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APPLICATIONS OF SOIL MECHANICS PRINCIPLES
TO
LANDFILL WASTE

by

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Doctor of Philosophy

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In the name of Allah the Most Beneficent and the Most Merciful

I dedicate my work to our
Holy Prophet Mohammad
(May Allah bestow Peace upon him)
May Allah enlighten our inner-selves, Amen!

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

SCHOOL OF CIVIL ENGINEERING AND THE ENVIRONMENT

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The hydrogeological behaviour of simulated (model) landfill waste was studied in the laboratory, to determine its hydraulic conductivity and suction characteristics. Accurate waste characterisation is vital for predicting and understanding landfill waste behaviour. A methodology was determined for producing a model waste that could be used to assess the applicability of established soil testing methods to waste.

Hydraulic conductivity characteristics of model waste were studied in relation to changes in dry density and effective stress. Three scales of tests were used to investigate the effect of particle size / aspect ratio on the hydraulic conductivity characteristics of model waste. It was found that hydraulic conductivity is not affected by the aspect ratio but it is the particle size that influences the permeability characteristics of waste. In general, a Darcian relationship was observed in all the permeability tests and that hydraulic conductivity decreased with the increase in dry density. A similar trend was observed in the case of an applied overburden pressure where effective stress conditions were replicated. The comparison of the hydraulic conductivity characteristics of model to landfill waste showed good correlation with values measured within the range of 10^{-6} to 10^{-3} m/s.

Suction characteristics of waste were studied through the application of the filter paper method. The application of this method was restricted to particle sizes less than 20mm. The experiments showed that model waste behaves similarly to a soil. Waste moisture characteristic curves for various waste dry densities were developed using van Genuchten model. The soil-physical properties / parameters for model waste developed for this investigation were found to be comparable to coarse soils. It also proved that model waste behaves as a consistent material and may be useful in investigating further into the suction characteristics of waste.

The filter paper method was found to be susceptible to changes in moisture content, particle size distribution and sensitive to sample preparation. A modified version of the filter paper method for in-situ application to real waste was assessed. The determination of moisture content of waste remained a critical issue. The filter paper technique gave an overestimation of suction values in the presence of pore fluid solute concentrations consistent with those typically present in leachate.

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Notations

MC_{dry}	*moisture content (dry weight basis)*
WC_{dry}	*water content (dry weight basis)*
MC_{wet}	*moisture content (wet weight basis)*
WC_{wet}	*water content (wet weight basis)*
M	*percentage moisture content*
Mc	*gravimetric moisture content in fraction*
w	*initial weight of sample as delivered*
d	*weight of the sample after drying at 105°C for 24 hours*
θ_w	*volumetric water content*
ρ_{wet}	*bulk density*
ρ_{dry}	*dry density*
γ	*unit weight*
g	*acceleration due to gravity*
F_c	*field capacity*
a	*absorptive capacity*
S_r	*specific retention*
e	*void ratio*
n	*porosity*
S	*degree of saturation*
θ_{Wmax}	*maximum volumetric water content*
n_e	*effective or drainable porosity*
S_y	*specific yield*
K	*hydraulic conductivity*
h_p	*pressure head*
h_e	*elevation head*
h_v	*velocity or dynamic head*
h	*total head*
u	*pore pressure*
h_{pe}	*static head or piezometric head*
i	*hydraulic gradient*
Δh	*change in total head*

L	*length over which change in total head is measured*
Q	*measured flow rate through the sample*
A	*cross-sectional area of the sample*
R_e	*Reynolds number*
v	*flow velocity*
v_s	*seepage velocity*
k	*intrinsic/absolute/specific permeability*
υ	*fluid kinematic viscosity*
μ	*dynamic viscosity*
ρ	*density of the fluid*
K_h	*horizontal hydraulic conductivity*
K_v	*vertical hydraulic conductivity*
Ψ	*suction or soil water potential*
∇H	*hydraulic head gradient*
σ_v	*vertical stress*
z	*depth at which vertical stress is determined*
σ_v'	*vertical effective stress*
u_w	*pore water pressure*
σ	*total stress*
σ'	*effective stress*
u_a	*pore air pressure*
χ	*parameter related to degree of saturation*
π	*osmotic suction*
T_s	*surface tension*
R_s	*radius of curvature of the water meniscus in the pore / capillary*
ψ_m	*matric suction*
Θ	*function of volumetric water content or water retention characteristic*
a, b, m	*curve-fitting parameters*
$\theta(R)$	*function of volumetric water content w.r.t pore radii* $\leq R$
R_{min}	*minimum pore radius in the soil*
$\theta(\psi)$	*volumetric water content as a function of suction*
C	$2T_s \cos \phi$
ϕ	*angle of contact between water and soil*

h	*dummy variable of integration representing suction, also suction head in van Gunechten equation*
$f(r)$	*function of pore size distribution*
ψ_e	*air-entry water potential*
θ_s	*saturated volumetric water content*
K_s	*saturated hydraulic conductivity*
K_r	*relative hydraulic conductivity*
θ_r	*residual volumetric water content*
Θ	*soil water content parameter*
n	*number of moles*
C_n	*molar concentration of solution*
R	*molar gas constant*
T	*temperature*
V	*volume*
BF	*biodegradable fraction*
LC	*lignin content*
σ_o	*overburden pressure*
P	*external pressure*
ǿ	*internal angle of friction of waste*
δ	*angle of friction between the waste and cell wall*
d	*internal diameter of cell*
B	*parameter for reduction in vertical stress due to ǿ and* δ
α, n, m	*van Genuchten soil parameters obtained by curve fitting*
Ø	*particle size range passing through sieve*

Chapter 1

Introduction

1.1. Need for the study

Landfill is widely regarded as the main disposal solution to the waste management problem. However, effective waste management requires a more sustainable approach in order to satisfy the concerns of society in terms of potential environmental damage from landfill. In order to move towards more sustainable landfill practice, the process of landfill and its long-term behaviour needs to be studied, particularly in terms of its geo-hydrological behaviour during the active and post closure period of landfilling. Waste is a heterogeneous material with variable compressibility, particle size, shape and texture, and its mechanical behaviour is complex. The application of soil mechanics principles to the testing and treatment of waste may enhance our understanding of the behaviour of this material.

1.2. Background

Landfill is widely practised as the final disposal route for municipal solid waste (MSW) all over the world. In the UK, the proportion of domestic waste disposed to landfill has increased from about 70% in the early 1990's (DoE, 1995) to nearly 85% in 1997-98 (DEFRA, 2000). Overall, landfill has turned out to be the final waste disposal solution for nearly 60% of the total waste generated in the UK (DEFRA, 2000). The concept of sustainable waste management recognises the role of landfill but seeks to improve waste management practices to limit potential environmental damage from landfill.

The characteristics of landfill waste have been changing continuously (Hutchinson, 1995) and have made the understanding of the behaviour of landfill difficult. Waste is often characterised as either inert or degradable and can vary in its composition within the same landfill. Over the years, the proportion of inert ash content has decreased considerably in comparison to the volume of paper, rag and plastics now found in landfill (Watts and Charles, 1990). European Commission directives on landfill emphasise 'sustainable development' practice in the waste management industry (EC, 1993) and requires a fundamental reduction in waste volumes disposed to landfill, supplemented by recycling and reuse and finally, optimising the disposal method for the waste. Though recovery of material from municipal waste is also practised widely through recycling and composting, the volume recovered is still low in the UK, at approximately 6.5% in 1995-96 to 8% during 1997-98 (DEFRA, 2000). This low percentage is unlikely to affect the overall landfill waste composition.

Waste composition such as, density and moisture content governs its hydrological and geotechnical (hyrogeological) behaviour and the processes that take place in landfill. Similarly, hydrogeological properties of refuse influence waste moisture characteristics that are required for the design of leachate drainage and control system, which in turn affects the stabilisation process in landfills (Leckie and Pacey, 1979; Pohland, 1980; Barlaz, et al, 1989; Knox, 1998).

The hydrological and geotechnical properties of waste have been studied both in the field and in the laboratory. These studies have led to the development of landfill models that seek to simulate the key processes of waste degradation and the subsequent changes in composition through various mass transfer processes. Certain waste (hydrological) models, for example, Sarsby and McDougall, (1996), idealise the behaviour of waste in terms of its key hydrogeological properties. Such models are largely the outcome of the application of soil mechanics principles to waste (based on laboratory and field investigations) but their application may not be entirely suitable due to variations in waste characteristics and the hydrgeological conditions commonly found in landfill. Blieker et al (1995) simulate the compression in refuse lifts by means of a rheological model using the data generated by Rao et al (1977) to calibrate the model and simulate the observed settlements in municipal solid waste (as interpreted by Oni, 2000). Beaven and Powrie (1995) have studied certain geotechnical properties of MSW such as hydraulic conductivity, effective stress and drainable porosity relationships to dry density and over burden pressures, etc., in a large-scale compression cell.

An important characteristic of waste which has received little attention is the suction-moisture relationship. This is of critical importance where the waste is unsaturated or partly saturated. The conventional effective stress equation ($\sigma' = \sigma$ - u) applicable to saturated waste is not applicable to unsaturated or partially saturated waste. In such cases the determination of waste suction characteristics along with the other hydrogeological properties becomes necessary in order to develop more realistic landfill models within a partially saturated framework.

The waste degradation process is considerably influenced by the hydrological regime existing in the landfill. The predictability of degradation in terms of time-scale, and its extent is uncertain and depends on the waste characteristics and to much extent on the hydrogeological conditions prevailing in landfill. Waste degradation has been studied for the purpose of modelling. Young (1989) presented a model that indicated that the hydraulic properties of refuse are significantly influenced by the biodegradation process in landfill, thereby increasing the complexity in estimating the hydrological properties. Though the present developments in landfill research have been able to provide some of the major details of landfill performance, however the hydrological characteristics of waste and how these properties change with time, still requires further study.

1.3. Proposed methodology and objectives of study

Investigations into landfill waste characteristics and the associated hydrogeological properties that are essential for a better understanding of waste behaviour in landfill have been the subject of laboratory studies. A purpose built large-scale test cell was constructed to allow the simulation of in situ landfill conditions (compression and overburden pressure) under controlled settings. Properties such as hydraulic conductivity were measured for a model waste in relation to waste dry density, effective stress, etc. Suction characteristics were also determined by taking representative samples of waste and applying an indirect measurement technique using filter paper (ASTM D5298-92). The suitability of an in situ application of the filter paper method has been also investigated.

It was essential to establish consistency in waste composition so as to simplify the study of waste behaviour. This was achieved to a great extent by preparing a model waste which was developed following an analysis of the waste inventory for a low-level radioactive waste repository. Consequently, the majority of the model waste components were inert except for the ligno-cellulosics (paper, wood, etc.) which are regarded as being reasonably stable in landfill in the short-term. The hydrogeological investigations into model waste, therefore, remained focused on studying waste behaviour without incorporating the effects of biodegradation, thereby reducing the complexity of the experimental regime. Another important variable in preparing the model waste was its particle size. The model waste was prepared in the laboratory according to a prescribed waste composition, suggested to be of specific particle size and shape, particularly for the reducible components in the model waste. The particle size was selected on the basis of dimensional similitude in proportion to the diameter of the test cell (aspect ratio).

The objectives of the study were to investigate the applicability of soil mechanics principles to the study of waste, for example whether waste hydraulic conductivity is Darcian in behaviour and relationship amongst the key hydrogeological parameters such as hydraulic conductivity and dry density can be established. Similarly, determination of waste suction characteristics and the influence of variations in moisture and density were also studied.

1.4. Scope of research:

The aims and objectives described above will seek to establish;

- The hydrogeological behaviour of waste and the extent that this behaviour may be compared to soil.
- A better understanding of waste behaviour by developing a methodology for the study of waste mechanics.

1.5. Thesis structure:

Chapter 1 discusses the problems associated in applying conventional soil mechanics principles to waste. The hydrogeological properties that are of primary concern in studying the behaviour of waste in landfill are identified. The inter-relationship of these properties in developing an interactive waste landfill model is also discussed.

A general perspective of waste characterisation and hydrogeological properties of waste is also presented. A literature review on the study of waste behaviour and its hydrogeological characteristics has also been included in Chapter 2.

Chapter 3 describes the development of an experimental set up and the apparatus developed for determining the hydrogeological properties of waste.

Chapter 4 describes the experiments to investigate the hydraulic conductivity of waste. Landfill conditions are simulated, particularly overburden pressures and effective stresses. The relationship between the hydraulic conductivity characteristics, density and overburden pressures (effective stresses) is presented.

Suction characteristics of waste and its determination by the filter paper method (ASTM D5298 92) are discussed and suction-moisture relationships for model waste, in the form of waste-moisture characteristic curves are presented. An in situ application of the experimented method is suggested. The repeatability of the filter paper method is assessed together with the effect of dissolved salt concentrations (typically found in leachate) on the sensitivity of the filter paper is also discussed in Chapter 5.

Chapter 6 summarises the results with a discussion on the observed behaviour of waste.

Chapter 7 concludes the findings of the research study with recommendations for further research.

Chapter 2

Definitions and Literature Review

2.1. Introduction

Waste is a heterogeneous material which when landfilled is often expected to behave in a predictable manner. To assist in understanding the behaviour of waste, it may be helpful to study certain characteristic properties of the waste more generally associated with soils – the hydrogeological characteristics of waste.

The process of identifying physical, chemical and biological waste properties is termed waste classification or characterisation. Whatever the basis of classification or characterisation, the object is to provide a description of the makeup of the waste together with identification of its basic behavioural properties. Consequently waste classification / characterisation is a key element in any sustainable waste management and disposal programme.

There has always been a requirement to characterise waste for development and planning purposes. A sustainable waste management system is therefore dependent upon the available waste characterisation data. Conventional characterisation techniques involve the estimation of generation, composition, weight-volume relationships etc. providing key inputs to the design of the waste containment systems. This is particularly true in the context of incineration schemes and of landfill containment and management systems where energy recovery is a primary objective. Similarly, the geotechnical characteristics in the latter case must also be adequately known to design gas and leachate management systems. Properties that govern the behaviour of waste may be similar to those that are known to describe the behaviour of soils. The following is an overview of the current understanding of waste behaviour in terms of conventional soil mechanics.

2.2. Definition of waste

Waste is defined as any substance or object which the producer or holder discards or intends to or is required to discard (Waste Management Licensing Regulation, 1994). Waste is a wide ranging term encompassing most unwanted materials, defined by the Environmental Protection Act 1990. It includes any scrap material, effluent or unwanted surplus substance or article that requires to be disposed of because it is broken, worn out, contaminated or otherwise spoiled. Explosives and radioactive wastes are excluded (DEFRA, 2000).

Solid waste comprises all the waste arising from human and animal activities that is normally solid and that is discarded as useless or unwanted (Tchobanogluos et al, 1993).

A comprehensive definition of *Solid waste management* has been given by Tchobanoglous et al (1993) who describe it as the discipline associated with the generation, storage, collection, transfer and transport, processing, and disposal of solid wastes in a manner that is in accordance with the best principles of public health, economics, engineering, conservation, aesthetics, and other environmental considerations, and that is also responsive to public attitudes. In this context waste characterisation plays a vital role in the successful and sustainable execution of a formal waste management system. Broadly speaking, *waste characterisation* defines the sources, composition and characteristics of solid waste. Therefore, waste characterisation, in itself, is a comprehensive tool that forms a key element of an *Integrated Solid Waste Management* system i.e. the selection and application of suitable techniques, technologies and management programmes to achieve specific waste management objectives and goals (Tchobanoglous et al, 1993).

2.3. Waste classification and characterisation

Waste classification and characterisation are the terms that have not been explicitly defined, and hence are often used interchangeably. Like soil classification, *waste classification* is used to mean the process of categorising the waste, according to its physical properties and composition, whereas *waste characterisation* may be used to further describe the behavioural characteristics as well.

The introduction of integrated waste management and sustainable landfill concepts called for the development of waste characterisation techniques (Savage, 1996). With the rapidly changing nature of waste due to recycling and waste minimisation processes it became more critical then ever to classify waste materials to allow their ultimate safe disposal. Waste characterisation is therefore critical in the planning, design and operation of solid waste management systems (Savage and Diaz, 1997). The lack of comprehensive and standardised data on waste arisings and its composition is considered to be one of the limiting factors in the development of effective solid waste management (Mastrogiacomi et al., 1999) and has yet to be fully comprehensively addressed.

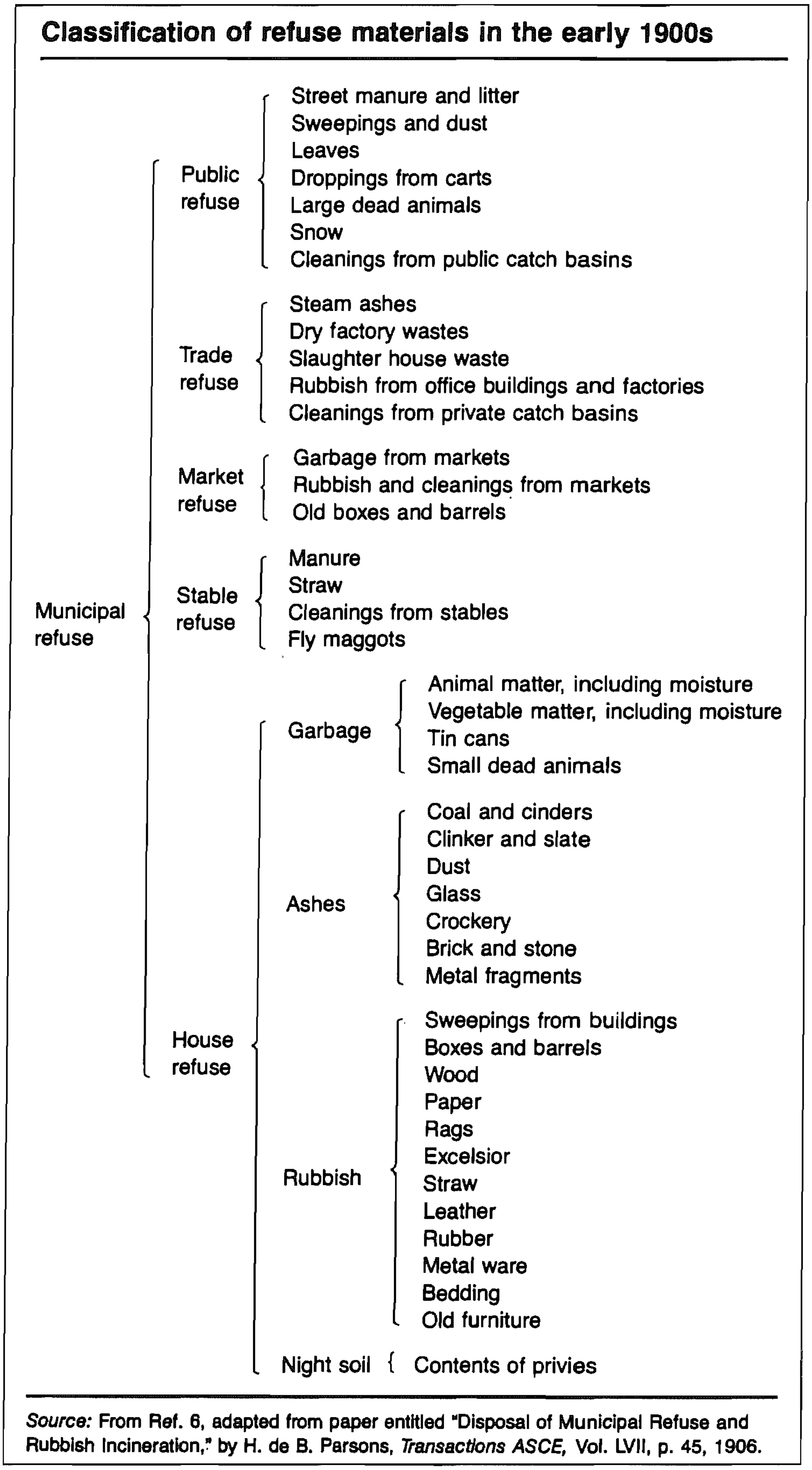
To a certain extent, waste classification procedures are now established and commonly accepted for certain waste types. The principles governing these procedures have led to formal guidelines for waste acceptance procedures laid in European Council Directives (e.g. 1999/31/EC). These directives state that the composition, leachability, long-term behaviour and general properties of waste must be known as precisely as possible prior to final disposal to the landfill.

