56.6** | **58.0** | **48.6** | **57.9** | **53.0** |
| **200** | 27.5 | 4.8 | 3.0 | 2.4 | **63.9** | **65.4** | **54.8** | **65.3** | **59.7** |
| **225** | 31.0 | 5.4 | 3.4 | 2.7 | **70.9** | **72.6** | **60.8** | **72.5** | **66.3** |
| **250** | 34.4 | 6.0 | 3.8 | 3.1 | **77.8** | **79.6** | **66.7** | **79.5** | **72.7** |
| **275** | 37.9 | 6.6 | 4.1 | 3.4 | **84.5** | **86.5** | **72.4** | **86.4** | **79.0** |
| **300** | 41.3 | 7.2 | 4.5 | 3.7 | **91.1** | **93.2** | **78.0** | **93.1** | **85.1** |
| **Footing Location** | | **BH20** | | | **Total Settlement (mm)** | | | | |
| **Applied Pressure (kN/m²)** | **Stress for each sub layer (kN/m²)** | | | | **Inundation** | | **Aged** | | **Ext.** |
| **$\Delta\sigma_{oi}$** | **$\Delta\sigma_{z1}$** | **$\Delta\sigma_{z2}$** | **$\Delta\sigma_{z3}$** | **$\Delta\sigma_{z4}$** | **Water** | **Leachate** | **Water** | **Leachate** | **Leachate** |
| **50** | 9.1 | 1.5 | 0.8 | 0.7 | **19.6** | **20.0** | **16.7** | **20.0** | **18.3** |
| **75** | 13.6 | 2.2 | 1.2 | 1.0 | **28.8** | **29.5** | **24.5** | **29.4** | **26.9** |
| **100** | 18.1 | 2.9 | 1.6 | 1.3 | **37.7** | **38.6** | **32.1** | **38.5** | **35.2** |
| **125** | 22.7 | 3.7 | 2.0 | 1.6 | **46.2** | **47.4** | **39.4** | **47.3** | **43.2** |
| **150** | 27.2 | 4.4 | 2.4 | 2.0 | **54.5** | **55.8** | **46.4** | **55.8** | **50.9** |
| **175** | 31.8 | 5.1 | 2.8 | 2.3 | **62.5** | **64.0** | **53.2** | **63.9** | **58.4** |
| **200** | 36.3 | 5.9 | 3.2 | 2.6 | **70.2** | **72.0** | **59.7** | **71.9** | **65.6** |
| **225** | 40.8 | 6.6 | 3.6 | 3.0 | **77.8** | **79.7** | **66.1** | **79.6** | **72.6** |
| **250** | 45.4 | 7.3 | 4.0 | 3.3 | **85.0** | **87.1** | **72.3** | **87.0** | **79.4** |
| **275** | 49.9 | 8.1 | 4.4 | 3.6 | **92.1** | **94.4** | **78.3** | **94.3** | **86.0** |
| **300** | 54.4 | 8.8 | 4.8 | 3.9 | **99.0** | **101.5** | **84.1** | **101.3** | **92.4** |