In broad terms, classification of waste defines the waste source e.g. domestic (municipal), commercial (industrial) etc. and to some extent its nature, hazardous (biological, radioactive) etc. Tchobanoglous et al (1993) has cited an earlier example of the classification of municipal refuse dating back to early 1900, (Table 2.1.).

The earlier classifications were of a more generalised form, i.e. broadly based on the source type and did not provide details of composition and other physical properties. Formal waste characterisation as practiced today is generally more comprehensive and has the following key functions:

- It identifies the physical characteristics of waste such as its composition, form, density etc.
- It includes demographic and socio-economic characteristics, such as generation rate, waste composition as influenced by the socio-economic levels, climatic and temporal affects.

It provides the basis by which various management and disposal processes are designed according to the needs of individual waste management plan.



Classification of refuse materials in the early 1900s

Municipal refuse	Public refuse		Street manure and litter
			Sweepings and dust
			Leaves
			Droppings from carts
			Large dead animals
			Snow
			Cleanings from public catch basins
	Trade refuse		Steam ashes
			Dry factory wastes
			Slaughter house waste
			Rubbish from office buildings and factories
			Cleanings from private catch basins
	Market refuse		Garbage from markets
			Rubbish and cleanings from markets
			Old boxes and barrels
	Stable refuse		Manure
			Straw
			Cleanings from stables
			Fly maggots
	House refuse	Garbage	Animal matter, including moisture
			Vegetable matter, including moisture
			Tin cans
			Small dead animals
		Ashes	Coal and cinders
			Clinker and slate
			Dust
			Glass
			Crockery
			Brick and stone
			Metal fragments
		Rubbish	Sweepings from buildings
			Boxes and barrels
			Wood
			Paper
			Rags
			Excelsior
			Straw
			Leather
			Rubber
			Metal ware
			Bedding
			Old furniture
		Night soil	Contents of privies

Source: **From Ref. 6, adapted from paper entitled "Disposal of Municipal Refuse and Rubbish Incineration," by H. de B. Parsons, *Transactions ASCE,* Vol. LVII, p. 45, 1906.**

Source: Tchobanoglous (1993), Table 3-12, pp 66

Table 2.1. Classification of refuse materials in early 1900s

The characterisation process also allows management processes to be reviewed and altered (during the operational phases of landfill) according to the changing character of waste.

A conventional waste characterisation process has the following key steps:

- Collection of geophysical, socio-economic and demographic information,
- Categorisation of the generating source,
- Determination / selection of sample size and its scaling factor,
- Quantification of waste generation rates,
- Waste composition
- Determination of the waste potential i.e. its suitability for various available disposal options such as composting, refuse derived fuel / incineration and landfill.
- Estimation of waste volumes for final disposal

Waste source categorisation is vital before undertaking formal waste characterisation, as source has been shown to have a significant impact on the engineering properties of waste. The categorisation of source as an integral part of the classification / characterisation process informs management processes such as storage, collection and transportation facilities etc.

Currently, waste characterisation or classification system has not been unified. For instance, the American Society for Testing and Materials (ASTM) alone has recognised over 25 methods for characterising mixed solid wastes and for the fractions or components derived from these wastes (Savage and Diaz, 1997).

Literature review

Jessberger and Kockel (1991) examined the suitability of geotechnical classification systems and terms that may be applicable to waste materials. The waste material is primarily categorised into ‘soil like waste’ and ‘other waste’ (details of classification are given in the text to follow).

Grisolia et al (1995) proposed a “technical classification” for solid waste. The classification system categorises waste into 3 classes,

Class A – *Inert stable elements*; those where the initial composition is not modified in the medium term and whose intrinsic strength and deformability characteristics do not affect the overall behaviour of the waste.

Class B – *Highly deformable elements*; comprising those materials which when subjected to load undergo substantial settlement which deeply distorts their original shape. Such materials may exhibit creep behaviour.

Class C – *Readily biodegradable elements*; those which undergo change in their constitution in the short term in ordinary conditions.

Class A includes; soils, metals, glass, ceramics, construction debris, ash, wood etc.
Class B comprises; paper cardboard, rugs and textiles, leather, plastics and rubber, tyres, etc
Class C includes, food waste, yard waste, animal waste, fine fragments (<20mm ø)

The data can be presented graphically on a triangular diagram (Figure 2.1.) depicting the percentages of the components falling in separate classes describing the type of municipal solid waste being represented.

Landva and Clark (1990) proposed a more detailed waste classification system based on the natural characteristic properties of individual waste constituents. The classifications proposed were 1) readily biodegradable, 2) slowly biodegradable and 3) non-degradable. For the purpose of engineering applications the following classes were specified:

1. Organic (O) which contains;

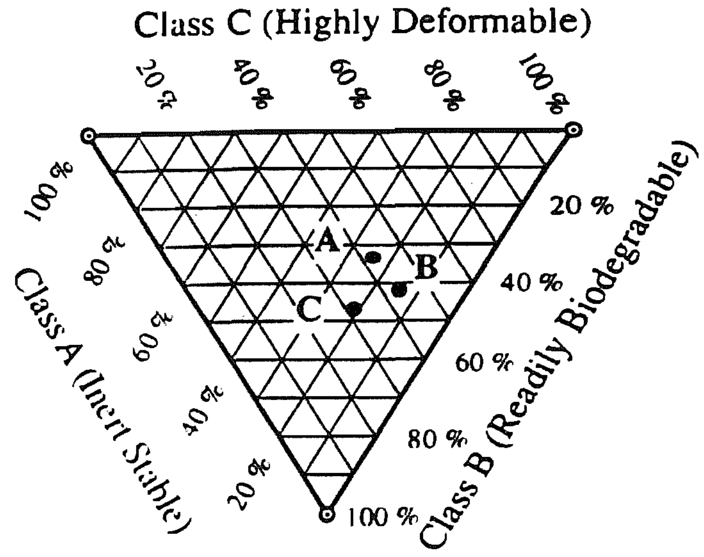
a) *Organic Putrescible (OP)* (readily biodegradable); food waste, garden waste, Animal waste, materials contaminated by such wastes.

b) *Organic Non-putrescible (ON)* (slowly biodegradable); paper wood, textiles, leather plastic, rubber, paint, oil grease, chemicals, organic sludge.

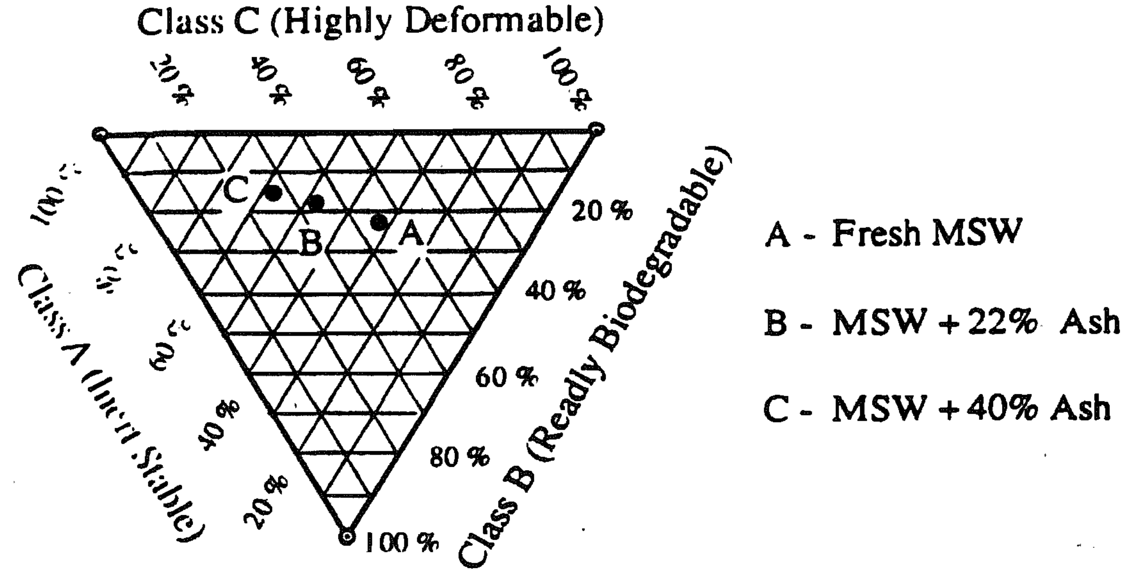
2. Inorganic (I) which contains;

a) *Inorganic Degradable (ID)*; metals (corrodible to varying degree).

b) *Inorganic Non-degradable (IN)*; glass, ceramics, mineral soil, rubble, tailings, slimes, ash, concrete, masonry.



a) Technical classification of MSW observed in landfills (A, B, C)



b) MSW technical composition of reconstructed laboratory samples (A, B, C)

Figure 2.1. Technical classification of MSW proposed by Grisolia et al (1995)

Landva and Clark emphasised that classification on the basis of the nature of material alone is not adequate and a classification similar to that used for geotechnical materials should be supplemented with measured properties, such as water content, specific gravity, organic content, and particle size analysis.

Jessberger and Kockel (1991) have quoted (Geotechnics of Landfill and Contaminated Land – Recommendations, 1991) a classification of the mechanical properties of waste on the basis of geotechnical methods and definitions. This classification broadly falls into two main groups:

- Soil like waste, defined as granular waste, for which conventional soil mechanics theories are applicable
- Other waste (non-sorted municipal waste etc.)

The testing regime for the geotechnical classification of waste is defined below:

Soil-like wastes:

- Moisture content
- Consistency limits
- Grain-size distribution
- Grain shape and roughness of grain surface
- Organic content
- Calcium carbonate content
- Density on placement

Other wastes:

- Description of the waste such that their mechanical behaviour can be defined.
- Grain size analysis
- Ignition loss
- Waste composition by sorting

The ***physical characteristics*** of waste that are of particular interest to waste managers are:

- Waste composition,
- Moisture content,
- Bulk density (specific weight),
- Particles shape, form and size distribution.

Waste composition may provide a significant indication of its likely geotechnical behaviour in landfill. Waste is an extremely heterogeneous material, which varies considerably in composition from location to location and also due to temporal variations. A typical physical composition of residential municipal solid waste data of the United States reported in 1990, excluding recycled material is given in Table 2.2.

	Percent by weight		
Components	**Range**	**Typical**	**Packaging Materials**
Organic			
Food wastes	6-18	9.0	-
Paper	25-40	34.0	50-60
Cardboard	3-10	6.0	
Plastics	4-10	7.0	12-16
Textiles	0-4	2.0	-
Rubber	0-2	0.5	-
Leather	0-2	0.5	-
Yard wastes	5-20	18.5	-
Wood	1-4	2.0	4-8
Misc. organics	-	-	-
Inorganic			
Glass	4-12	8.0	20-30
Tin cans	2-8	6.0	6-8
Aluminium	0-1	0.5	2-4
Other metal	1-4	3.0	-
Dirt, ash, etc.	0-6	3.0	-

Source: Modified from Tchobanoglous et al (1993), Table 3-4 pp 49.

Table 2.2. Typical residential MSW composition of the United States (1990)

A typical waste composition for the waste as delivered to landfill, obtained from the urban collection and civic amenities in the UK, is summarised in Table 2.3.

Constituents	**Weight, % (as received)**
Paper	29.2
Putrescible	19.0
Unsorted fines	8.6
Glass	8.4
Ferrous metal	8.0
Misc. combustibles	5.8
Plastic films	4.2
Misc. non-combustibles	4.0
Garden waste	3.8
Textile	3.0
Dense plastic	2.8
Wood	2.2
Non-ferrous metal	1.0
Total	100

Source: Oni, 2000, Table 3.3, page 35

Moisture content = 33% (by wet weight)
Bulk density (uncompressed) = 170 kg/m^3

Table 2.3. Typical composition of the urban collection and civic amenity waste as delivered to landfill (DoE, 1995)

The composition of municipal solid waste is also affected by the socio-economic and demographic characteristics of the households contributing to the waste streams. Data highlighting this effect have been reported by Tchobanoglous et al (1993) and are presented in the Table 2.4.

Waste management schemes, such as recycling and self-participatory recovery practices at domestic level also have a significant impact on refuse composition. Thus the composition of waste may well vary from the generation point (source) to the point of ultimate disposal. Hence it is important to consider all such activities when estimating the refuse content and its composition prior to disposal. Waste composition parameter itself is also one of the key factors in evaluating the requirement of the intermediate waste management processes such as recovery, recycling, re-use etc. and in working out the viability of these intermediate processes in the waste management scheme. Consequently, the waste composition influences the selection of an appropriate disposal process, for instance incineration, when the waste should be highly calorific and having little moisture content.

	Percent by weight		
Components	**Low-income**	**Middle-income**	**Upper-income**
Organic			
Food wastes	40-85	20-65	6-30
Paper	1-10	8-30	20-45
Cardboard			5-15
Plastics	1-5	2-6	2-8
Textiles	1-5	2-10	2-6
Rubber	1-5	1-4	0-2
Leather			0-2
Yard wastes	1-5	1-10	10-20
Wood			1-4
Misc. organics	-	-	
Inorganic			
Glass	1-10	1-10	4-12
Tin cans	1-5	1-5	2-8
Aluminium			0-1
Other metal			1-4
Dirt, ash, etc.	1-40	1-30	0-10

Source: Modified from Tchobanoglous et al (1993), Table 3-5 pp 50.

Table 2.4. Typical distribution of components in residential MSW for low, middle and upper-income countries

Moisture content of waste is an important consideration in waste management processes. Collection, handling, transportation and storage techniques and facilities may be affected to a considerable extent by the moisture content and its variation within the waste stream. Seasonal effects such as rain, humidity and temperature can cause substantial variation in the moisture content of refuse. Conventionally, moisture content can be reported in two ways: the *wet-weight basis* or the *dry-weight basis.* The term water content is also used therefore, the two forms of expression are represented by MC_{dry}, (WC_{dry}) or MC_{wet},(WC_{wet}) respectively. For convenience the ratio may also be expressed as a percentage value. Tchobanoglous et al (1993) has given a formula for determining the overall moisture content of the waste and is expressed in terms of wet-weight measurement:

$$M = \frac{(w-d)}{w}100 \qquad \text{Equation 2.1}$$

where: M = Percentage moisture content

w = initial weight of sample as delivered

d = weight of the sample after drying at 105°C for 24 hours.

For practical purposes, the moisture content for the municipal solid waste is reported usually on a wet-weight basis, as the estimated values of moisture content are used for determining in situ weight / volume relationships. It is sometimes useful to report water content in waste on a volumetric basis. Water content is then termed as *volumetric water content* (θ_w) which is the ratio of the volume of water to the volume of waste sample (total volume). This form of expression is useful in determining volumetric relationships provided that density measurements are also available.

Some typical components of municipal solid waste and their typical moisture contents reported by Tchobangolous et al (1993) are shown in the Table 2.5.

Type of waste (MSW – uncompacted)	Moisture content % by wet weight	
	Range	Typical
Food wastes	50-80	70
Paper	4-10	6
Cardboard	4-8	5
Plastics	1-4	2
Textiles	6-15	10
Rubber	1-4	2
Leather	8-12	10
Yard waste	30-80	20
Wood	15-40	20
Glass	1-4	2
Tin cans	2-4	3
Aluminium	2-4	2
Other metals	2-4	3
Inerts	6-12	8
Ashes	6-12	6
Rubbish	5-20	15

Source: Modified and adapted from Tchobanoglous et al (1993) Table 4-1, pp 70

Table 2.5. Moisture contents of individual components of municipal solid waste

Some of the typical moisture (water) contents of the constituents of waste occurring in the municipal solid of the United Kingdom are given in the Table 2.6.

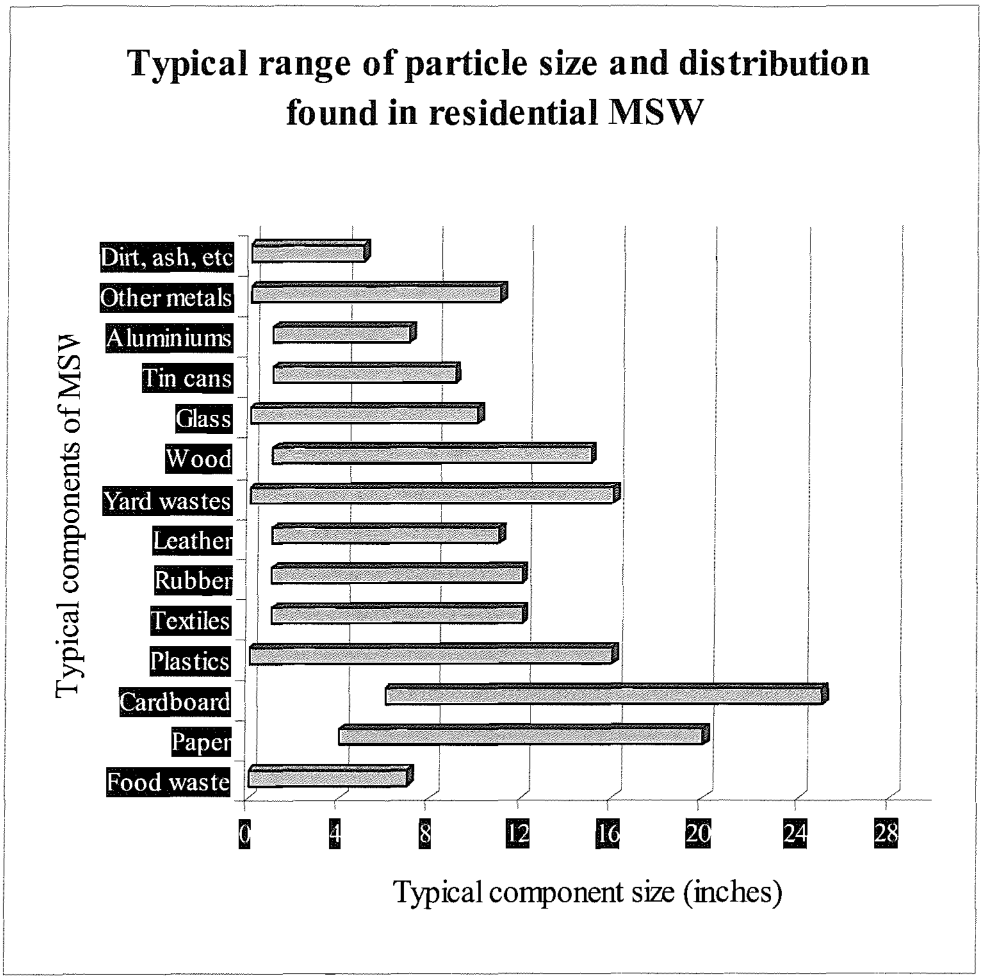
Constituents	**Wet weight, %**
Paper / card	25.1
Putrescible	69.1
Fines	36.9
Glass	0
Ferrous metal	8.8
Misc. combustibles	45.0
Plastic films	33.4
Misc. non-combustibles	8.9
Textile	16.1
Dense plastic	11.3
Non-ferrous metal	12.3
Bulk moisture content	37.8

Source: Adapted from Beaven, 2000, Table 2.5, page 52

Table 2.6. Moisture content of typical components of UK household waste

The *bulk density* or *specific weight* of municipal solid waste is important for appropriate management processes such as handling, transportation and storage and also for the adequate design of the final disposal facility. It is a highly variable waste characteristic and requires special considerations that take into account a number of other physical waste characteristics. These include the specific weight of municipal solid waste in conjunction with a description of its condition i.e. *loose, as found in container, uncompacted* and *compacted* state etc. (Tchobanoglous et al, 1993). The specific weight parameter provides a useful indication of the weight / volume relationship which facilitates waste management operations requiring weight-volume estimations.