**Table 6.4: Settlement calculation of BH26 and BH31**

| Footing Location | BH26 | | | | Total Settlement (mm) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Applied Pressure (kN/m²) | Stress for each sub layer (kN/m²) | | | | Inundation | | Aged | | Ext. |
| $\Delta\sigma_{oi}$ | $\Delta\sigma_{z1}$ | $\Delta\sigma_{z2}$ | $\Delta\sigma_{z3}$ | $\Delta\sigma_{z4}$ | Water | Leachate | Water | Leachate | Leachate |
| **50** | 6.9 | 1.6 | 1.1 | 0.8 | **12.2** | **12.5** | **10.4** | **12.5** | **11.4** |
| **75** | 10.3 | 2.4 | 1.6 | 1.2 | **18.1** | **18.5** | **15.5** | **18.5** | **16.9** |
| **100** | 13.8 | 3.2 | 2.1 | 1.6 | **23.9** | **24.5** | **20.4** | **24.4** | **22.3** |
| **125** | 17.2 | 4.0 | 2.7 | 2.0 | **29.6** | **30.3** | **25.2** | **30.2** | **27.6** |
| **150** | 20.7 | 4.8 | 3.2 | 2.4 | **35.1** | **36.0** | **30.0** | **35.9** | **32.8** |
| **175** | 24.1 | 5.6 | 3.8 | 2.8 | **40.6** | **41.5** | **34.6** | **41.5** | **37.9** |
| **200** | 27.5 | 6.4 | 4.3 | 3.2 | **45.9** | **47.0** | **39.2** | **47.0** | **42.9** |
| **225** | 31.0 | 7.2 | 4.8 | 3.6 | **51.1** | **52.4** | **43.6** | **52.3** | **47.8** |
| **250** | 34.4 | 8.0 | 5.4 | 4.0 | **56.3** | **57.7** | **48.0** | **57.6** | **52.6** |
| **275** | 37.9 | 8.8 | 5.9 | 4.4 | **61.3** | **62.8** | **52.3** | **62.8** | **57.3** |
| **300** | 41.3 | 9.6 | 6.4 | 4.8 | **66.3** | **67.9** | **56.5** | **67.8** | **61.9** |
| **Footing Location** | **BH31** | | | | **Total Settlement (mm)** | | | | |
| **Applied Pressure (kN/m²)** | **Stress for each sub layer (kN/m²)** | | | | **Inundation** | | **Aged** | | **Ext.** |
| $\Delta\sigma_{oi}$ | $\Delta\sigma_{z1}$ | $\Delta\sigma_{z2}$ | $\Delta\sigma_{z3}$ | $\Delta\sigma_{z4}$ | **Water** | **Leachate** | **Water** | **Leachate** | **Leachate** |
| **50** | 4.4 | 0.8 | 0.6 | - | **12.2** | **12.5** | **10.5** | **12.5** | **11.4** |
| **75** | 6.5 | 1.3 | 0.9 | - | **18.2** | **18.6** | **15.6** | **18.6** | **17.0** |
| **100** | 8.7 | 1.7 | 1.2 | - | **24.0** | **24.6** | **20.7** | **24.6** | **22.5** |
| **125** | 10.9 | 2.1 | 1.5 | - | **29.8** | **30.5** | **25.6** | **30.5** | **27.9** |
| **150** | 13.1 | 2.5 | 1.8 | - | **35.5** | **36.3** | **30.5** | **36.3** | **33.2** |
| **175** | 15.3 | 3.0 | 2.1 | - | **41.1** | **42.0** | **35.3** | **42.0** | **38.4** |
| **200** | 17.4 | 3.4 | 2.4 | - | **46.6** | **47.6** | **40.1** | **47.6** | **43.6** |
| **225** | 19.6 | 3.8 | 2.7 | - | **52.0** | **53.2** | **44.7** | **53.1** | **48.6** |
| **250** | 21.8 | 4.2 | 3.1 | - | **57.3** | **58.7** | **49.3** | **58.6** | **53.6** |
| **275** | 24.0 | 4.7 | 3.4 | - | **62.6** | **64.0** | **53.8** | **64.0** | **58.5** |
| **300** | 26.1 | 5.1 | 3.7 | - | **67.8** | **69.3** | **58.3** | **69.3** | **63.4** |

Figures 6.3, 6.4, 6.5 and 6.6 show the total settlement of the Al-Jahra site at locations BH15, BH20, BH26 and BH31 respectively. It can be noticed that the total settlement increases as the applied pressure increases. At locations BH20 and BH26, the soil layers compressed more than that occurs at locations BH15 and BH31. This can be explained due the presence of thicker sandy soil strata at these locations.