Particle size and its *distribution* in raw unprocessed solid waste also vary widely and waste may contain particles that range from 0.1mm to a few meters – several orders of magnitude (Savage, 1996). Waste components lying at the extreme ends of the particle size distribution curve may cause difficulties in management and disposal. Tchobanoglous et al (1993) has reported a typical size distribution of the components found in MSW, shown in Figure 2.2.



Source: Adapted from Tchobanoglous et al (1993), Fig 4-3 pp 75.

Figure 2.2. Typical size distribution of the components found in residential MSW

The component particle size and the distribution of sizes within the waste mass is an important consideration in the recovery of materials, especially when mechanical separation techniques are used, such as sieving, magnetic and air separation. One of the most effective and commonly used mechanical separation techniques uses screens or sieving methods to facilitate particle size grading and recovery of useful material for recycling purposes, prior to final disposal of the residue to landfill.

2.4. Geotechnical characteristics of landfill waste

Some of the important geotechnical characteristics of waste that are important to landfill engineers for the operation and maintenance of landfill processes are discussed in the following text.

2.4.1. Waste moisture content

In general, all refuse has some inherent water in the form of moisture. The waste matrix usually contains large volumes of free voids that can be occupied either by water or air / gas or both. These pores are normally well connected or sometimes may form isolated pockets due to the presence of air / gas in a partially saturated state. Of the voids present in the waste matrix, generally the macro-pores are large enough to form channels or pathways for water to flow, whereas micro-pores exist within the individual waste components such as paper, cardboard, textile, etc. The movement of leachate is predominantly influenced by the presence of macro-pores, their degree of saturation and the hydraulic boundary conditions existing around the particular waste zone. *Leachate* is defined as liquid that has percolated through solid waste and has extracted dissolved or suspended material (Tchobanoglous, 1993). Water in such system, may either be present as free moisture entrapped in voids or in the form of adsorbed water. Free water may be held in the voids due to surface tension in which case it may not drain from the waste matrix under the influence of gravity. Free water enters into the waste stream either at the time of generation or may enter at later stages due to climatic conditions prevailing during storage, handling, transportation, etc. The major ingress of moisture is at the time of disposal at the landfill site due to rain or due to contact with a ground water source. Some water is consumed and also produced due to aerobic and anaerobic decomposition of waste respectively. The water produced due to aerobic digestion of waste forms part of the leachate. Free and adsorbed water together constitute the total moisture (water) content of the waste whose distribution within the waste mass is one of the prime factors in determining the hydrogeological behaviour of a waste.

The water or moisture content of waste can be determined by oven drying the waste to 105°C (gravimetric analysis). The water or moisture content of a waste is a highly variable characteristic which depends on climatic, geo-physical and other conditions. In the UK, waste arising in the summer has a lower moisture content than that emplaced in winter. Therefore, its storage, handling and transportation are affected accordingly. Wet waste on disposal is generally more easily compacted than a relatively drier waste. However, the transportation of wet waste is generally less cost effective than drier waste.

As discussed earlier, there are two stages where waste moisture content data are critical. One is at source which is important for waste collection, transportation and processing (if required) prior to final disposal. The other is at disposal, where the water content often needs to be estimated. In the landfill context, the estimation of waste moisture content when placed in the landfill is of critical importance for the assessment of the degree of compaction required for placement of waste or the estimation of the compacted bulk density.

Another important aspect of moisture content of waste is the critical role it plays towards sustaining the biodegradation process by providing an environment for the survival and growth of micro-organisms. Mobile water also provides the means of transporting essential nutrients and salts required by those micro-organisms already flourishing in the waste.

Although it is practically impossible to assign a single representative value of moisture content for the wastes already emplaced in landfill, efforts have been made to determine in situ waste moisture content on a site-by-site basis (Blight et al., 1991; Yuen et al., 2000; Oni, 2000)

Literature review

The moisture retained in the waste itself represents the largest volume of water content within the waste system. The moisture storage of the landfill system changes according to the infiltration and evapotranspiration of water in the landfill which may also vary depending upon the heterogeneity of the emplaced waste material (Oni, 2000).

The overall moisture content of a waste fill is the sum of the moisture contents of the individual waste constituents (micro-pores) together with the water content present in the voids (macro-pores). In order to estimate the moisture content of waste in a landfill, large sample volumes are required to be tested for their moisture content and this is a cumbersome process. However, Landva and Clark (1990) suggested that large samples of waste could be dried in pottery type kiln furnaces for accurate determination of moisture content and organic content of the waste.

For large sample volumes as required for landfill waste, estimation of moisture content on volumetric basis rather than gravimetric is considered to be more appropriate. Bengtsson et al (1994) stated that most reported initial volumetric moisture content values in municipal solid waste landfills vary between 0.15 -0.2 (as interpreted by Oni, 2000).

The moisture storage capacity of refuse is dependant upon its porosity which in turn is influenced by the compaction and density of the waste material. Blight et al (1991) measured the storage capacities for landfill waste in Cape Town and Witwatersrand. The moisture capacities ranged from 225% for fresh waste (mostly paper and cardboard) to 55% for one to five year old waste when compressed to high densities. Similarly for the Waterval landfill, South Africa, 65 to 125% was reported.

Yuen et al (2000) investigated the moisture profile in landfill by using a neutron probe. The study concluded that the neutron probe provides a practical tool to monitor moisture content in municipal solid waste landfills and is considered to be the best available method for indirect and non-destructive determination of the moisture content. Similar use of neutron probes has been reported by Oni (2000), who investigated the distribution of moisture in the top soil cover of a municipal waste landfill. The probing was carried out in 1 and 2m deep holes. The effect of depth and the seasonal variations in moisture content was observed. The moisture content increased sharply beyond the 140cm depth mark and similarly the moisture content measured near the ground surface during the summer was about half (15%) of the measured in winter (33%), indicating the range that may be encountered at an active site.

Harris (1979) reported a range of landfill moisture contents just after compaction. Natural moisture content was identified to be dependent upon the weather conditions and the waste type. The typical natural moisture content of waste was reported to be in the range of 20-25% on dry weight basis. Compaction tests carried out on fresh pulverised waste indicated that the optimum moisture content was in the order of 50 to 70%. Lee et al (1991) has reported typical water content in Japanese landfill as 22% - 67% on dry weight basis (interpreted by Swarbrick, 1994).

An added feature of the moisture content of waste in landfill is related to the biodegradation process. As the waste degrades, part of the available water content is removed from the system due to the activity of the micro-organism population in the breakdown of the degradable fractions. The by-product of this process is the generation of landfill gas (Tchobanoglous et al, 1993). Reduction in the moisture content of the waste mass may also be due to daily evaporation. Part of this process is assisted by the biodegradation process which causes the temperature to rise inside the landfill above ambient temperatures.

2.4.2. Waste density and unit weight

There are a number of terms defining refuse density relevant to landfill. The particular term or definition that interests a landfill engineer is the bulk density (ρ_{wet}) and is defined as the ratio of the waste mass to volume in its in situ state. Occasionally, dry density (ρ_{dry}) is used to overcome the large variations in the density values owing to the moisture content of the waste. The density of a material being disposed to the landfill provides a rough estimation of waste volume take-up which is required for the effective management during the operational phase of the landfill.

The unit weight (γ) is also commonly used in geotechnical calculations and in a landfill context would be used to estimate over burden pressures (vertical stresses) at certain depths within landfill. It is the product of bulk density and the acceleration due to gravity (g) and is expressed in kN/m^3.

The waste density depends not only upon the composition of waste but critically on the compaction achieved during emplacement by mechanical means. The in-situ moisture content of waste generally aids in the process of compaction. However, other factors such as the thickness of the compacted layer and the elastic rebound of waste are often important in the context of compaction.

In waste management, two types of density definitions are important. The initial bulk density at the source which is subjected to a degree of compaction that is either at the collection and transportation stage or at the waste facility by mechanical means following disposal. The pre-collection density may vary due to geographical location, season and the storage time. The other type of density is its in-situ density that is when the waste is placed in landfill. The relevant term expressing the in-situ state of weight per unit volume is the unit weight (γ). This is arguably of more importance to geotechnical engineers and landfill operators as it governs the volume of waste and hence the effective use of landfill. The other aspect is the increase in overburden pressure which is the function of unit weight and depth of the waste in landfill.

Mechanical compaction at the landfill site is often practiced in order to increase the in situ density and maximise landfill volume (voidage).

Literature review

Tchobanoglous (1993) reported the range of densities when collected and compacted by a typical waste compactor are in the range of 178 to 415 kg/m^3 with a typical value of 300kg/m^3. There has been a wide range of in situ density values reported for landfill waste. Oweis and Khera (1990) have reported some values for the landfill refuse; the US national average is 486 kg/m^3, and for unsaturated bulk waste is 1100 kg/m^3 (Swarbrick, 1994).

Landva and Clarke (1990) calculated the possible maximum and minimum densities for a range of refuse compositions. The resultant average unit weights of the constituents of refuse ranged from 3.8 to 16.3kN/m^3. They also estimated the bulk unit weight by assuming inter-particle (macro) porosity as 30 to 60% which yields an average bulk unit weight of 1.6 to 2.8kN/m^3 for the lightest combination and an average of 6.8 to 12kN/m^3 for the heaviest.

Thomas et al (1999) studied the in-situ characteristics of French landfill waste. They reported that the unit weight of in-situ waste depends upon the composition, the compaction ratio and the drainage conditions within the waste. In order to measure the in-situ unit weight several pits of 2m^3 volume were excavated in the upper layer of the waste just after compaction. The excavated waste was weighed and the volume of the excavation was estimated by filling the pit with water (without allowing water to seep in through the bottom and sides of the pit). The unit weights were determined at varying levels i.e. at 6, 11 and 16m from the base of the landfill. Unexpectedly, the observations failed to show consistent increase in the unit weight with the increase in depth of waste showing considerable variations in the unit weight at particular levels due to the disposal of waste from variable waste streams. The estimated values of unit weight at different levels are given in Table 2.7.

Level	Waste height above the base of landfill (m)	Unit weight values $\gamma_{(\text{in situ})}$ (kN/m^3)	Avg unit weight (kN/m^3)
I	6	8.2 – 16.1	11.8
II	11	7.8 – 16.0	11.3
III	16	9.9 – 14.0	11.4
Total			11.5

Source: Thomas et al, 1999

Table 2.7. In-situ wet unit weight at Torcy landfill

A summary of some of the typical data on the unit weights of different types of municipal solid waste (MSW) has been reported by Oni (2000) in a tabulated form, is given in Table 2.8.

Type of refuse	**Unit weight kN/m^3**	**Source**
Normally compacted crude MSW	3.55 – 4.88	Tchobanoglous (1993)
Well compacted crude MSW	5.88 – 7.28	
Fresh crude domestic waste	5.23 – 5.80	Blakey (1982)
Pulverised domestic waste	7.85 – 9.81	
Crude domestic waste	6.12	Adapted from Holmes (1980)
4-year old crude domestic waste	6.26	Holmes (1980)
10-year old crude domestic waste	7.99	
17-yearl old crude domestic waste	9.42	

Source: Oni, 2000

Table 2.8. Typical unit weights of emplaced refuse fills

2.4.3. Field capacity and absorptive capacity

In addition to the free voids (macropores) available in the waste mass in which free water may or may not already be retained, there is an additional factor that increases the waste's tendency to absorb and accumulate water. This extra capacity is due to the presence of highly porous waste materials such as paper, cardboard, textiles etc. (micropores). Waste when placed in the landfill further accumulates water due to percolation (either from the surface due to rain infiltration or from the base through elevated water table zones) and also in the post closure period when the production of water in the form of leachate as a by-product of the biodegradation process occurs. The tendency of the waste matrix to hold or adsorb water depends upon the availability of voids, their interconnectivity, particle shape and size and the amount of absorbent material. When the quantity of water increases above the waste holding capacity, it starts migrating down under the influence of gravity. This break through point is known as the field capacity (F_c) which is defined as the capacity of a porous medium to retain water per unit mass (or volume). Absorptive capacity (a) is always less than the field capacity ($a = F_c - w$) and is defined as the quantity of water that a porous medium can hold prior to reaching its field capacity. w is the in-situ water or moisture content of the soil at which absorptive capacity is measured. Field capacity and absorptive capacity can be expressed in terms of the volumetric water content. When the absorptive capacity has been fully utilised free draining conditions exist (Beaven, 2000). A similar definition commonly used in soil science is the specific retention (S_r) which describes a soil's field capacity. Absorptive capacity can be expressed either in volume/weight or volume/volume relationship (Beaven, 2000), such as;

Litres of liquid 'absorbed' per wet tonne of waste (litres/t_{wet})
Litres of liquid 'absorbed' per dry tonne of waste (litres/t_{dry})
Litres of liquid 'absorbed' per unit volume of waste (litres/m^3 or volume %).

Table 2.9 shows values of absorptive capacity of waste as reported by some earlier researchers.

SOURCE	Test Cell Size and Refuse type	Density t/m^3	Original WC_{wet} %	Final WC_{wet} %	Primary Absorptive Capacity l/t_{wet}	Total Absorptive Capacity l/t_{wet}
Newton (1976)	8 m^3 pulverised MSW	0.5			230	
Robinson *et al*(1981)	8 m^3 pulverised MSW		40			225
Blakey (1982)	300 m^3 crude MSW	0.57				330
Blakey (1982)	0.2 m^3 pulverised MSW	0.76	26		165	290
Campbell (1982)	4000 m^3 crude MSW	0.66	25		100	
	4000 m^3 crude MSW	0.95	25		41	
	4000 m^3 crude MSW	1.01	25		24	
Holmes (1980)	0.2 m^3 drums 17 yr old MSW	0.96	31.5			115
	0.2 m^3 drums 17 yr old MSW	0.64	31.5			307
Harris (1979)	0.2 m^3 drums crude MSW		26.5			570
Fungaroli (1979)	Indoor lysimeter crude MSW	0.33				867
Kinman *et al* (1982)	6 m^3 crude MSW	0.5	35	54		425
Jones & M (1982)	6 m^3 crude MSW	0.4	14.7		345	
Pohland (1975)	1.6 m^3 simulated pulverised MSW	0.4				1300
Rovers & F (1973)	9 m^3 and 1.8 m^3 crude MSW	0.33				372.5

Table modified from Knox (1992)

Source: Beaven (2000)

Table 2.9. Reported values of absorptive capacity for house hold wastes (MSW)

Vorster (2001) explained that field capacity of in landfill waste is a parameter that is not only dependent on its material characteristics but also a function of the relative position of the waste mass in relation to the phreatic surface. A typical profile of moisture content with depth for landfill waste is likely to be of the form shown in Figure 2.3. As the water table in the landfill varies the capillary fringe changes, which influences the field capacity of waste. Thus boundary conditions play an important role in determining the field capacity of waste material in landfill. In other words, the material in landfill would start releasing leachate at a different moisture contents depending on how far it is above the phreatic surface and on the material's characteristic moisture retention curve (which would probably also vary from layer to layer). In order to estimate the field capacity of a waste, a weighted average of moisture contents should be determined at which release of leachate would start.

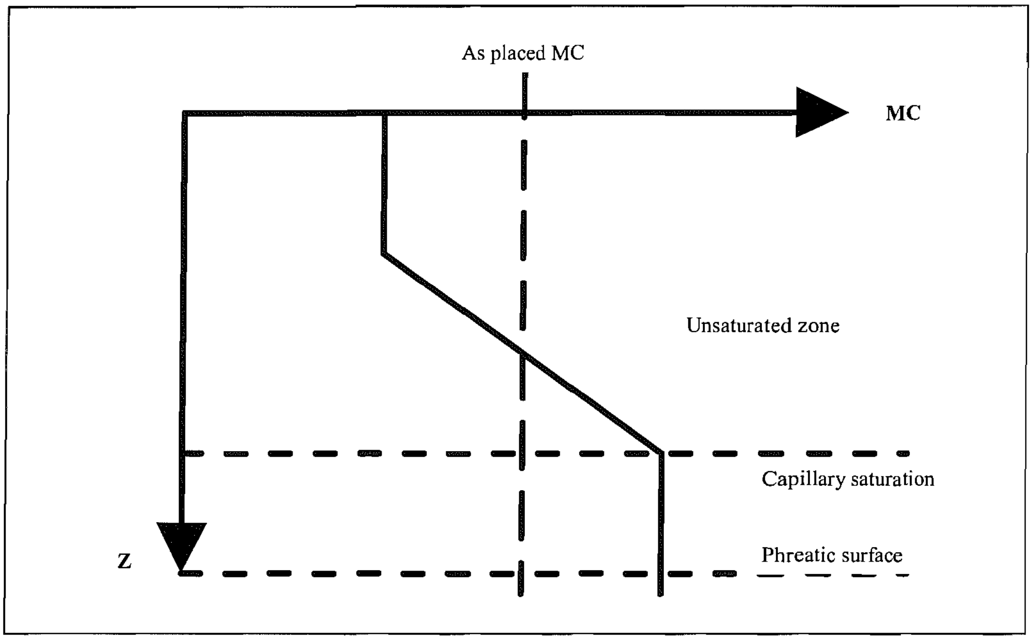


Figure 2.3. Typical profile of equilibrium moisture content in waste landfill

Determination of the hydrological characteristics of waste is necessary in order to design critical engineered features such as landfill leachate management systems. The initial moisture content when the waste is emplaced varies considerably with time and the type of waste. The production of water that occurs during the aerobic digestion of waste is limited to top few meters of the waste, where oxygen is available. The infiltration, evaporation and leachate formation which involves the consumption of water in gas production (CH_4 and CO_2 – anaerobic digestion) bring continuous changes to the entire hydrological regime of a landfill. These changes are dependent upon the density and age of waste which is reflected in its absorptive capacity and ultimately the field capacity of the placed refuse. Leachate movement, therefore, takes place when the waste has reached its field capacity.

2.4.4. Void ratio and Porosity

Void ratio (*e*) is the ratio of volume of voids to the volume of solid mass in a given volume of waste. This parameter provides a measure of the compressibility of the waste or to describe the extent of compaction. Therefore, the useable landfill volume can be estimated on the basis of known void ratio and density parameters. Porosity (*n*) defines the ratio of void volume present in a given volume of waste. These voids may be filled with air or water or both. The degree of saturation (*S*) determines the volume of voids filled with water. At full saturation or at near saturation levels all the voids may be filled with water, though air / gas entrapped within the voids may not allow 100% saturation. At such a state (S=1), porosity is equal to the maximum volumetric water content (θ_{Wmax}). Void ratio and porosity are interchangeable and related through the following expressions:

$$n = \frac{e}{1+e} \qquad \text{Equation 2.2.}$$

and

$$e = \frac{n}{1-n} \qquad \text{Equation 2.3.}$$

Effective or drainable porosity (n_e) is the term usually used for defining the waste void characteristics and is the volume of water released from a unit volume of fully saturated waste material under the influence of gravity when allowed to drain freely (Beaven, 2000). This is analogous to the term specific yield (S_y) commonly used in hydrogeology.