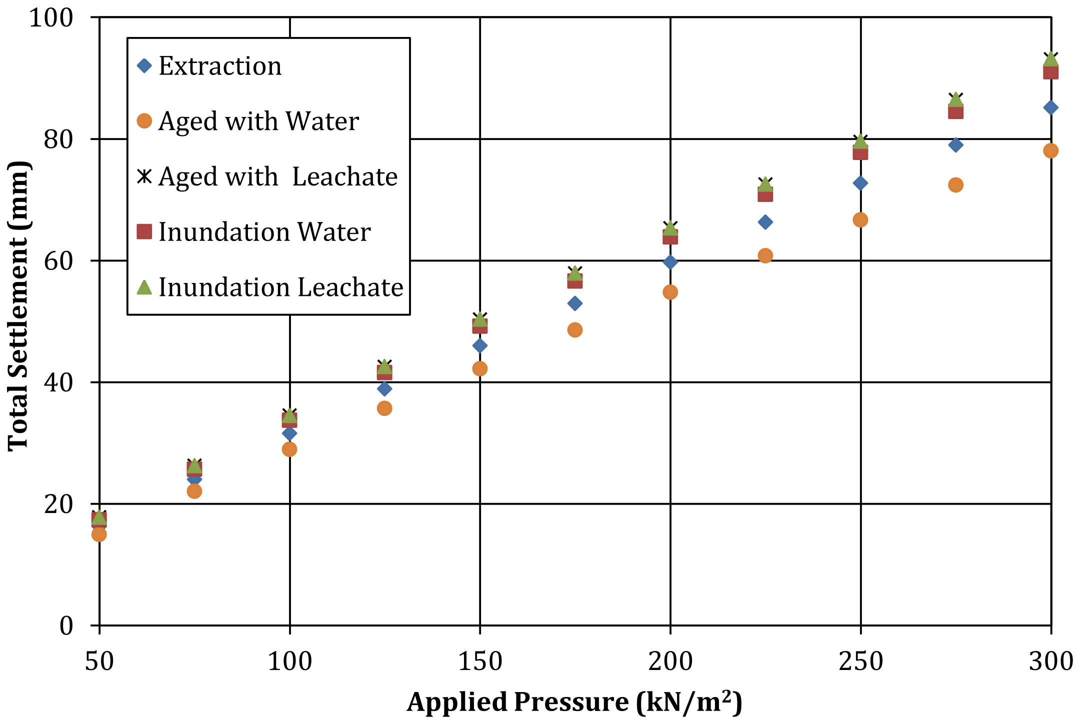


**Figure 6.3: Total settlement vs applied pressure at BH15**

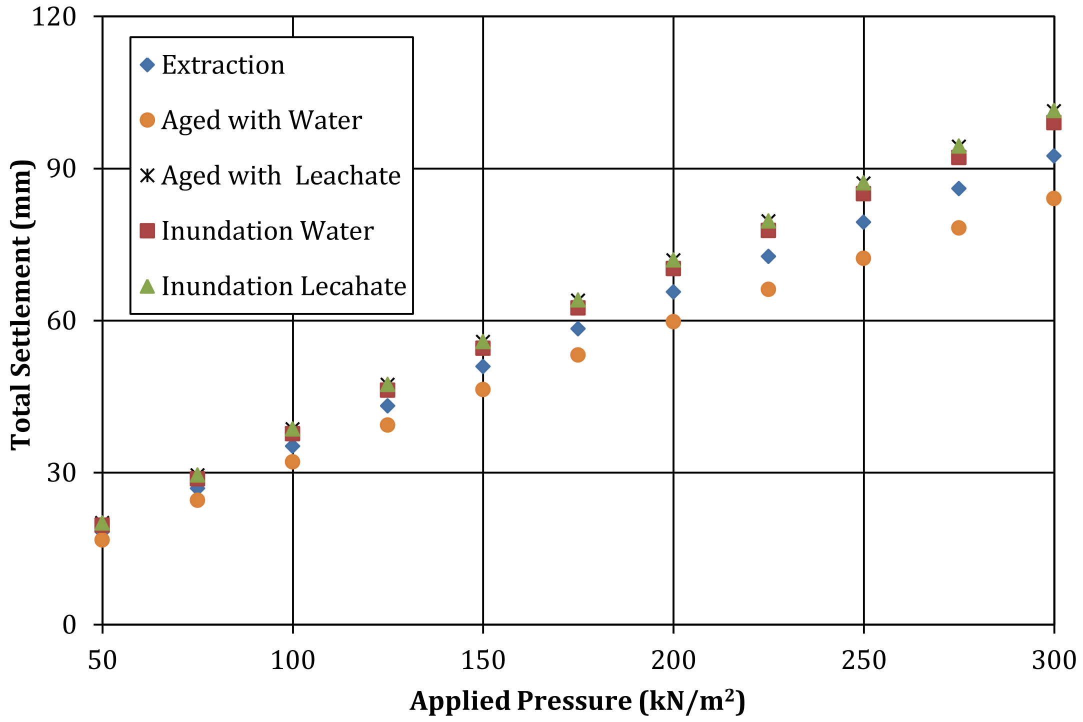


**Figure 6.4: Total settlement vs applied pressure at BH20**

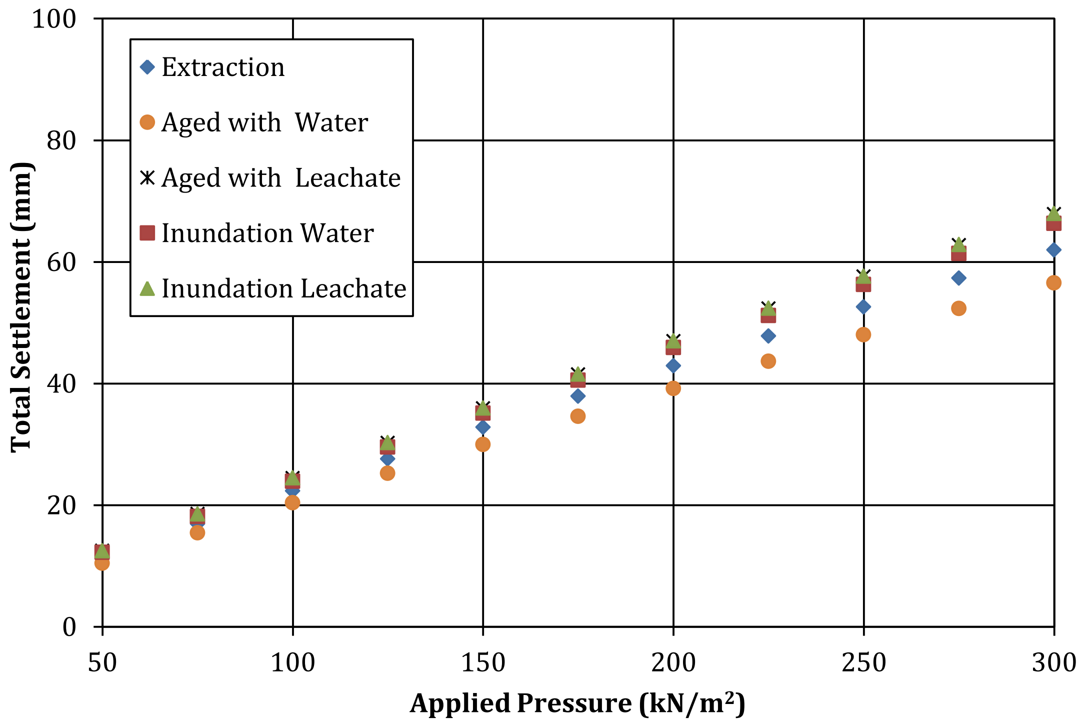


**Figure 6.5: Total settlement vs applied pressure at BH26**

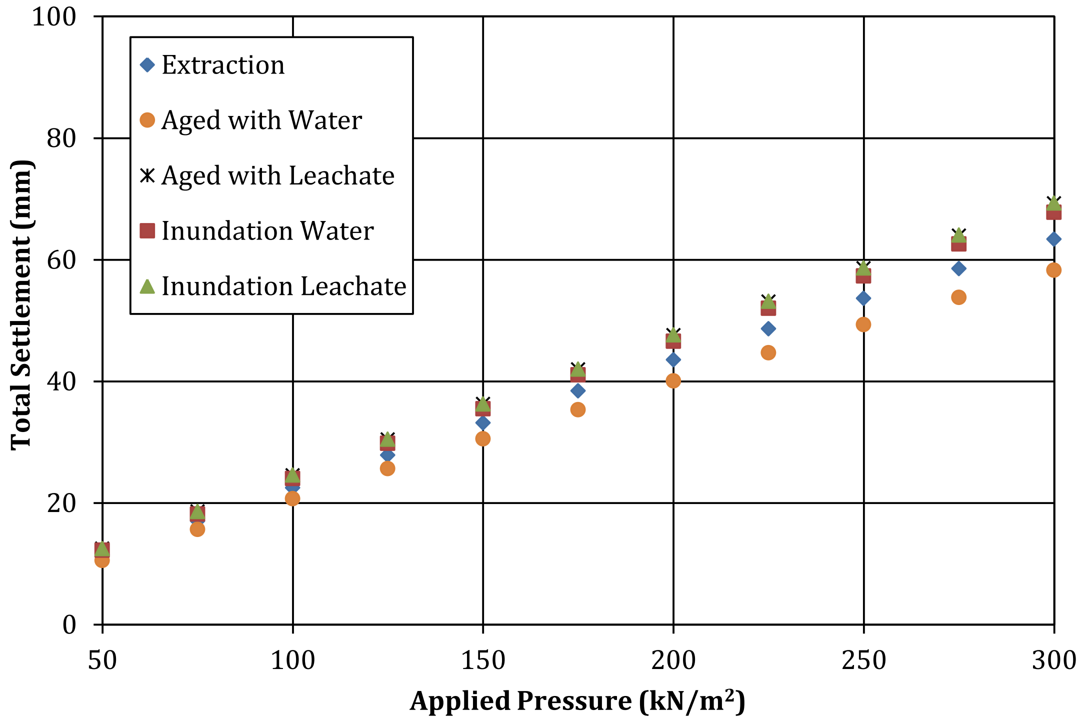


**Figure 6.6: Total settlement vs applied pressure at BH31**

Figures 6.3 to 6.6 show no significant differences between the three techniques that were used to prepare soil specimens for the laboratory tests. However, the aged condition with water yielded a lower settlement as compared to the aged leachate condition. This can be attributed due to a higher moisture content in the leachate – aged specimen than the water – aged specimen (about 5%) that allows a greater reduction in suction and the bond between soil particles which caused the soil to be more compressible (Bartlett and James 1980).