2.4.5. Hydraulic conductivity or coefficient of permeability

A particularly important geotechnical property of soil and perhaps landfill waste in terms of understanding its hydrogeological behavioural is the hydraulic conductivity (*K*) (often termed coefficient of permeability). It is defined as the tendency or ability of a fluid to flow through a porous medium.

Head

In fluid mechanics, energy associated with the fluid in flow is represented in terms of its *head* – energy potential. Head is the energy (potential or kinetic) per unit mass of fluid (Lambe and Whitman, 1979) and is expressed in terms of its measurement from a fixed arbitrary point (datum). There are usually three types of head involved in describing the fluid flow in soil:

- *Pressure head* (h_p), is equivalent to pore pressure divided by the unit weight (γ) of the fluid (u/γ)
- *Elevation head* (h_e), is the distance or height from the datum
- *Velocity or dynamic head* (h_v), which is equivalent to ($v^2/2g$)

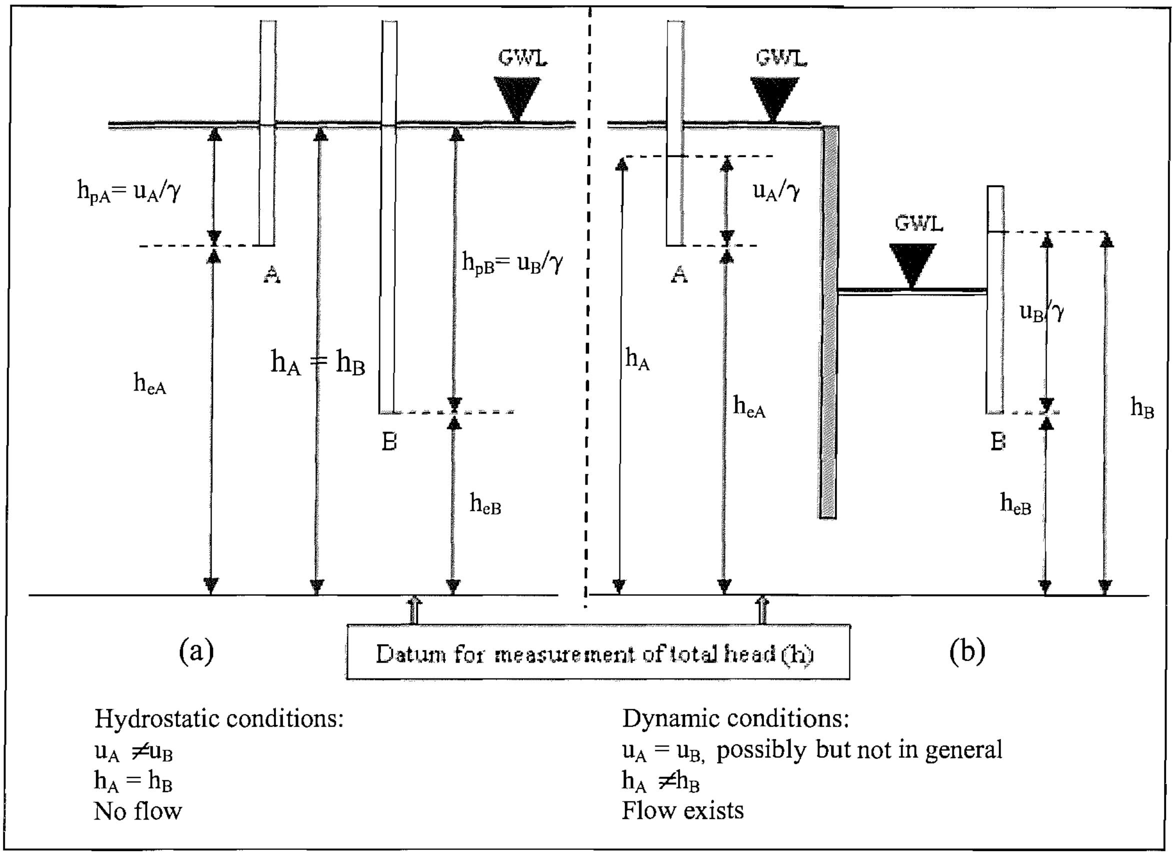
All of these types of heads (energy potentials) provide the measure of the various potentials that fluid has by virtue of its position and motion in the soil. These are expressed in the units of length.

- *Total head* (h), is the sum of all the above mentioned energy potentials ($h = h_p + h_e + h_v$).

The velocity or dynamic head (h_v), is more significant in pipe and channel flows situations and is in general neglected when low velocities flow are involved as is usually the case in landfill applications. The terms *Static head or Piezometric head* (h_{pe}) are interchangeable terms used to measure the combined effect of the pressure head and the elevation head and is equivalent to the total head when the dynamic head is negligible, i.e.:

$$h = h_p + h_e = h_{pe} \qquad \text{Equation 2.4.}$$

Figure 2.4 gives a quantitative description of the various heads involved in describing the hydraulic potentials of water at certain points in a soil (porous) medium. The change in the various energy potentials in (a) static and (b) dynamic conditions is noticeable as they both reach steady state.



Hydrostatic conditions:
$u_A \neq u_B$
$h_A = h_B$
No flow

Dynamic conditions:
$u_A = u_B$, possibly but not in general
$h_A \neq h_B$
Flow exists

Source: Modified and adapted from Powrie, (1997), "Soil Mechanics: Concepts and Applications", Figure 3.4, pp 85

Figure 2.4. Description of various heads experienced in static and dynamic conditions.

Hydraulic gradient

As the piezometric or total head comprises two components; pressure and elevation head, there are also two gradients associated with these heads, which are pressure gradient and elevation gradient, respectively. The drop in the total head over a distance is the measure of the potential for flow and is called the *Hydraulic gradient* (*i*). Mathematically, it is the difference or change in the total head (*hydraulic potential*) over a height or distance (*L*), measured along the direction of flow (Figure 2.5.).

$$i = \frac{\Delta h}{L} \qquad \text{Equation 2.5.}$$

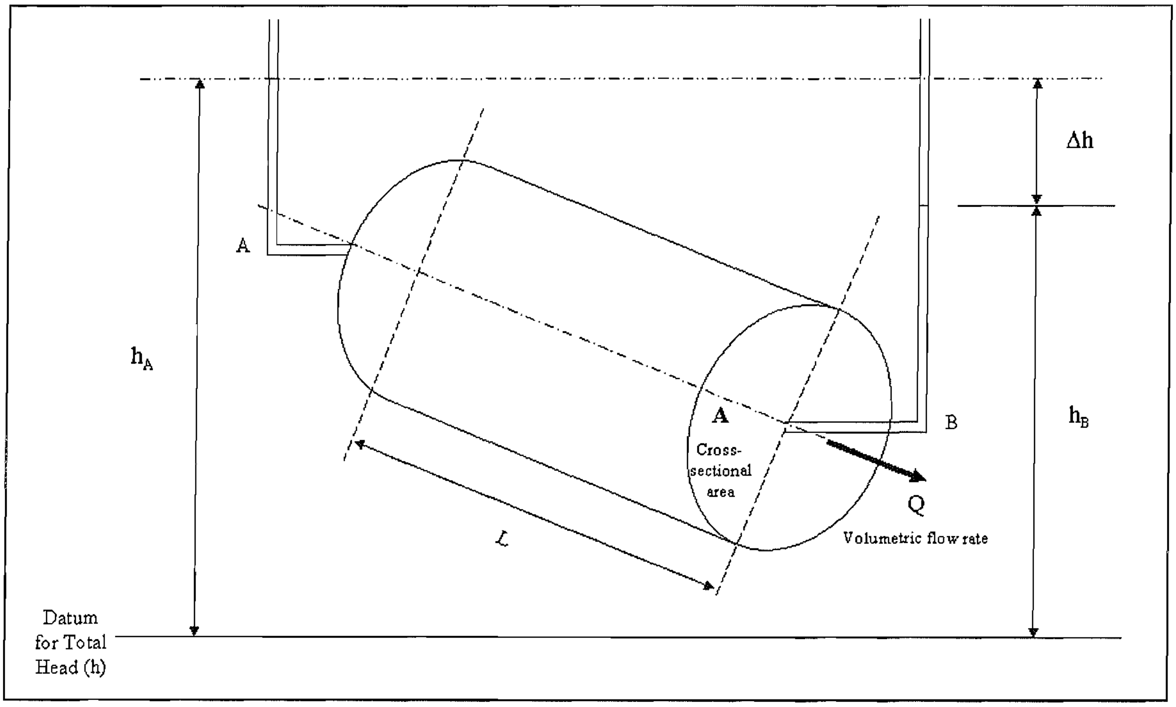
It has no units as it is a ratio between similar quantities.

Permeability and Darcy's expression

In the mid 19th century, H. Darcy performed experiments to study the flow properties of water through sand filter beds (Lambe and Whitman, 1979). He measured the flow rate (*Q*) across a definite cross-sectional area (*A*) of a sample by varying its length (*L*) and the water pressure at the top and bottom of the sample (Figure 2.5). On the basis of his observations, he derived the following empirical equation, which is known as Darcy's equation:

$$Q = K\left(\frac{\Delta h}{L}\right)A = KiA \qquad \text{Equation 2.6.}$$

Where, i = hydraulic gradient
and K = hydraulic conductivity or
Darcy's coefficient of permeability



Source: Modified and adapted from Powrie, (1997), "Soil Mechanics: Concepts and Applications", Figure 3.5, pp 85

Figure 2.5. Illustration of parameters in Darcy's expression

Flow velocity and K

Darcy's equation (Equation 2.6) may also be expressed as;

$$\frac{Q}{A} = Ki = v \quad \text{Equation 2.7}$$

As the cross-sectional area (A) of the sample also represents the total area available to fluid flow, therefore, the flow rate per unit area will give the *flow velocity* (v) which is the directional movement of water in the resultant direction of decreasing head. In terms of v, K can be interpreted as the *approach velocity* or *superficial velocity* when the hydraulic gradient is unity. Hence,

$$K = \frac{v}{i} \quad \text{Equation 2.8}$$

or

$$K = v \text{, when i = 1} \quad \text{Equation 2.9}$$

The average velocity of flow through the soil is termed as *seepage velocity* (v_s) and mathematically it may be represented by the following expression.

$$v_s = \frac{K \cdot i}{n} \quad \text{Equation 2.10}$$

Where n is the porosity of the soil or the porous medium for which the hydraulic conductivity being measured.

Darcy's relationship shows that a flow (Q) through a cross sectional area (A) under the influence of a hydraulic gradient (i), is proportional to the hydraulic conductivity (K) of the porous medium. Equation 2.6 has proved to be valid for most types of laminar fluid flow in soils. Flow in a porous medium may be characterised (in terms of whether it is laminar or turbulent) by means of the Reynolds number (R_e). The value of R_e depends on the velocity of flow (v), the average diameter of the particles comprising the medium (D) and the viscosity of the fluid (μ) according to the flowing expression.

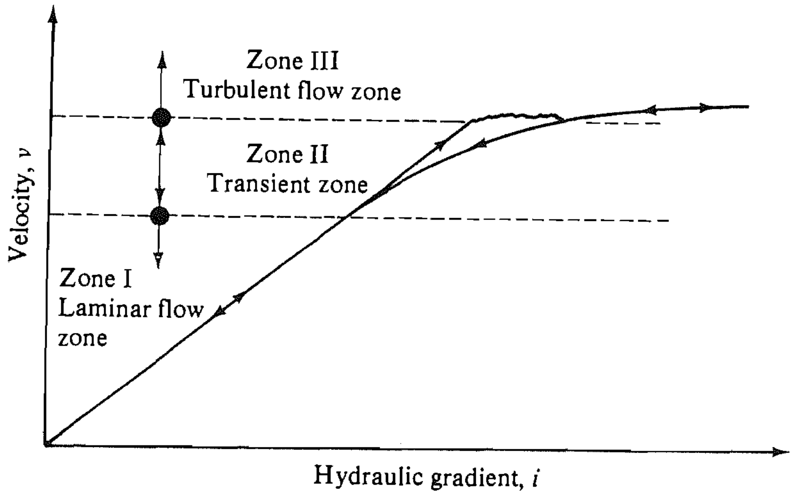
$$R_e = \frac{\rho v D}{\mu} \quad \text{Equation 2.11.}$$

From Equation 2.7 and Equation 2.11, we have

$$R_e = \frac{\rho KiD}{\mu}$$ Equation 2.12.

Many experiments have been attempted (Muskat, 1946 and Scheidegger, 1957) to determine the upper limit of R_e for which flows remain laminar and hence the limit to which Darcy's law is valid (Lamb and Whitman, 1979). Values of R_e for which the flow in a porous medium becomes turbulent have been measured as low as 0.1 and as high as 75. Equations 2.8 and 2.9 show the interdependency of Reynolds number on both the soil permeability and the hydraulic gradient. For a hydraulic gradient of 1, the value of average particle diameter corresponding to a Reynolds number of unity is approximately 0.5mm, which is in the coarse sand range. It has been established that Darcy's law holds true for silts through to medium sands at high hydraulic gradients (Lamb and Whitman, 1979) and the same can be said for steady-state flow through clays. It is suggested that for soils more pervious than medium sand, the actual relationship between the gradient and velocity may depend on the hydraulic gradient if this is high enough to cause turbulent flow, in which case should be determined experimentally.

A typical relationship between velocity and hydraulic gradient in a course soil in which turbulent flow may occur is shown in Figure 2.6.



Source: Das (1990) "Principles of Geotechnical Engineering", pg 95

Figure 2.6. Nature of variation of velocity v with hydraulic gradient i

Intrinsic permeability

The Darcy coefficient of permeability depends upon the properties of the permeating fluid as well as the soil matrix (Powrie, 1997). In order to express the permeability characteristics of the soil medium independently of the nature of the permeating fluid *intrinsic permeability* or *absolute* or *specific permeability* (k) is determined.

$$k = \frac{K\upsilon}{g} = \frac{K\mu}{\rho g} \qquad \text{Equation 2.13}$$

Where:
k = intrinsic permeability (m^2)
υ = fluid kinematic viscosity (m^2/s)
μ = dynamic viscosity ($N.s/m^2$)
ρ = density of the fluid (kg/m^3)
g = acceleration due to gravity (m/s^2)

This is particularly useful in the case of landfill where leachates of varying consistencies and viscosities are encountered (section 2.4.9). In addition, temperature variations may be significantly substantial and are likely to affect the coefficient of permeability to a considerable extent. For example the measured coefficient of permeability will vary by a factor of 2 for a given soil and permeant (water) between 20-60°C (Powrie, 1997) and that is the temperature range that may be encountered in a degrading waste mass (Tchobanoglous et al, 1993).

As discussed earlier, a measure of the hydraulic conductivity of emplaced waste is required to assess contaminant transport (leachate quality and assessment of the extent of possible contamination due to the infiltration of the leachate in to the surrounding environment adjacent to the landfill facility) and to allow leachate collection and drainage facilities to be designed. Production of landfill gas due to waste biodegradation will also have a considerable affect on the hydraulic conductivity of liquids in waste (Chen and Chynoweth, 1995).

The waste matrix comprises macro and micro-pores. The dominant intrinsic flow pattern in waste is principally due to the presence of macro-pores. Hydraulic conductivity is not generally remain uniform within the waste and vary from layer to layer and waste cell to waste cell. It may also change with respect to the direction of flow i.e. anisotropic. Waste placed in landfill may have simultaneous flow in two dimensions (vertical and horizontal direction). Both of these directional flows in saturated conditions may conform to Darcian flow provided the flow velocities remain laminar. The ratio of the coefficients of conductivity between horizontal (K_h) and vertical (K_v) directions may some time be important to note. The ratio may vary from location to location, particularly if daily cover material is used to limit moisture ingress during the operational filling phase of the landfill facility. Hudson (1999) has reported a value of $K_h = 5K_v$ for the tests carried out in the large Pitsea compression cell on crude domestic waste. This value may be as high as $K_h = 8\text{-}10K_v$ depending upon the type of waste and loading configuration.

Unsaturated hydraulic conductivity

Darcy's law is valid when the porous medium is nearly saturated, and hence best describes the saturated hydraulic conductivity. The hydraulic conductivity of an unsaturated porous material or waste will be less than that of the same material when saturated. This may be due to partially filled pores, reducing the cross sectional area through which the flow can occur to; flow being restricted to smaller pores which have reduced conductivity; and finally due to the tortuosity of the flow path occurring due to the non-continuous inter-linked pores (Hillel, 1971 as interpreted by Beaven, 2000)

In an unsaturated material, water in the pores is held by surface tension (capillary tension) and the physical attraction between the water and the particles (adhesion). These forces are responsible for developing negative pressure heads known as suction (section 2.4.8). The suction (ψ) has an inverse relationship with the volumetric water content (θ). It is understood that unsaturated hydraulic conductivity of a soil represents its ability to transmit and drain water and also reflects the ability of the soil to change matric suction as a result of changes in boundary conditions. The permeability of an unsaturated soil varies widely with its degree of saturation (Fredlund and Rahardjo, 1993) and as well depends on the material characteristics of soil. Generalising these statements, we can mathematically express the flow and hydraulic conductivity relationship as (Beaven, 2000);

$$Q = -K(\theta)\nabla H \qquad \text{Equation (2.14)}$$

$$q = -K(\psi)\nabla H \qquad \text{Equation (2.15)}$$

Where, ∇H is the hydraulic head gradient. Eq (2.14) and (2.15) are the forms of Darcy's expression.

It has been verified that Darcy's law also applies for the flow of water through an unsaturated soil (Fredlund and Rahardjo, 1993). However, the coefficient of permeability in an unsaturated soil cannot generally be assumed to be constant. Rather, the coefficient of permeability is a variable which is predominantly a function of water content or the matric suction of the unsaturated soil (as shown above in Equations 2.14 and 2.15). Water can be visualised as flowing only through the pore spaces filled with water. The air-filled pores are nonconductive channels to the flow of water. Therefore, the air-filled pores in an unsaturated soil can be considered as behaving similarly to the solid phase, and the soil can be treated as saturated soil having reduced water content (Childs, 1969 as interpreted by Fredlund and Rahardjo, 1993). Subsequently, the validity of Darcy's law can be verified in the unsaturated soil in similar manner to its verification for a saturated soil. However, the volume of water (or water content) should be constant while the hydraulic gradient is varied.

2.4.6. Measurement of hydraulic conductivity

A considerable volume of data on the hydraulic conductivity of waste is available. These data have been obtained from the field as well as the laboratory.

Field tests

In the following text an introduction to most common of the field test has been presented together with the literature review on the field data of landfill wastes' hydraulic conductivity.

Pumped well techniques

These techniques are commonly referred to as pumping tests. Hydraulic properties of aquifers are determined by pumping a well at a constant rate and observing the drawdown of the piezometric surface or water table in observation wells at some distance from the pumped well. Two types of tests are commonly used;

- steady state test
- non-steady or transient state test

With the steady state test pumping is continued over a considerably longer periods allowing the water levels in the observation wells to approach equilibrium (constant level). With the transient pumping tests, water-level drops in observation well are measured in relation to time.

Observation wells

These are the wells for measuring drop of piezometric surface i.e. water table in response to pumping which may be either existing wells or piezometers especially installed for this purpose. At least three observation wells at different distances from the pumped well are required so that results can be averaged and any erroneous data can be disregarded. Observation wells may be located 10 to 100m from the pumped well. For thick aquifers, distances of 100 to 300m are more desirable. An arrangement consisting of a pair of observation wells at distances, one, two and four times the thickness of aquifer from the pumped well is considered to be suitable. Each pair consists of a shallow well reaching just into the aquifer and a deep well extending to the bottom of the aquifer. For unconfined aquifers, observation wells should be at a distance of at least 1.5 times the aquifer thickness from the pumped well to avoid errors due to vertical flow components in the vicinity of the well.