The modelling of the settlement of the site shows how the surrounding soil will settle after leachate percolation. The modelling represents the three phases of percolation; first the leachate starts to flow through the soil pores, then the soil layers become saturated due the flow of leachate and then, after the fluid flow seizes and drainage has completed, there will be a gradual loss of moisture from the soil.

The maximum allowable settlement of the shallow foundation is 50 mm as per Kuwait ministry of works. At locations BH15 and BH31, the soil system can sustain 100kN/m$^2$ of applied pressure, but at locations BH20 and BH26 the applied pressure should be limited to 75kN/m$^2$ due to the presence of an increased sand fraction in the soil. The suggested maximum applied pressure that can be used for designing footings in these strata is 50kN/m$^2$, which allow the soils to settle by about 10 to 30 mm.

## 6.4 Modelling of Al-Jahra Site (Solute Transport)

The experimental data from chapter 5 were considered out to validate and calibrate the numerical model. Hydrus-1D (Simunek et al. 2009) software package was used in this context. The model has been used for simulating water and solute movement in one-dimensional variably saturated and unsaturated media.

The HYDRUS program numerically solves the Richard's equation for variably-saturated water flow and advection-dispersion type equations for solute transport (Simunek et al. 2009). The one-dimensional form of Richard's equation can be presented as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x} + cos \propto\right)\right] - S \qquad (6.8)$$

where h = water pressure head, $\theta$ is the volumetric water content, t is time, x is the distance in x-direction, S is the sink/source term, α is the angle between the flow direction and the vertical axis (α= 0° for vertical flow and 90° for horizontal flow and 0° <α<90° for inclined flow) and K is the unsaturated hydraulic conductivity. The hydraulic conductivity is a function of relative hydraulic conductivity, $K_r$, and the saturated hydraulic conductivity, $K_s$.