There are a number of solutions available to estimate transmissivity or hydraulic conductivity of an aquifer. These solutions are in the form of equations that are used for different type of aquifer. For instance, Thies, Chow and Cooper-Jacob solutions are used for confined aquifers using transient state method of pumping.

Leaky aquifers are those which receive water through an overlying material. Pumping water from a well placed in such an aquifer causes a downward flow from the overburden to the aquifer, which any point is proportional to the vertical difference between the water table in the overburden and the piezometric surface of the aquifer. The assumption is usually made that the water table in the overburden is not affected by pumping, so that the downward flow is proportional to the drop in piezometric surface and is valid during the early stages of well pumping. The solutions for the steady state methods are given by the De Glee-Hantush-Jacob and Hantush solution, while for transient conditions solutions are given by Walton and Hantush methods (Smith, 1987).

Rate-of-rise techniques

With this technique, local values of *K* of aquifers or other subsurface materials are determined from the rate of rise of water level in a well or similar hole after this level is abruptly lowered by the sudden removal of a certain volume of water from the well. This removal can be accomplished with a bucket or bailer. Another technique consists of submerging a closed cylinder or other solid body in the well, letting the water level reaches equilibrium, and then quickly pulling it out. Enough water must be removed or displaced to lower the water level in the well 10 to 50cm.

The main advantage of rate-of-rise tests are that pumping is not required, observation wells are not required, and the test can be completed in a short time. Rate-of-rise tests can be used on wells after construction to get a preliminary estimate of aquifer condition. They are also useful where continuous pumping at a constant rate is difficult, where observation wells are not available, where there is an interference from other wells, or where there are other disturbances such as smear and local disturbances around the well that conflict with the basic conditions required for pumping tests. Disadvantages of the techniques are that *K* is measured on a relatively small portion of the aquifer. There are three types of rate-of-rise tests; slug test, auger-hole method and piezometer method.

Measuring hydraulic conductivity in vadose zone

Sometimes it is required to determine the hydraulic conductivity in the partially saturated zone, for instance to evaluate the suitability of sites for groundwater recharge projects, to predict seepage, to determine ultimate drainage requirements of new irrigation projects where water table is expected to rise, to assess the potential of ground water contamination below waste disposal site, to calculate infiltration rates, to analyze surface-subsurface water relationships, or to determine the suitability of sites for land treatment of sewage or other waste water.

The principle of measuring *K* of soil or other material that is in the vadose zone, and hence not saturated with water of greater-than-atmospheric pressure at the time of the measurement, is to artificially wet a portion of the soil and to evaluate *K* from a flow system created in the wetted zone. Since artificial wetting seldom gives complete saturation (entrapped air is difficult to avoid), the resulting *K* value will be less than *K* at saturation. Limited experimental data indicate that *K* after artificial wetting may be about one-half value at complete saturation. The techniques are: air-entry permeameter, infiltration-gradient technique, double tube method and well pump-in technique.

Conventional pumping tests, which are often used to determine the hydraulic characteristics of aquifers, are used at landfill sites to measure the hydraulic conductivity of waste.

Literature review

Lloyd et al (1979) used a point dilution method to determine the hydraulic conductivity of mature domestic refuse. A fluorescein tracer was added to two narrow (<100mm outer diameter) bore holes in a landfill and the concentration of dye in the bore holes was monitored over a period of 14 days. The rate of the decay, together with a measured (or inferred) leachate hydraulic gradient at each bore hole resulted in a calculated hydraulic conductivities of between 4 and 5.5×10^{-5} m/s (as interpreted by Beaven, 2000).

Oweis and Khera (1986) indirectly estimated the hydraulic conductivity of refuse in Hackensaw Meadows landfill in New Jersey, by applying an analytical solution to the height of leachate in landfill. Leachate within the (above ground) landfill drained freely to drains at the edge, creating a leachate mound within the landfill. An analytical solution using the height of the mound, the distance between drains and the recharge rate led to an estimated hydraulic conductivity of 2.6×10^{-6} m/s (as interpreted by Beaven, 2000).

Oweis and Khera (1990) undertook pumping tests on a 35 meter deep landfill having a 9 meter saturated zone. Leachate drawdown data were collected from a fully penetrating pumped well and three observation boreholes located at approximately 9, 22 and 61 meters from the pumped well. Two tests were undertaken, the first at a pumping-rate of 4.5 m^3/hr for a duration of 24 hours (to the point when the pumping well dried up) and a second at a pumping rate of 2.7 m^3/hr which lasted for 2.5 days. Analysis of the drawdown and recovery data from the pumping well and the two nearest observation wells produced a range of hydraulic conductivities between 2.4x10^{-5} and 9.4x10^{-6} m/s. (as interpreted by Beaven, 2000).

Ettala (1987) undertook field measurements on two landfills in Finland. There was a difference in the disposal technology of waste (mechanical compaction) exercised at the two sites. The hydraulic conductivity measurements were based on the volume of the basin, leachate discharge and the levels of water table in the refuse. At the Lahti landfill site, the saturated hydraulic conductivity was estimated by pumping leachate at the rate of 150-200 m^3/day from a borehole and checking the water table in observation holes around the hole. The values differed markedly within the Lahti site due to the variation in the refuse content as incinerator ash emplaced in the particular segment of Landfill give a high conductivity values. The reported values were 2.1 to 2.5x10^{-3} m/s for Hollola site which was filled with slight compaction and 5.9x10^{-5} to 2.5x10^{-4} m/s for Lathi site. Estimations using the Jacob method as a function of time gave the saturated hydraulic conductivity as 4.8x10^{-4} m/s and the distance dependent value i.e. function of the distance between the well and observation well, was 1.5x10^{-4} m/s for the Lathi site.

Landva and Clarke (1990) conducted large-scale tests in pits excavated at various Canadian landfill sites. The hydraulic conductivity was determined by measuring the percolation rate. Hydraulic conductivities ranging between 1x10^{-5} and 4x10^{-4} m/swere reported. The unit weights of the refuse were also estimated so that a possible correlation between the hydraulic conductivity could be determined. The unit weight determined fell in the range of 10 to 14kN/m^3. However, no correlation was found between the hydraulic conductivity and unit weight of refuse. Since the tests were performed at the surface of the landfill and limited to a maximum depth of 4m, the hydraulic conductivity values may be substantially affected by partial saturation.

Townsend et al (1995) observed the rate of percolation and hence hydraulic conductivity from four large-scale infiltration ponds with basal areas ranging from 550 to 1690m^2 at a landfill site in Florida, USA. Infiltration continued for a long period i.e. 28 months and total volume of leachate percolated was estimated at around 34,500 m^3 Steady state percolation rates were used to estimate the vertical hydraulic conductivity at the base of each pond and ranged between 3-4x10^{-8} m/s. This low value may be due to several reasons, including the degree and nature of compaction, particle size, waste degradation, landfill gas production and intermediate soil covers (as interpreted by Beaven, 2000).

Beaven (1996) reported the result of a pumping test undertaken in 1985 on a 9m depth of landfill with a 5-6m saturated zone. The pumping test was carried out over a period of 5 days at a pumping rate of $2.9m^3/hr$. The drawdown was monitored in a network of observation wells at spacing between 5 and 75m from the pumped well. The analysis of results indicated a hydraulic conductivity of $1x10^{-4}$ m/s. The pumping test was repeated 9 years later when the depth of landfill had increased to 23m and the depth of the saturation zone to 6-7m. A pumping rate of $0.4m^3/hr$ was maintained for a period of 12 days and the analysis of the drawdown indicated that the hydraulic conductivity of the refuse had decreased to $8x10^{-6}$ m/s (as interpreted by Beaven, 2000).

Burrows et al (1997) determined the hydraulic conductivity characteristics by conducting over 50 pumping tests in four different UK landfill sites. These sites used clay liner for intermediate and final cover. The depth of wells varied between 10 to 30m in waste aged between 5 to 20 years. Conventional hydrogeological slug and pumping test techniques were used on the waste. Four well test formats were used;
Short-term drawdown / recovery tests on single wells, short term step tests on single well, long term drawdown / recovery tests on single wells and long term drawdown / recovery tests on multiple pumping and observation well sets. All the tests were terminated upon establishment of quasi-semi-steady-state drawdown conditions induced by constant rate pumping of between 0.05 and $2m^3/hr$. Analysis of the results involved the use of hydrogeological models based on Darcian flow and the methods of Theis (1935), Cooper and Jacob (1946), Rorabaugh (1953), Boulton (1963) and Neuman (1975) amongst others. The sites comprising a mixture of domestic, commercial and industrial waste, yielded hydraulic conductivity values between $3x10^{-7}$ to $2.2x10^{-5}$ m/s. The results from a well located in a waste from a rural settlement gave an average of $3x10^{-5}$ m/s. The authors concluded that the flow within the waste was neither homogeneous nor isotropic at some levels. Preferential flow paths existed in the waste, however hydraulic conductivity was found generally to decrease with depth.

Laboratory studies

The determination of waste hydraulic conductivity using laboratory based methods is difficult as overall sample size will be limited causing difficulty in the production of a representative sample with respect to waste heterogeneity and particle size distribution typically found in the field. However, attempts have been made to estimate the hydraulic conductivity at laboratory scale in large 'test cells' establishing with dimensional similitude.

Principle

Soils consist of solid particles with voids between them. In general, these voids are interconnected, enabling water to pass through them; hence soils are generally permeable to water. The degree of hydraulic conductivity is determined by applying a hydraulic pressure difference across a fully saturated soil sample and measuring the consequent flow rate of water from the sample. The flow of water through all types of soils is governed by the same physical laws and the methods used for determining hydraulic conductivity depend upon the characteristic of the materials, i.e. ease of flow through the soil.

Types of test

Determination of soil hydraulic conductivity in a laboratory is commonly undertaken using the following methods;

- Constant head permeability test, and
- Falling head permeability test

The constant head test is used for soils of high hydraulic conductivity typically ranging from K=1 to 10^{-4} m/s or occasionally for very fine sands, silts and clay-silt with laminates (K in the range 10^{-5} to 10^{-7} m/s). The falling head test is used for highly impermeable soils ($K \sim 10^{-9}$ m/s) such as clays.

The constant head permeability test (BS 1377: Part 5: 1990:5 and ASTM D2434) is used for the measurement of highly permeable soils such as sands and gravels with K typically lying in the range 1-10^{-4} m/s. The size of the permeameter may vary depending upon the particle size of the material being measured. For instance particle sizes of 5mm, 10mm and 75mm are used in 75mm, 114mm and 406mm diameter permeameters respectively. As a general rule the ratio of the cell diameter to the diameter of the largest size of particle (in significant quantity) should be at least 12 (Head, 1994).

Disturbed soil samples may be re-compacted within the permeameter by using specified compaction effort, to achieve certain dry densities. Water then flows (either in a downward or upward direction) through the column of soil through an applied pressure difference which remains constant, i.e. under a constant head, such that the flow is laminar. The volume of water passing through the soil sample over a known time is measured to determine the flow velocity. The loss of head between two points across the sample height is also measured to provide the hydraulic gradient. The coefficient of permeability of the soil is then determined using Darcy's equation (2.6).

Under certain situations it may be necessary to determine hydraulic conductivity under constant axial load to replicate the effect of soil stress state on effective porosity. A loading yoke and weight hanger arrangement provides a constant axial load to the soil sample through a platen resting on the soil surface. Similarly, (ASTM D2434) describes the use of a mechanism to provide a constant axial load on the sample. The application of vertical load during the permeability test may help develop relationships between the density or overburden pressure or effective stress and hydraulic conductivity characteristics and to help understand the hydrogeological behaviour of a particulate medium (soil or waste).

Literature review

Korfiatis et al (1984) while studying unsaturated flow through refuse performed constant head permeability experiments on several refuse samples compacted in a permeameter. The samples yielded values of saturated hydraulic conductivity ranging from1.3×10^{-2} m/s to 8×10^{-3} m/s for a reported density of around 890 kg/m^3 (considered to be high compared to the values reported in the literature).

Bleiker (1993) determined the hydraulic conductivity of refuse obtained from varying depths within a landfill which was found to vary between 1×10^{-6} to 5×10^{-9} m/s for dry densities ranging from 500 and 1200 kg/m^3. The authors considered that, owing to experimental errors, lower hydraulic conductivities than these might be expected in field conditions. However, the fact that the samples fitted into such a small testing rig indicates that the grain size of the refuse was very small and may well have been reduced by the effects of the drilling used to extract the waste samples. Larger cored samples of material were obtained from the Brock West Landfill site and falling head permeability tests carried out. No details are provided for the core diameters. The samples were tested in a flexible membrane within a rigid walled tube. The membrane was pressurised against the sides of the core whilst a falling head test was undertaken along its length. Hydraulic conductivities between $3x10^{-7}$ and $1x10^{-8}$ m/s were obtained, but no data on the density of the refuse was given (as interpreted by Beaven, 2000).

Chen and Chynoweth (1995) conducted hydraulic conductivity measurements on processed municipal refuse mainly comprising refuse derived fuel (RDF) from paper and plastics having a nominal particle size of 1.27 x 0.01 cm. RDF material in a dry state was then packed into 3 Plexiglass columns, each 122cm high and 38cm in diameter. The waste density in each of the 3 columns was set at $160kg/m^3$, $320kg/m^3$ and $480kg/m^3$ respectively simulating depths of 3 to15m. The columns were setup as a constant head permeameter. Water flowed continuously through the columns under hydraulic gradients of 2 to 4. Hydraulic conductivities were calculated according to Darcy's equation and was found to be time-dependent. The temporal variation was attributed to varying degrees of saturation following gas formation due to degradation process and the movement of fine particles in the column. Average hydraulic conductivities were $9.6x10^{-4}$, $7.3x10^{-6}$ and $4.7x10^{-7}$ m/s for dry densities of 160 kg/m^3, 320 kg/m^3 and 480 kg/m^3 respectively.

Gabr and Stephen (1995) carried out experiments on the geotechnical properties of municipal waste at laboratory scale. Constant and falling head permeability tests were performed on triaxial compression specimens (BS 1377 and ASTM D2434). The experiments were conducted by tracking flow rates through the specimen following saturation and before consolidation. The measured waste permeability varied over 2 orders of magnitude. This variation did not follow any trend in relation to either hydraulic gradient or unit weight and was attributed to the heterogeneity of waste. Alternatively, a few pieces of impervious material included in specimens could have a large effect on the measured permeability.

A summary of some of the reported hydraulic conductivity values obtained by using field and laboratory investigations are given in Table 2.10.

SOURCE	**Summary of test and refuse type**	**Density (wet) t/m³**	**Applied stress kPa**	**Hydraulic conductivity m/s**
FIELD TESTS				
Lloyd (1977)	Point dilution method in 100 mm boreholes in landfill	N/A	N/A	$4\text{-}5.5 \times 10^{-5}$
EMCON (1983)	Field permeameter used on 10 year old refuse	N/A	N/A	1.5×10^{-4}
Colden (1990)	Tidal stress theory used to interpret fluctuations in leachate levels in landfill	N/A	N/A	2×10^{-2}
Landva (1986, 1990)	Flow net analysis on seepage from pit in surface of landfill	1-1.4	N/A	4×10^{-4} to 1×10^{-5}
Townsend et al (1990)	Infiltration from large-scale infiltration ponds	N/A	N/A	$3\text{-}4 \times 10^{-8}$
Oweis (1986, 1990)	Pumping test on 35 m deep landfill with 9 metre saturated zone.	0.68	N/A	2.4×10^{-5} to 9.4×10^{-6}
Beaven (1996)	Pumping test on 9 metre deep landfill repeated when depth increased to 23 metres	N/A	N/A	1×10^{-4} 8×10^{-6}
Burrows (1997)	Numerous pumping tests on 3 landfills, ?approx. 20 metre deep with ?10 m saturated zone	N/A	N/A	2.2×10^{-5} to 3.9×10^{-7} Av' 5.6×10^{-7}
LABORATORY TESTS				
Chen (1977)	Laboratory tests on milled refuse	0.24 (dry) 0.72 (dry)	N/A N/A	1×10^{-4} 1×10^{-7}
Fungaroli (1979)	Laboratory tests on shredded MSW of varying particle sizes	0.1^{1} 0.35^{1}	N/A N/A	1×10^{-4} 1×10^{-6}
Korfiatis (1985)	Flow through refuse investigated	0.88	N/A	$\sim 1 \times 10^{-4}$
Landva (1984)	Wastes excavated from landfill tested in 470 mm diameter oedometer	N/A N/A	20 400	6.8×10^{-5} 6×10^{-9}
Oweis & Khera (1986)	Waste materials	0.57 1.14	N/A N/A	1.5×10^{-4} 7×10^{-6}
Bleiker (1993)	Refuse recovered from boreholes in landfill tested in laboratory	0.5 (dry) 1.2 (dry)	N/A N/A	1×10^{-6} 5×10^{-9}
Chen & Chynoweth (1995)	Processed (RDF) waste packed into columns at different densities	0.16 0.48		9.5×10^{-4} 5×10^{-7}

Source: adapted from Beaven (2000)

Table 2.10. Summary of the reported values of hydraulic conductivity of MSW

2.4.7. Effective stress and hydraulic conductivity

There is not much reported information concerning the relationship between the two geotechnical parameters, effective stress and hydraulic conductivity, for waste. It has been established that hydraulic conductivity of waste in landfill is dependent on the overburden pressure which, together with the pore water pressure, controls the effective stress developed in the waste. The effective stress exerted on the fabrics of the refuse is very important in analysing the behaviour of waste due to changes in loading and subsurface water pressures (Oni, 2000). In particular, this aspect is important in modelling the geotechnical behaviour of landfill waste when one of the components (say effective stress) is known since the hydraulic conductivity of the percolating leachate may then be reasonably estimated. The effective stress – hydraulic conductivity relationship aids the design of the leachate collection and leachate recirculation processes usually employed at the landfill site. However, when the waste is partially saturated this relationship is complex and is more or less governed by the in-situ stress state of the waste. It has been difficult to establish the relationship through field measurements and no other data is available. Attempts have been made to develop a relationship at laboratory scale (Oni, 2000 and Beaven 2000) which are discussed in the subsequent section.

Vertical stress – total and effective

In landfill, waste is typically buried in layers. This process induces a gradual increment in pressure on the underlying waste mass due to the increasing self-weight of the overlying waste. This induced pressure may be regarded in terms of the total (vertical) stress (σ_v) and mathematically can be expressed as:

$$\sigma_v = \gamma \int_0^z (z)dz \qquad \text{Equation 2.16.}$$

Where z is the depth of the waste from the surface to any point or layer down the landfill where the stress is to be estimated and γ is the unit weight of waste (which may be averaged or taken as constant) over the considered depth. It has units of pressure, kN/m^2. The presence of water within the waste layers affects the total stress value particularly when the water accumulates to form a continuous column i.e. extending from water table to a certain depth in the waste fill. The water generates pressure in pore spaces filled with water in the waste matrix reducing the total stresses in the saturated waste regions. The net effect is the reduction in total vertical stress which is referred to as vertical effective stress (σ_v'). The fluid pressure that is developed in the pore space is termed pore pressure or more specifically, pore water pressure (u_w). Pore water pressure in a hydrostatic condition is again a function of the unit weight and the height of a continuous column of water above the point in consideration.