The van Genuchten (1980) model has been used to obtain the unsaturated hydraulic conductivity function in terms of soil water retention parameters. The van Genuchten equation can be presented as:

$$\theta = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1+|\alpha h|^n]^m} & h < 0 \\ \\ \theta_s & h \geq 0 \end{cases} \tag{6.9}$$

where $\theta_r$ is the residual soil water content, $\theta_s$ is the saturated soil water content and alpha α , n and m are the parameters in the soil water retention equation.

The hydraulic conductivity can be obtained as:

$$K(h) = K_s S_e [1 - \left(1 - S_e^{1/m}\right)^m]^2 \tag{6.10}$$

where $m = 1 - {}^{1}/_{n}$ and n > 1 and the effective saturation, $S_e$ is calculated using,

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{6.11}$$

The values of $K_s$ , $\theta$ and h were obtained from the test results presented in chapter 4. The $\theta_r$, $\theta_s$, α, m and n were obtained from Hydrus-1D default parameters for the silty sand and clayey sand soils. Table 6.5 present the required input parameters in the Hydrus-1D software.

**Table 6.5: The required input parameters in the Hydrus-1D**

| Parameters | Unit | Silty Sand | Clayey Sand |
|---|---|---|---|
| $K_s$ | cm/day | 6.6 | 0.68 |
| $\theta_r$ | $cm^3/cm^3$ | 0.034 | 0.1 |
| $\theta_s$ | $cm^3/cm^3$ | 0.46 | 0.38 |
| α | 1/cm | 0.016 | 0.027 |
| n | - | 1.37 | 1.23 |
| m | - | 0.270 | 0.187 |
| h | cm | 69 | 350 |
| θ | % | 0.38065 | 0.25379 |
| Time | days | 5 | 14 |

The laboratory column test data were considered out to validate the 1D simulation. The simulations were undertaken at isothermal conditions. During the transport simulation, chemical interaction between chemicals were ignored. The partial differential equation governing one-dimensional chemical transport of solutes for a variably saturated porous medium (Simunek et al. 2009) can be presented as:

$$\frac{\partial \theta c_l}{\partial t} = \frac{\partial}{\partial x}\left(\theta D_l^w \frac{\partial c_l}{\partial x}\right) - \frac{\partial q c_l}{\partial x} \qquad (6.12)$$

where c is the solute concentration in liquid ($mol/m^3$), q is the volumetric flux density ($m^3/s$), $D_l^w$ is the dispersion coefficient in liquid ($m^2/s$). Equation (6.12) does not consider any sorption processes while modelling 1D water flow.

The initial conditions of the chemical concentrations are listed in Table 6.6 below.

**Table 6.6: The initial heavy metal concentration**

| Solute | Concentration |
|---|---|
| Copper | 0.1297 Mg/l |
| Arsenic | 0.3512 Mg/l |
| Nickel | 0.1647 Mg/l |
| Chromium | 0.2945 Mg/l |

Figures 6.7 and 6.8 show the results of numerical simulations and the experimental data for the silty sand and the clayey sand soils respectively.