Terzaghi (1931) introduced the concept of effective stress in saturated soils and suggested corrections to the total stress (σ) value:

$$\sigma' = \sigma - u_w \qquad \text{Equation 2.17.}$$

For unsaturated conditions encountered in landfill, Terzaghi's Equation (2.17) fails to determine the real value of effective stress in waste. The introduction of the concept of partially saturated medium such as landfill waste is analogous to soils, therefore, it is better to understand the behaviour of a degrading and gas producing waste as an partially saturated soil model rather than a saturated one (Powrie, 1999).

In the case of partially saturated soils, pores are filled with air, water or a mixture of air and liquid. Liquid is virtually incompressible compared to the air/liquid and air filled pores which are highly compressible. Therefore, pore pressure has two components; pore water pressure (u_w) and pore air pressure (u_a). Bishop (1959) suggested the following expression for estimating the effective stress in partially saturated soils, by replacing the pore water pressure term (u_w) with [$u_a - \chi(u_a - u_w)$]. Hence, the effective stress equation (Equation 2.17) can be modified as follows:

$$\sigma' = \sigma - [u_a - \chi(u_a - u_w)] \qquad \text{Equation 2.18.}$$

Where χ is a parameter related to the degree of saturation (S = volume of water/volume of voids) of soil and to a lesser extent depends upon the soil fabric structure. The parameter χ does not strictly represent the ratio of the area over which the water pressure acts; rather it correlates linearly with the degree of saturation.

Hence,

when S=100%, $\chi = 1$, Equation (2.18) yields $\sigma' = \sigma - u_w$

and when S=0%, $\chi = 0$, Equation (2.18) reduces to $\sigma' = \sigma - u_a$

The values of u_a and u_w for partially saturated soils can be estimated by laboratory techniques using fine pore and coarse pore ceramics respectively (Smith, 1987).

On rearranging Equation (2.18):

$$\sigma' = (\sigma - u_a) + (u_a - u_w)\chi \qquad \text{Equation 2.19.}$$

Equation (2.19) indicates that the geotechnical behaviour of partially saturated waste is dependant upon the two stress parameters, $(\sigma - u_a)$ and $(u_a - u_w)$, where u_a may be the intrinsic pore air pressure developed due to gassing of waste and sub-atmospheric conditions existing in the pores. The term $(u_a - u_w)$ is the measure of matric suction (ψ_m) which is an important characteristic of unsaturated porous media (soils and landfill waste) in governing its geotechnical behaviour. As identified by Bishop (1959) for soils, the combined effect of these two stress parameters varies in relation to the degree of saturation (S). Again rearranging Equation (2.19) and replacing $(u_a - u_w)$ with (ψ_m) we have:

$$\sigma' = \sigma - (u_a - \psi_m \chi) \qquad \text{Equation 2.20.}$$

Equation (2.20) is another form of Terzaghi's equation which replaces pore water pressure (u_w) with the expression $(u_a - \psi_m \chi)$. This new characteristic parameter is more likely to represent the in-situ stress-state of unsaturated waste and may be useful in determining certain hydrogeological and behavioural properties of landfill waste.

Literature review

Beaven (2000) conducted experiments in 2m diameter consolidation cell on different types of waste and determined the relationship between the applied stress and hydraulic conductivity. The relationship studied was for the effective stress generated in first compression loading. The results are summarised in Table 2.11. The description of types of waste used in the study, are given in the Section 4.4.

Similarly, Oni (2000) determined the same relationship for MSW using a small scale consolidation cell (240mm diameter, 230mm height). The waste particles were reduced to smaller fragments (20mm x 5mm). However, the applied overburden pressures were considerably lower than the applied stresses used by Beavan (2000).

Applied stress (kPa)	**Average pore water pressure (kPa)**	**Hydraulic conductivity (m/sec)**
DM3		
40	31	1.5x10^{-4}
87	55	8.2x10^{-5}
165	32	3.1x10^{-6}
322	39	4.4x10^{-7}
603	38	3.7x10^{-8}
PV1		
40	37	3.3x10^{-4}
87	41	3.4x10^{-5}
165	42	2.4x10^{-6}
322	36	2.2x10^{-7}
603	35	4.8x10^{-8}
AG1		
40	30	1.5x10^{-4}
87	34	5.0x10^{-5}
165	42	6.0x10^{-6}
322	49	5.0x10^{-7}
603	56	3.5x10^{-8}

Source: Adapted from Beaven (2000), pg 213

Table 2.11. Applied stress and hydraulic conductivity relationship in MSW

Applied vertical stress (kPa)	**Dry density (kg/m^3)**	**Hydraulic conductivity (m/sec)**
1.04	199.65	3.60x10^{-2}
2.02	221.14	6.09x10^{-3}
3.00	234.36	5.62x10^{-3}
3.99	255.12	2.50x10^{-3}
4.97	268.56	1.79x10^{-3}
5.96	290.63	1.37x10^{-3}
6.94	302.52	8.16x10^{-4}
7.92	314.15	6.53x10^{-4}

Source: Adapted from Oni (2000), pg 121

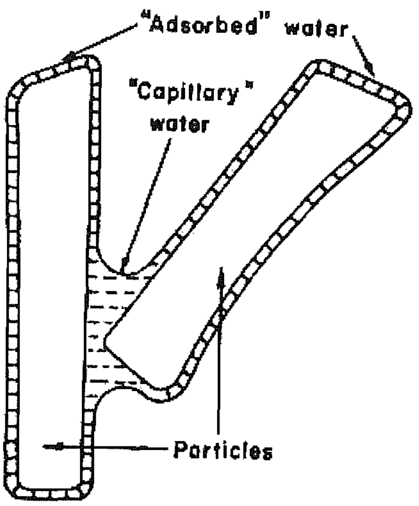
Table 2.12. Applied vertical stress and hydraulic conductivity in modified MSW

The effective stress parameter is considered to be far more complex to determine experimentally than the density parameter even at laboratory scale. It is even more difficult for waste material due to uncertainties such as compressibility of the waste particles, pre-compaction, rebound, reduction in effective stress due to side wall friction, etc. Therefore considering 'first time compression loading' much simpler measurements were involved in developing relationship between the applied (overburden) pressure and hydraulic conductivity in large-scale tests. In this study, however, the dry density and hydraulic conductivity relationship for the model waste is presented in more detail using three different scales of test.

2.4.8. Suction characteristic – definitions and concept

In soil science, 'the free-energy state of water', is commonly referred to as hydraulic potential of soil or simply as suction (Fredlund and Rahardjo, 1993). When the soil water is at a pressure lower than the atmospheric pressure, it is commonly considered to be under a tension or suction (Hillel, 1971). Quantitatively, (matric) suction is defined as the net effect of pore air and pore-water pressures (neglecting the effects of dissolved solutes). Suction is developed in the capillaries by the virtue of surface tension of water and the effective radius of the pores that tend to hold or retain water in the matrix of porous media. In the absence of capillary water, it is the measure of the potential of the matrix of soil or a porous medium owing to its texture, compactness and inter-particle space, to hold water against the pull of gravity. Suction is denoted by ψ.

Water, when partially occupying the voids in a porous medium, exerts partial vapour pressure which, when compared to the saturation pressure over a flat surface, gives the relative humidity (Fredlund and Rahardjo, 1993). Relative humidity has an inverse logarithmic relationship to suction that varies with change in temperature. In mechanical terms, suction may well be expressed as a function of capillary tension. Water in the pores, has tendency to form a 'contractile skin' at the air-water interface due to its surface tension (Figure 2.7).

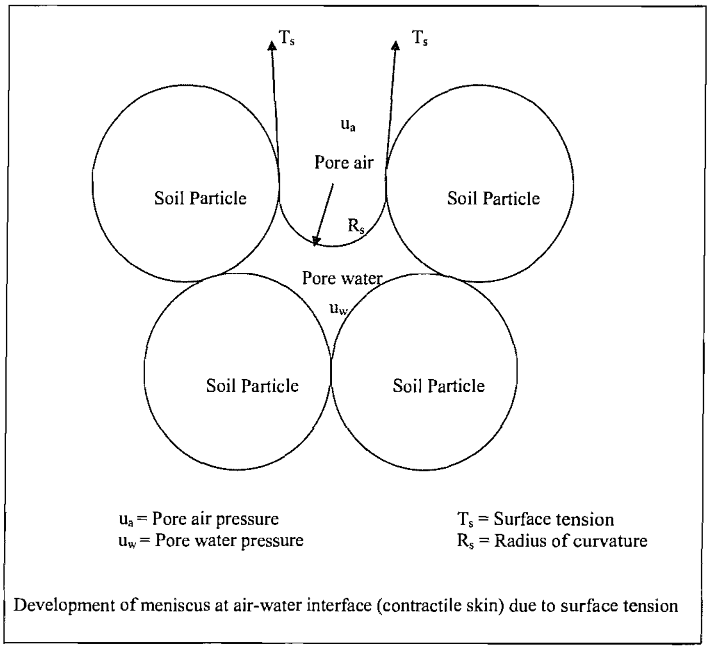


Particle-water interaction in an
unsaturated state

Source: "Soil and Water – Physical principles and processes", Daniel Hillel, Academic press, 1971.

Figure 2.7. Capillary tension and adsorption

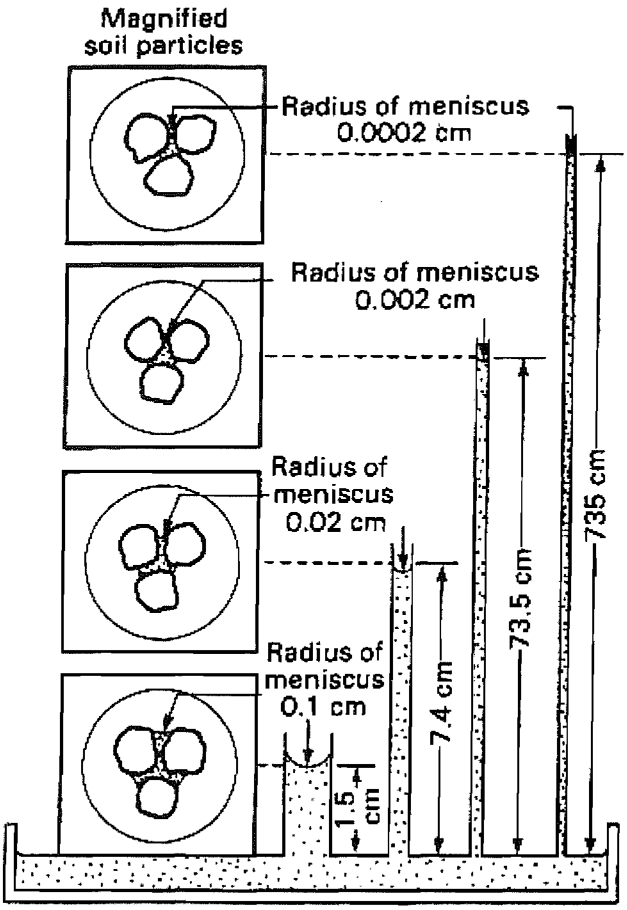
Figure 2.8 describes the surface tension pull (T_S) and the radius of curvature (R_s) developed in partially saturated soil due the formation of contractile skin i.e. air-water interface.



Development of meniscus at air-water interface (contractile skin) due to surface tension

Figure 2.8. Various pressures involved in the creation of capillary tension

The surface tension pull is dependent upon the radius of curvature or the radius of meniscus of water, which in turns depends upon the nature of the particles (e.g. texture, shape and size) and the inter-particle space (i.e. porosity of the matrix). The degree of saturation (*S*) has an inverse relationship to the water retention characteristics and therefore to suction. A particulate material, when partially saturated will allow suction which can be measured as a function of capillary rise, to develop within the pore spaces as shown in Figure 2.9.



Capillary height and radius of meniscus relationship varying with degree of saturation

Source: "Soil Mechanics for Unsaturated Soils", Fredlund and Rahardjo, John Wiley and Sons, 1993.

Figure 2.9. Measure of capillary tension and its relationship to radius of meniscus

Explanation to Figure 2.9

The capillary rise is dependent upon the radius of meniscus or curvature formed by water interacting with the particles of the particulate medium. If the inter-particle voidage, the size, shape and texture of the particles remained unchanged then the capillary rise depends upon the quantity of water present. Hence the potential of the particulate medium depends upon the inter-particle voidage, the shape, texture and size of the particles together with the amount of water available to fill-in the inter-particle voidage. The figure shows the formation of radius of meniscus (curvature) with the interaction between the matrix and water. The resulting capillary rise on formation of a continuous column of water is ultimately dependent upon the radius of curvature formed.

Components of suction:

Suction has two components. The major one represents the capillary pressure termed as matric suction. It is defined as the affinity of soil for water in the absence of salt content gradients in the water (Houston et al, 1994). The minor component is known as the osmotic suction and describes the solute pressure exerted in the matrix due to the salts dissolved in the liquid present in the voids. Osmotic suction may be determined when both total and matric are determined. The mathematical expression for the total suction can be expressed as:

$$\psi = (u_a - u_w) + \pi \qquad \text{Equation 2.21.}$$

i.e. Total = Matric + Osmotic suction

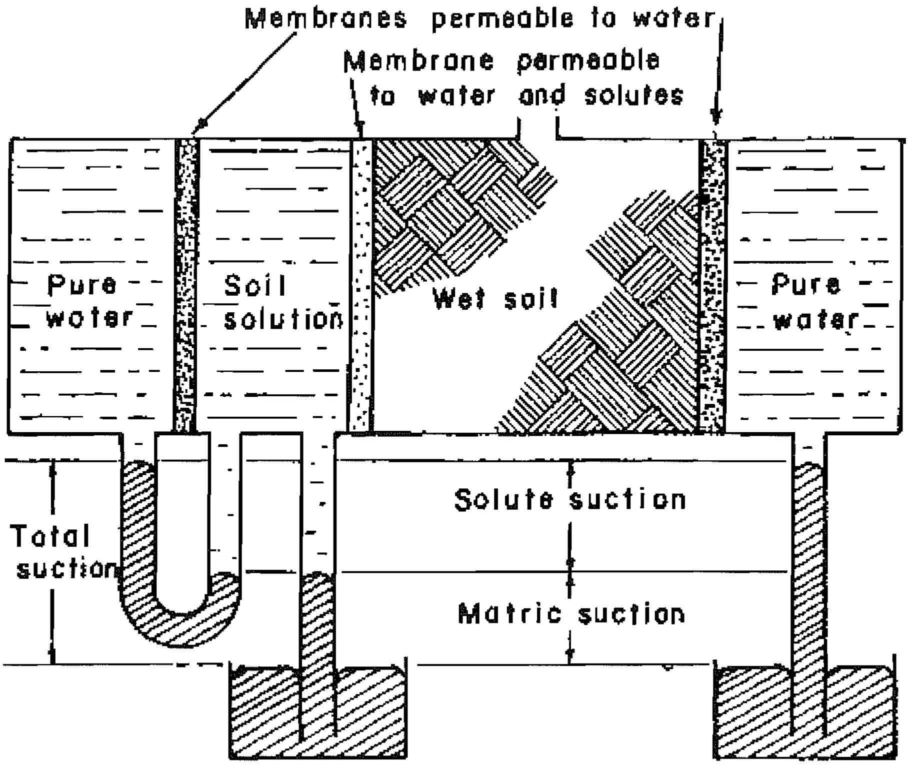
where:

ψ = Total suction,

$(u_a - u_w)$ = Matric suction, ψ_m

π = Osmotic suction.

Suction is expressed in kPa, MPa or pF units. The typical relationship between the total suction and its components may be understood, with the help of Figure 2.10.



An isothermal equilibrium system showing the pressure difference and the components of Total suction – Matric and Osmotic (Solute) suction
Source: "Soil and Water – Physical principles and processes", Daniel Hillel, Academic press, 1971.

Figure 2.10. Qualitative representation of suction and its components

Explanation to Figure 2.10.

A soil-water system has been demonstrated with certain permeable membranes used in different arrangements. When soil is separated from either pure water by means of a semi-permeable membrane (allowing movement of water only), the water potential developed across the partition is Total Suction. When the similar separation is provided between a soil containing dissolve salts and pure water, the driving potential is Solute (osmotic) suction. The membrane allowing both water and solute movement when placed separating a saturated and an unsaturated soil gives rise to Matric suction.

Matric suction is related to the matrix of the particulate medium. It is developed due to capillary tension (Figure 2.8). When this tensile force is allowed to exert its pressure within a continuous medium such as capillaries, it can provide potential for water to rise. The tensile force is also inversely dependent upon the diameter of the capillary (the radius of curvature at the air water interface inside the capillary, Figure 2.9). In the absence of water, the potential of the matrix to draw water against the gravitational influence under sub-atmospheric conditions is represented by its matric suction. Thus, matric suction varies with the moisture content present (degree of saturation), internal air and pore water pressures. Matric suction is also related to the material properties of particles comprising the matrix, such as shape, size and texture.

Matric suction can be expressed in terms of surface tension as (Figure 2.6),

$$\psi_m = (u_a - u_w) = \frac{2T_s}{R_s} \qquad \text{Equation 2.22.}$$

Equation 2.19 gives a mathematically expresses the relationship between surface tension (T_s) and matric suction ($u_a - u_w$), where R_s is the radius of curvature governing the actual pull exerted on the water surface in a capillary. Matric suction (ψ_m) is the difference of pore air pressure (u_a) and pore water pressure (u_w).

In the case where there is an absence of dissolved salts and when the particulate material is in a fully unsaturated state (i.e. $S << 1$ or approaches zero), the matric suction value approaches to the total suction value. Therefore, for some geotechnical problems associated with unsaturated particulate materials, total suction changes may be substituted for the changes in matric suction (Fredlund and Rahardjo, 1993).

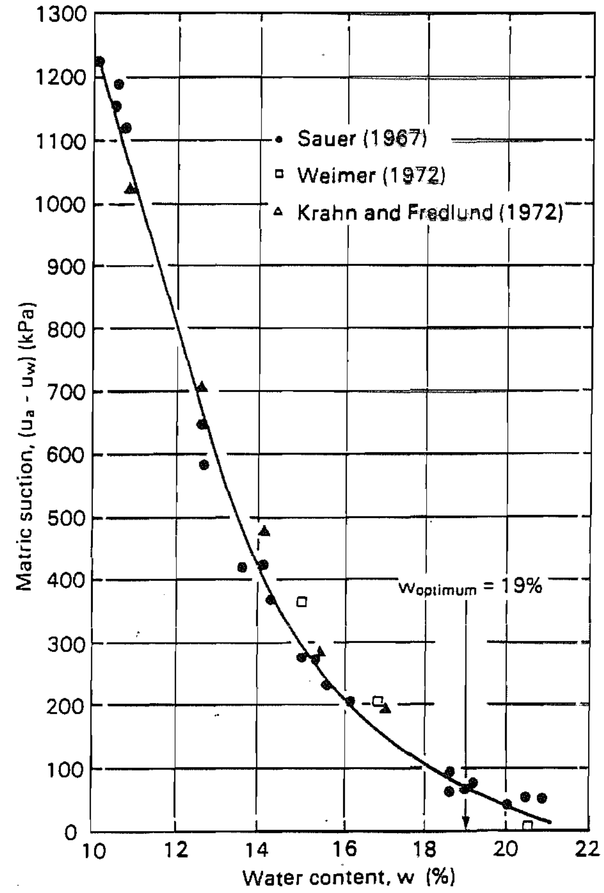
As shown in Figure 2.5, there are two types of water associated with the particle and the inter-particle space. One is the adsorbed water and the other is the capillary water. Matric suction is primarily associated with the air-water interface – the contractile skin, while the osmotic suction is much more closely related to the diffused (adsorbed) moisture layer around the particles (Fredlund and Rahardjo, 1993). The two components of suction are regarded as the independent stress state variables and may have either an individual or combined effect on the overall stress behaviour of the material.
Matric suction is an isotropic pressure associated with the air-water interface i.e. the contractile skin (Fredlund and Rahardjo, 1993). Normally, in unsaturated soils, matric suction is substantially higher than the effective stress and such a condition is likely to exist in waste above the leachate mound. When the matric suction is known, with a reasonable estimate of the pore air pressure, the effective stress can be fairly estimated for unsaturated soils (Equation 2.16).

Suction-moisture relationship

Suction may only be a meaningful and a useful hydrogeological parameter in understanding waste behaviour when is reported in relation to the moisture or water content (water retention characteristics). The particular characteristic may be expressed in a unique form termed a suction-moisture characteristic. Apart from the moisture characteristics, suction depends upon several other intrinsic properties of the porous medium, such as the matrix (structure, inter-particle voidage), particle size, shape and texture, etc. When these intrinsic characteristics remain unchanged then suction is solely dependant upon the moisture or the water content of the medium.

The suction-moisture relationship may be reported in several useful forms, expressed either as gravimetric (w), volumetric (θ_w) or as the degree of saturation (S). In its more generalised form, in context to soils, suction-moisture relationship is termed the soil-water characteristic (Vanapalli, *et al.*, 1999) or soil-moisture characteristic (Fredlund and Rahardjo, 1993 and Hilel, 1971) and in general its water retention characteristic.

It has been identified that in a porous medium, suction is a more fundamental measure of the moisture condition rather than its water content (Blight, *et al.*, 1992). Hence, an appropriate term for representing suction characteristics in waste may be *waste-moisture characteristic* and is the term subsequently adopted in this thesis. This relationship when represented graphically yields a curve which, in the case of waste, may be known as *waste-moisture characteristic curve.* This relationship may be established for any porous material. Figure 2.11 shows some of the examples of soil-moisture characteristic curves.



Source: "Soil Mechanics for Unsaturated Soils", D. G. Fredlund and H. Rahardjo, 1993.

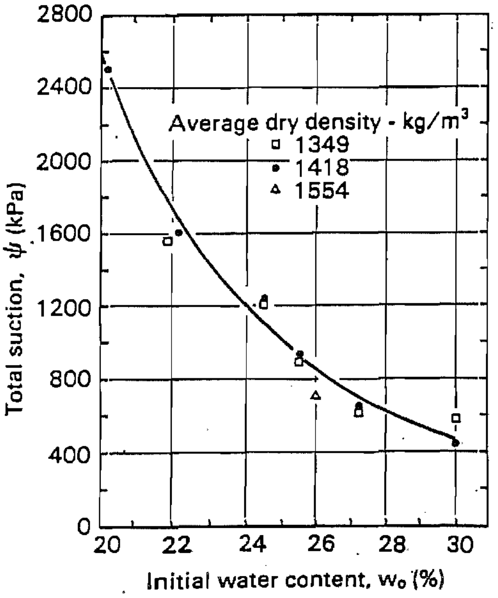


Figure 2.11. Typical examples of soil-moisture characteristic curves

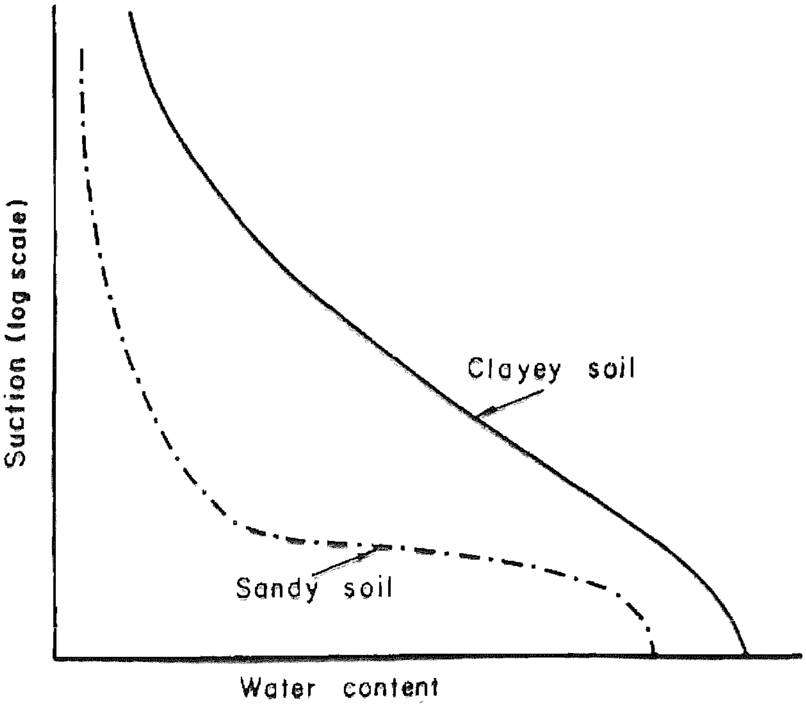
Suction characteristic curve and its significance

Suction characteristic curves may help describe the water flow and solute movement processes through unsaturated soils (Koekkoek and Booltink, 1999). The characteristic curve also referred to as water retention curves is based on a constitutive relationship that describes the hydraulic properties of a porous medium (Vogel, 2000) and is useful in the estimation of various parameters commonly used in describing the unsaturated behaviour in soil (Fredlund and Rahardjo, 1993), for example, permeability and shear-strength. In case of soil, these parameters may be estimated fairly once the respective soil-water characteristic curve is established (Fredlund and Xing, 1994). Other geotechnical properties, such as shrinkage potential, shear modulus or in situ stress may also be determined and predicted through the use of these characteristic curves (Vanapalli *et al.*, 1996).

The following is a discussion on some of the general forms of moisture characteristic curves and how they may be used qualitatively in determining certain characteristic properties of soils in particular and other porous materials in general. Figure 2.12 shows some of the general forms of soil-moisture characteristic curves for different soil types (sand and clay).

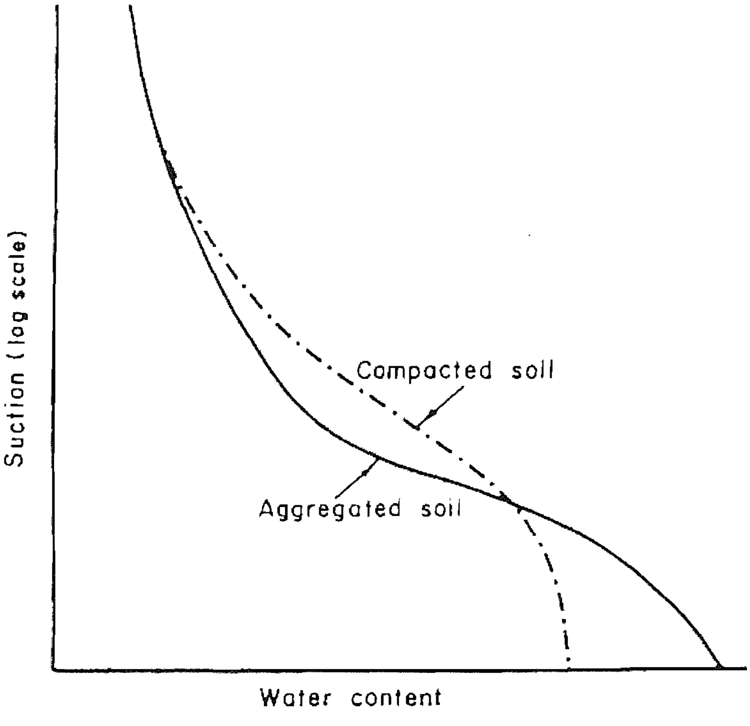
Explanation to Figure 2.12.

Figure (a) represents typical moisture characteristic curves for sand and clay. It is important to note that the slopes of the curve (differential or specific water capacity) help to identify the classification behaviour of the soil. Differential or specific water capacity (C_θ) is the measure of change in suction with respect to the change in the water content. It is dependent on the matric potential of the soil (Hilel, 1971). By inspecting the difference in the curvature of the curves of the two materials a qualitative estimation of the type and characteristics of the soil particles can be usefully made. In the case of clay the characteristic relationship has a gradual uniform slope, whereas in sand the slope changes continuously. Similarly, a change in the compactness (density) of the material may be reflected from a moisture characteristic curve as indicated in Figure (b). The same material, if compacted, yields a curve showing a considerable difference to that when 'aggregated' i.e. loosely set. Therefore, the information available from the moisture characteristics curves is particularly informative and useful in interpreting the nature of the in-situ state of the material.



(a)

Source: "Soil and Water – Physical principles and processes", Daniel Hillel, Academic press, 1971.



(b)

Figure 2.12. Soil-moisture characteristic curves – qualitative representation

Applications of moisture characteristic curves

Fredlund and Xing (1994) proposed a general equation for the characteristic curve:

$$\Theta = a\, e^{-(b\psi)m} \qquad \text{Equation 2.23.}$$

Θ is the function of volumetric water content (or water retention characteristic) where a, b and m are the curve-fitting parameters. However, this general equation requires further modification describing the water retention characteristic as a function of pore size distribution, i.e.:

$$\theta(R) = \int_{R_{\min}}^{R} f(r)dr \qquad \text{Equation 2.24.}$$

where $\theta(R)$ is the volumetric water content when all the pores with radii less than or equal to R are filled with water and R_{min} is the minimum pore radius in the soil. Using the capillary law which states that there is an inverse relationship between matric suction and the radius of curvature of air-water interface or in other words, the air-water interface bears an inverse relationship to the pore size being de-saturated at a particular suction. Equation 2.20 can be resolved to the following equation:

$$\theta(\psi) = \int_{\psi}^{\psi_{\max}} f\left[\frac{C}{h}\right]\frac{C}{h^2}dh \qquad \text{Equation 2.25.}$$

where $C = 2T_s \cos\phi$; T_s = surface tension and ϕ is the angle of contact between water and soil. h is the dummy variable of integration representing suction. Equation 2.21 is the general form describing the relationship between volumetric water content and suction. If the pore-size distribution $f(r)$ of a soil is known, the soil water characteristic curve can be uniquely determined. A non-linear, least-square approach was used to determine the best-fit parameters from the experimental data. The equation has a form similar to that of an integrated frequency distribution curve. The equation provides a good fit for sand, silt and clay soils over the entire suction range starting from 0 to 1000 MPa. However, its application to landfill waste has not been investigated. A part of this study conducts an exploratory investigation into the determination of suction characteristic of waste by developing waste-moisture characteristic curves. Those curves then may provide means to check the applicability of the general equation to waste.

Determination of unsaturated hydraulic conductivity

The unsaturated hydraulic conductivity function for soil can be calculated directly from a moisture retention function and a single measurement of hydraulic conductivity at some water content (Campbell, 1974). If the moisture retention function can be represented by:

$$\psi = \psi_e(\theta/\theta_s)^{-b} \qquad \text{Equation 2.26.}$$

where ψ_e is the air-entry water potential, θ_s is the saturated water content and b is an empirically determined constant, then the hydraulic conductivity is given by,

$$K = K_s(\theta/\theta_s)^{2b+3} \qquad \text{Equation 2.27.}$$

where K_s is the saturated hydraulic conductivity. For many soil samples, agreement between calculated and measured hydraulic conductivities is found to be good.

Van Genuchten (1980) has reported a number of closed-form equations for predicting the hydraulic conductivity of unsaturated soils. The equation based on Mualem's model for estimating the relative hydraulic conductivity (K_r) from a given soil-water retention curve may be expressed as:

$$K_r = \Theta^{1/2}\left[\int_0^{\Theta}\frac{1}{h(x)}dx \div \int_0^{1}\frac{1}{h(x)}dx\right]^2 \qquad \text{Equation 2.28.}$$

where h is the pressure head, given here as a function of the dimensionless water content;

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad \text{Equation 2.29.}$$

In Equation 2.29 s and r indicate saturated and residual values of soil-water content (θ) respectively. Similar equation based on Burdine's model can be expressed as:

$$K_r(\Theta) = \Theta^2\left[\int_0^{\Theta}\frac{1}{h^2(x)}dx \div \int_0^{1}\frac{1}{h^2(x)}dx\right] \qquad \text{Equation 2.30.}$$

The coefficient of permeability (permeability function), for an unsaturated soil, is primarily determined by the pore-size distribution of the soil and is found to be reasonably predictable from the soil-moisture characteristic curve. The permeability function in terms of volumetric water content can be computed from a measured soil-moisture characteristic (drying or wetting) curve. The fit between the measured and computed values has been found to be excellent (Fredlund et al, 1994).

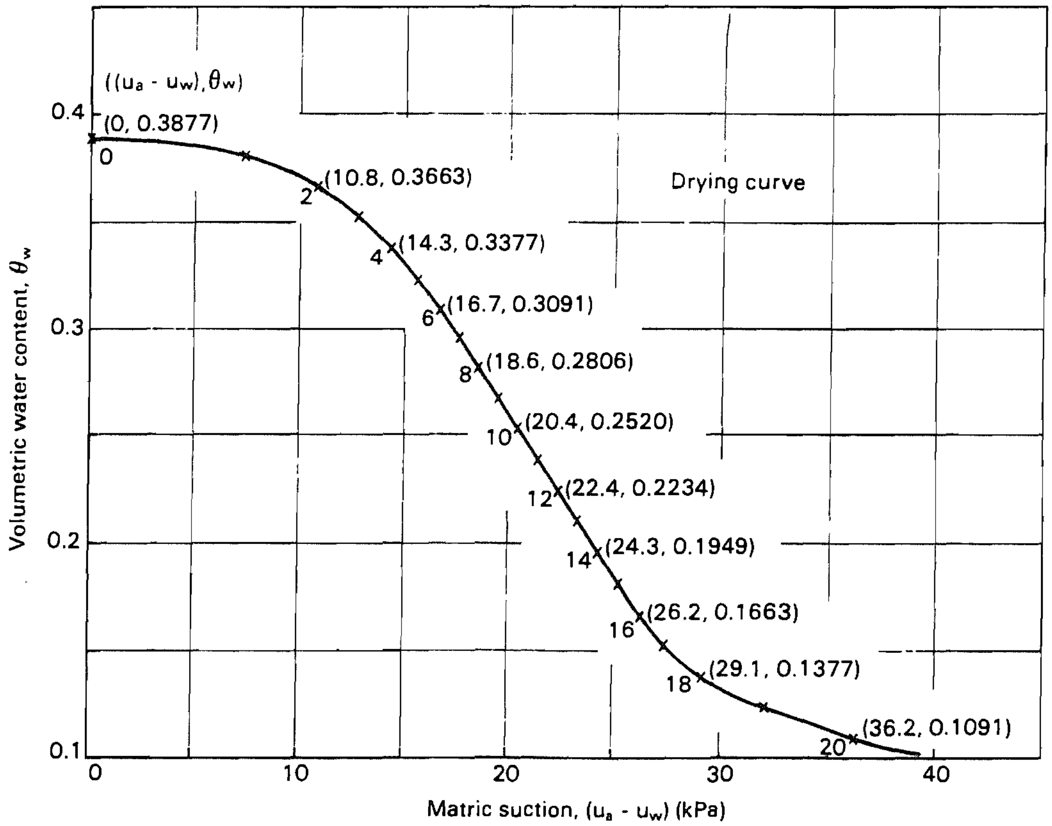


Figure 2.13. Prediction for coefficient of permeability using a soil-water characteristic curve

An application of soil-water characteristic curve is illustrated with the help of an example (Fredlund and Rahardjo, 1993). A soil-water characteristic curve shown in the Figure 2.11 obtained by direct measurement can be used for determination of coefficient of permeability function i.e. $K(\theta_w)$. The drying curve is divided into '*m*' equal intervals of volumetric water content as shown. In this case the maximum and minimum values of volumetric contents are 0.38 and 0.11 respectively. The curve has been divided into 20 intervals with 20 midpoints. The first volumetric water content corresponds to saturated conditions i.e. $(u_a - u_w = 0)$. Each volumetric water content mid point $(\theta_w)_i$. corresponds to a particular matric suction $(u_a - u_w)_i$. The permeability function $K(\theta_w)$ is predicted in accordance with the following equation:

$$K(\theta_w)_i = \frac{K_s}{K_{sc}} A_d \sum_{j=i}^{m} \left\{(2j+1-2i)(u_a - u_w)_j^{-2}\right\} \qquad \text{Equation 2.31.}$$

$$i = 1, 2, \ldots\ldots\ldots, m$$

where:

$K(\theta_w)_i =$ predicted coefficient of permeability for a volumetric water content $(\theta_w)_i$, corresponding to ith interval

$i =$ interval number which increases as the volumetric water content decreases.

$j =$ a counter from i to m

$m =$ total number of intervals between the saturated volumetric water content θ_s and the lowest volumetric water content on the experimental soil-water characteristic curve

$K_s =$ measured saturated coefficient of permeability

$K_{sc} =$ saturated coefficient of permeability

$A_d =$ adjusting constant

$$= \frac{T_s^{\,2} \rho_w g.\theta_s}{2\mu_w.N^2}$$

T_s = surface tension of water

ρ_w = density of water

g = acceleration due to gravity

μ_w = absolute viscosity of water

θ_s = volumetric water content at saturation or zero suction

p = a constant which accounts for the interaction of pores of various sizes. The magnitude of p can be set to 2

N = total number of intervals computed between θ_s and $\theta_w = 0$

$(u_a - u_w)_j$ = matric suction corresponding to the jth interval

The term $\sum_{j=i}^{m}\left\{(2j+1-2i)(u_a-u_w)_j^{-2}\right\}$ in the Equation 2.31 defines the shape of the permeability function. The A_d term is used to factor or scale the coefficient of permeability function and it is constant when predicting the coefficients of permeability values. However, the values of coefficient of permeability, K, are adjusted in accordance with the saturated coefficient of permeability, K_s by use of the (K_s/K_{sc}) term.

Osmotic or solute suction

Osmotic pressure (π) is developed due to the difference in solute concentration within a solution when kept separated by some physical barrier or semi-permeable medium. The pressure develops across the separation barrier tending to equalise the concentration of solution across the separating boundaries. The solute or osmotic pressure may be quantitatively expressed by Vant Hoff's equation which is in fact the general gas equation and is given by:

$$\pi = \frac{nRT}{V} \qquad \text{Equation 2.32}$$

or

$$\pi = C_n RT \qquad \text{Equation 2.33}$$

where,

C_n = molar concentration of solution

R = molar gas constant

T = temperature

In the context of landfill waste, solute concentrations in leachate are usually considerably higher and more inconsistent in composition than experienced with fluid in soils. Osmotic suction in waste may be of critical importance in determining its hydrogeological behaviour than for other porous materials.

In most conventional geotechnical investigations, the change in total suction is more or less the same as the change in matric suction, particularly in the higher water content range i.e. $\Delta\psi \approx \Delta(u_a - u_w)$. Therefore, for unsaturated soils, matric suction changes can be substituted for total suction changes and vice versa (Fredlund and Rahardjo, 1993).

In the context of osmotic suction which may be quite significant in waste due to the formation and presence of leachate, it may be appropriate to discuss here some of the leachate characteristics that are likely to contribute towards the suction characteristics of waste.

Solute concentrations and composition of leachate

Leachate is a consequence of the inherent liquid content of the waste and infiltration of rain water during the placement of the refuse. Leachate is characterised by means of a number of chemical characteristics which are typically monitored and measured in landfill waste. These properties may be summarised as:

- pH
- Total solids; dissolved and suspended
- Total hardness
- Ammonia
- Organic nitrogen
- BOD
- COD
- TOC
- Cations (metals; K, Ca, Mg, Fe, heavy metals)
- Anions (chloride, sulphate, phosphate, nitrite and nitrate)

Gettinby et al (1996) presented a review of leachate quality and composition obtained at various municipal solid wastes landfill sites over the last 4 decades. The concentrations and ranges of leachate constituents have been reported from various sources and presented in Table 2.13.