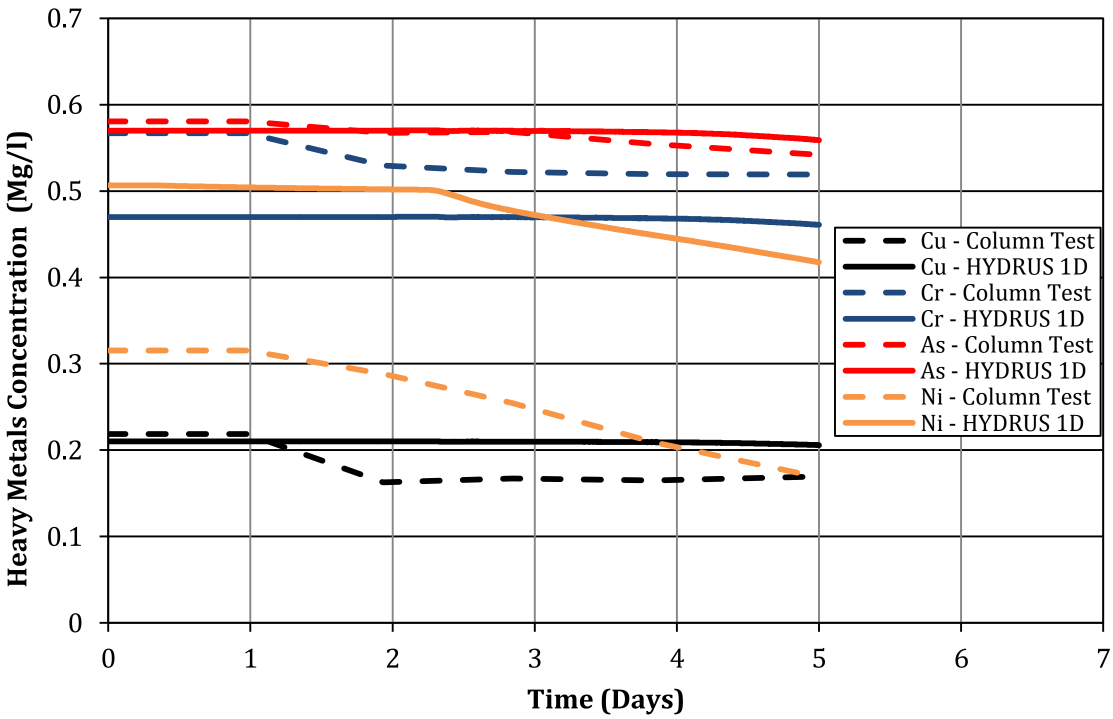


**Figure 6.7: Comparison between column test and HYDRUS 1D results for silty sand**

The column tests for the silty sand and the clayey sand were run for 5 and 14 days respectively as described in chapter 3 (section 3.5.2). The results show in general, good agreements between the model and test results for both soils except for the Ni solute in the silty sand soil. Over all, it can be considered that the HYDRUS-1D is suitable for Kuwait soils.

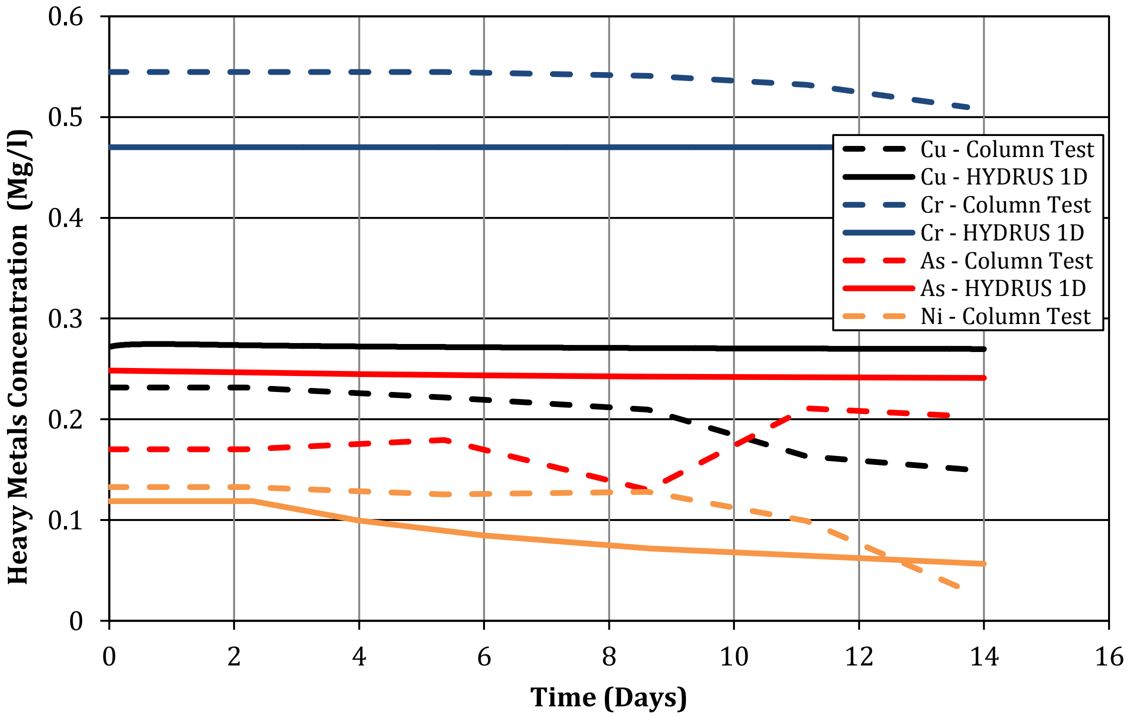


**Figure 6.8: Comparison between column test and HYDRUS 1D results for clayey sand**

## 6.5 Concluding Remarks

Calculations of the bearing capacity, the settlement and the solute transport were undertaken using the HYDRUS-1D software to investigate the impact of the landfill leachate on the behavior of Al-Jahra site. The main observations from this chapter can be summarized as follows:

1. The basic geotechnical calculations showed that the bearing capacity of the soils at Al-Jahra site is higher than the acceptable values usually adopted in Kuwait.

2. Significant settlement may occur at the site due to the presence of more than 70% of sand. The immediate settlement is the primary contributor to the total settlement.

3. Good comparison was noted between the experiment results (column tests) and numerical simulation results (HYDRUS 1D).

4. The numerical simulation can be used further to simulate the movement and transport of the contamination through the soil layers.

# Chapter 7

# CONCLUSIONS

The key objective of this research was to evaluate the impact of landfill leachate on the uncontaminated soil and the surrounding environment of Kuwait. The findings presented in this thesis are considered in terms of the influence of leachate on both geotechnical and geoenvironmental properties of soils.

The study focused on the Al-Jahra site, the largest open landfill site in Kuwait, as the way the waste is disposed of in this site leading to contamination of the surrounding clean soils and the groundwater. Two natural soils (a silty sand and a clayey sand) were selected for the study that represent the common soils in the Al-Jahra city region and are also more broadly represent the common soils of Kuwait. The leachate was obtained from the Al-Qurain landfill site as this is the only source of leachate in Kuwait, as reported by Al-Fares (2011).

The basic physical properties of the soils were determined by standard laboratory methods prior to the main testing program.

The interaction between the soils and the fluids (water and leachate) was investigated by considering three different specimen preparation methods. The first method was to mix the soil with leachate at increments of 0%, 10%, 20%, and 40%

by the weight of the soils; this is a traditional method and is usually used to measure the positive or negative influence of the moisture. The second method consisted of soil specimens being inundated with leachate or water to simulate realistic interaction between different fluids and the soils. The third method involved submerging specimens in the different fluids until chemical equilibrium was reached to simulate the long-term case when leachate has passed through the soil and the soil has returned to dry conditions.

After the soil specimens were prepared using the methods described above, the geotechnical properties (shear strength and compressibility), and the geoenvironmental properties (adsorption and retention) of the soils were determined. A detailed study was undertaken to investigate the effect of the leachate on the bearing capacity and settlement of the soils at the Al-Jahra site. The soil column test data (adsorption and retention) were used to verify the efficiency of HYDRUS 1D model.

Based on the findings reported in this thesis, the following conclusions were drawn:

1. A comprehensive series of laboratory tests were performed on two soils interacting with water and leachate in the context of waste disposal in Kuwait (A total of 156 tests).

2. It has been shown that the silty sand soil which is prevalent in Kuwait is not affected by leachate. The geotechnical properties (shear strength and volume change) were not affected by the leachate flow through the soil.

3. Where a low amount of clay minerals are present in the soil, as is the case in some locations in Kuwait (West and North), the soil is affected by leachate. For the clayey sand used in this study, as the leachate content in the soil was increased, the angle of internal friction increased, whereas the apparent cohesion decreased.

4. The silty sand did not exhibit any significant adsorption and retention of heavy metals, whereas the clayey sand showed significant adsorption and retention behaviour.

5. These laboratory test were considered results to examine the performance of the soil/landfill system via calculation/modelling exercises. Since soil in Kuwait commonly possess more than 70% sand fraction, the allowable settlement is the focus of attention and the suggested maximum applied pressure can be limited to 50kN/$m^2$ in certain areas.

The relevant findings from this PhD study will be presented to the Kuwait Municipality and Council of Ministers of Kuwait by Dr. Rana Al-Fares, to encourage and enforce environmental regulations for correct landfill design in Kuwait.

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