Table 2.14 highlights the difference in the leachate constituent concentrations for acetic and methanogenic leachates. The values of pH, BOD_5 and COD vary considerably between the two phases as much of the system nutrients are exhausted and the waste material stabilizes.

Thirumuthi (1991) conducted a study on sanitary landfill leachate quality and summarized the concentration ranges of constituents reported in leachate generated at 15 different landfills located in Canada, France, the UK and USA. There were significant differences in leachate composition that occur not only between various landfill sites but also between the various locations within individual landfill sites. Some typical characteristics of raw leachate are given in Table 2.15.

Parameter	**Range (mg/l)** *except for pH*
pH	3.7 – 8.5
BOD_5	81 – 33360
COD	40 – 89520
TOC	256 – 28000
TS	0 – 59200
TDS	594 – 44900
TSS	10 – 700
Alkalinity ($CaCO_3$)	0 – 22800
Total P	0 – 130
NO_3 / NO_2 / N	0.2 – 10.29
Ca *	60 – 7200
Cl	4.8 – 2467
Na	0.7 – 700
K *	28 – 4770
SO_4	1 – 1000
Mg *	17 – 15600
Fe	0 – 2820
Zn	0 – 370
Cu	0 – 9.9
Cd	0.03 – 17
Pb	0.10 – 2.0

Source: Modified and adapted from Gettinby et al (1996)

Table 2.13. Composition of leachate with its typical concentrations

Acetic phase		Methanogenic phase	
Parameter	Range*	Parameter	Range*
pH	4.5-7.5	pH	7.5-9.0
BOD_5	4000-40000	BOD_5	20-550
COD	6000-60000	COD	500-4500
SO_4	70-1750	SO_4	10-420
Ca	10-2500	Ca	20-600
Mg	50-1150	Mg	40-350
Fe	20-2100	Fe	3-280
Mn	0.3-65	Mn	0.03-45
Zn	0.1-120	Zn	0.03-4
Sr	0.5-15	Sr	0.3-7

*Except for pH all values are in mg/l

Data presented by Ehrig (1989) adapted by Gettinby (1996)

Table 2.14. Comparison of values of leachate parameters in different biodegradation phases

Constituents	**Ranges of concentration (mg/l)** *except for pH*	
General	Minimum	Maximum
pH	5.2	8.2
Alkalinity ($CaCO_3$)	37	14000
TDS	2000	15800
SS	100	700
TS	500	15800
Metals		
Al	1.5	2.7
As	0.0006	0.2
Ba	0.1	0.3
Ca	29	4300
Cd	0.0005	0.007
Cr	0.002	1.0
Co	0.01	1.8
Cu	0.01	0.3
Fe	0.3	2050
Pb	0.002	12.3
Ni	0.01	6.1
Na	235	2400
Zn	0.01	130
Non-metals		
Ammonium N	1	1700
Chloride	30	2900
Nitrate N	0.1	10
Ortho P	0.5	39
Total P	0.6	75
Organics		
BOD_5	11	38000
COD	20	70000
TOC	196	23000
TVA	186	15000
Organic N	3	770

Source: Original data from Thirumuthi (1991) reported by Gettinby 1996

Table 2.15. Characteristics of raw leachate

2.4.9. Suction measurement

Some of the commonly used techniques and instruments for the determination of suction in soils that are broadly classified as direct or indirect measuring techniques are (Fredlund and Rahardjo, 1993):

- Psychrometers – direct in situ measurement technique that determines total suction by measuring relative humidity. This instrument can measure total suction of soil in the range from 100kPa to 8000kPa

- High air entry discs – ceramic discs that have fine uniform pores which work on the principle of balancing surface tension (air entry value) at the interface of soil and disc surface. The method can only be applied to laboratory samples. The measuring ability of the high air entry disc (pressure plate) depends upon the air entry value of the disc used. Up to 15 bar (1500kPa) discs are available.
- Tensiometers – measure directly the negative pore water pressures when placed in equilibrium with soil. The hydraulic potential (suction) is developed across the ceramic cup of the tensiometer depending upon the air entry value of the cup. This method can be employed in situ or in the laboratory using undisturbed soil samples. It can measure matric suction up to 100kPa effectively.
- Thermal conductivity sensors – an indirect technique that measures change in thermal conductivity which is related to the change in the ambient moisture content of the soil. The corresponding value of suction is determined by using a calibration curve which bears a relationship between the change in moisture to the change in matric suction. Accurate measurement of matric suction from 0-300kPa is possible.
- Filter paper method – is an indirect technique based on the principle of equalisation of suction through transfer of moisture or vapour from the specimen when brought in a contact with the filter paper in a close container. The moisture transferred to the filter paper is gravimetrically measured and the value is correlated to suction by using calibration curve developed for the filter paper. The method has been adopted for the determination of suction in waste in this study and its principle and methodology are discussed in detail in Chapter 5.

Specialised techniques

Guan and Fredlund (1997) developed a suction probe to measure directly matric suctions greater than 100kPa. The suction probe contains a small volume of water, a high-range pressure transducer, and a 15 bar rated ceramic disc. Cyclic pre-pressurization, up to 12000kPa is used to dissolve micro air bubbles which may cause cavitation. Using a pressure-plate cell, the suction probe has proved to be accurate, having a rapid response for pore-water pressures as low as – 500kPa. Measurements performed by means of this probe were found comparatively much closer to actual values. The suction probe is recommended for measuring suction in soils with a low degree of saturation.

Kasap et al (1994) investigated the attenuation of ultrasonic waves at 117 kHz as means of measuring the water content of a highly porous ceramic medium, in order to evaluate indirectly the water suction of soils. A porous ceramic disc, with a porosity of approximately 66% was prepared with a volumetric water content related to the estimated matric suction value. The ultrasonic technique has been shown to be suitable for matric suctions, above approximately 50kPa. Although the output voltage versus water content relationship was non-linear it could, nevertheless, be represented with reasonable accuracy by a logarithmic-parabolic calibration curve, which was independent of the excitation voltage. The main disadvantage of the technique, however, is that the calibration curve depends upon the salt content of the water in the ceramic disc. However, when the ultrasonic method was used in conjunction with other techniques, it provided a useful further means of characterising matric suction.

A simple and inexpensive electro-optical switch (infrared light-emitting diode – IR LED) has been developed, indicating that soil water suctions can be measured accurately by employing nylon filter discs with varying pore sizes (Cary et al, 1991). Nylon filter discs, that becomes translucent when water is absorbed, open or close an electro-optical switch at a specific soil water suction, and this suction is associated with the air-entry value of the filter disc and works on the same principle as digital tensiometer. Sensors, constructed by inserting a nylon filter disk in a switch, are sensitive between the suction ranges of 0.0004 to 2.4MPa and have been successfully tested in a silt loam soil, under drying as well as wetting conditions.

Determination of suction characteristics in landfill waste

So far very little has been reported in relation to the determination of suction in MSW. The above discussion deals particularly with soils and therefore may be applicable to waste, provided that the waste behaves in a similar manner as soil and this remains the primary objective of the study. The main concern regarding the waste in context of its suction characteristics is its particle size. Since the suction (water retention) characteristic is dependent upon the waste particle size and its arrangement in the waste matrix, suction in waste for a given value of moisture content may vary considerably.

Another important aspect is the effect of leachate (salt) composition on the suction characteristics which has not previously been studied directly. Its effects on the determination and measurement of suction using filter paper method are one of the subjects of investigations presented in Chapter 5.

Literature review

The investigation into the suction characteristic of landfill waste has not been extensive. Suction plays a vital role in governing the mechanical behaviour of particulate material particularly in unsaturated soils. It is one of the key hydrogeological characteristic that requires comprehensive understanding, in order to assess the geotechnical behaviour of soils. In the context of a landfill, where the change in moisture content of waste is erratic, the corresponding change in the suction characteristic must be measured, so as to formulate a better understanding of waste behaviour and to allow more representative models that capture the engineering behaviour of the waste to be developed.

Suction-moisture characteristics

Vanapalli et al (1999) described the use of the soil-moisture characteristic curves over a limited suction range, i.e. 0 to 1500kPa for the modelling of unsaturated soils. However, the change in suction from saturated to a dry state is between 0 and 1000MPa. It is understood that the initial moisture content responsible for the moulding of soil has a dominating affect on the aggregation of soil matrix which in turn influences the soil-moisture characteristics. In the low suction range (0-1500kPa) it is the macrostructure that influences the soil-moisture characteristics in samples compacted with dry of optimum initial water contents. Such samples exhibit a much steeper slope for their soil-moisture characteristic curves. On the other hand, specimens compacted at wet of the optimum moisture contents, microstructure governs suction characteristics.

Suction in waste

Blight et al (1991) reported some suction values determined in two landfills while investigating the moisture requirements for bacterial activity in semi-arid climatic conditions. The study was carried out at the end of the dry season so as to ensure that the values obtained represented maximum suctions. The suctions were measured using psychrometers, therefore the readings represent total suction. The suction values experienced in one landfill at a depth of 8m were consistently below 300kPa while at a different landfill study site the suction determined at a depth of approximately 5m depth was up to 400kPa.

Korfiatis et al (1984) used leaching columns of waste instrumented with tensiometers. Suction profiles were obtained together with a suction moisture relationship. Suction was measured in 3 refuse samples at various moisture contents. An exponential relationship defining the suction-moisture characteristic curve was established. The suction-moisture relationship developed for the particular wastes is given in Figure 2.14.

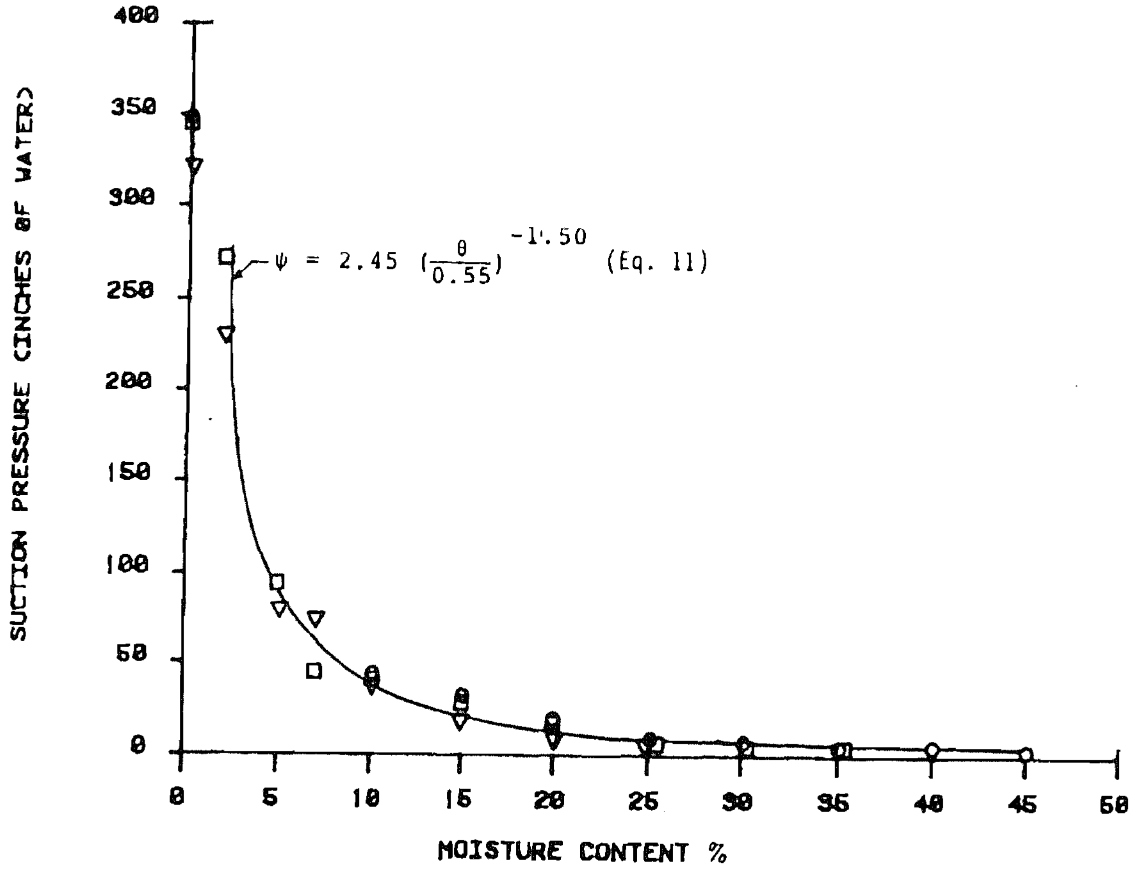


Figure 2.14. Suction pressure-moisture content curve of refuse developed by Korfiatis et al (1984)

Chapter 3

Materials and Methods

3.1. Introduction

Municipal solid waste (MSW) is extremely heterogeneous in terms of composition, has a wide ranging particle size distribution and a highly variable ratio of inert to degradable fraction. To remove some uncertainties in the measured waste performance that arises from heterogeneity, it was necessary to formulate a model waste that replicates key features of waste composition, and which will allow its performance to be assessed at a scale convenient for a conventional soil mechanics laboratory.

3.2. Need for a characteristic model waste

Waste comprises a range of constituents in varying proportions and sizes. For the purpose of repeatable laboratory scale experiments involving waste, a representative samples and sample sizes that are generally relatively smaller than those typically obtained from the field, are required. Also, it is impracticable to accommodate all waste components in the limited waste volumes necessary for laboratory based tests. To overcome these constraints a *model waste* was devised that is largely representative of municipal solid waste in terms of composition, but would fit with the scale of apparatus available in the laboratory. Consistency of composition and reduced particle size distribution were considered to be the key changes necessary in the development of a model waste, for determining various hydrogeological and geotechnical properties of waste.

3.3. Composition of model waste

The recipe for the model waste was adopted from a previous landfill study (Richards, 2001). The model waste was representative in terms of composition to wastes accepted at a site licensed to accept low level radioactive materials. Table 3.1 and Figure 3.1,

General Classification	**Individual Waste Component**	**%age of Total Waste as prepared**
Cellulose/Lignocellulosics (33%)	Tissue	11%
	Wood Shaving	11%
	Paper Sacks	11%
Plastics (26%)	Polyethylene Sack	5%
	Polyethylene Bottle	5%
	PVC Sheeting	16%
Rubber (12%)	Rubber Gloves	12%
Other (29%)	Ferrous Metal Shaving	8%
	Electric Cable	7%
	Absorbent Granule	7%
	Glass Bead	7%
Total Composition by weight		100%

Table 3.1. Composition of model waste (dry weight basis)

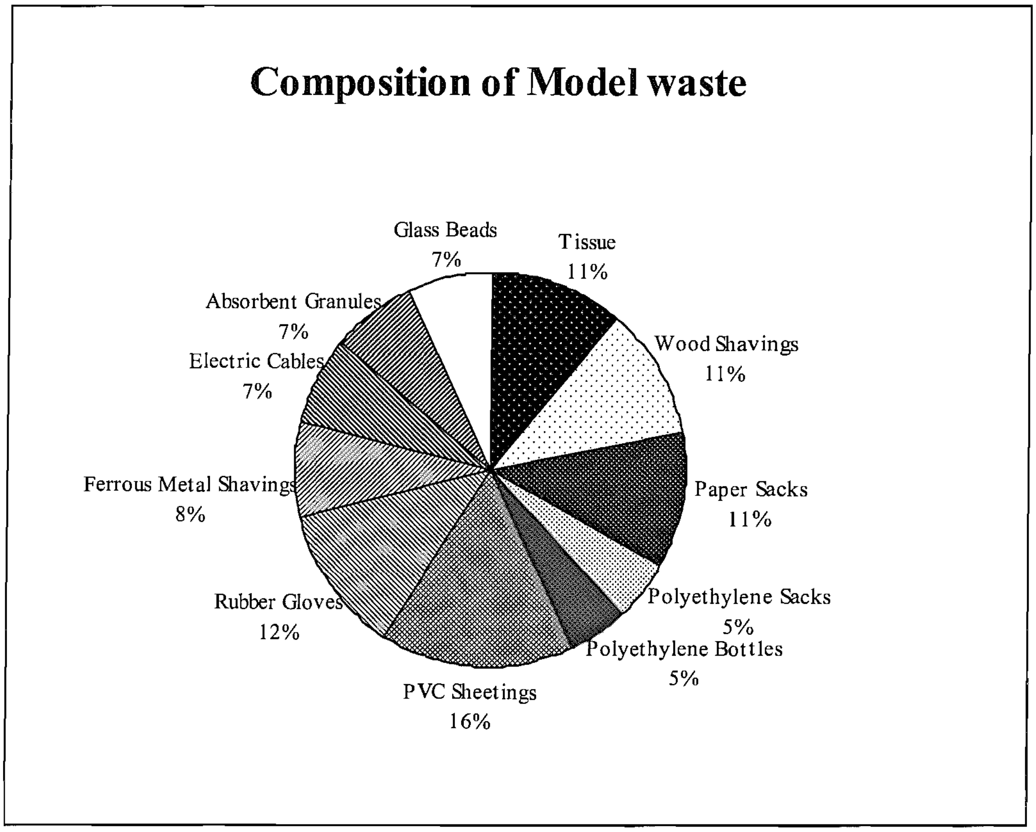


Figure 3.1. Composition of model waste (dry weight basis)

shows the percentage composition on dry weight basis and description of the model waste composition respectively. In the initial experiments undertaken to determine waste suction characteristics, sand was used in the proportion 2:3 by dry weight mass to simulate the daily cover being placed at the actual site.

3.3.1. Characteristic features of the model waste

The model waste was more or less characteristic of certain industrial wastes in that no putrescible or readily biodegradable fractions existed. Comparing the typical composition of the model waste with the waste composition arising from UK household waste indicates that the putrescible fraction of MSW is approximately 20% (DoE, 1994 as interpreted by Beaven, 2000). Other components of MSW such as; plastics, paper material, rubber, glass, wood, metal, constitute the model waste, however their proportion is substantially different from the typical MSW values. Assessment based on the nature of the individual components, model waste is considered moderately inert with degradation processes chiefly limited to the ligno-cellulose fraction. This characteristic feature of the model waste was considered essential to minimise biodegradation likely to occur during the experimental phase. The ligno-cellulose fraction of the model waste comprised approximately 30% of the total waste composition which is assumed to degrade over long term (beyond the experimental) period. Ligno-cellulose materials are the combination of lignin and cellulose whose exact chemical nature is still unknown. These compounds are found in news print and certain plant trimmings. The biodegradability of many organic compounds found in MSW may be estimated on the basis of lignin content expressed in terms of volatile solids content and may be expressed by the following equation (Tchobanoglous, 1993):

$$BF = 0.83 - 0.028\ LC \qquad \text{Equation 3.1.}$$

where

BF = Biodegradable fraction of the organic waste components expressed on a volatile solids (VS) basis

0.83 and 0.028 are empirical constants

LC = lignin content of VS expressed as percent of dry weight

Equation 3.1 suggests that if the lignin content is higher, the BF value will be lower and vice versa. Hence newsprint and cardboard (see Table 3.2) having a higher percentage of lignin are much more stable and will take considerably longer to degrade in comparison to office paper and yard waste.

The rate at which the various components degrade varies markedly. For practical purposes, the principal organic waste components in MSW are often classified as rapidly and slowly decomposable. In the case of model waste the lingo-cellulose fractions were supposed to decompose slowly, even though the major constituents fall in the office paper category and the remaining material is wood which can be assumed as to have the characteristics of yard waste.

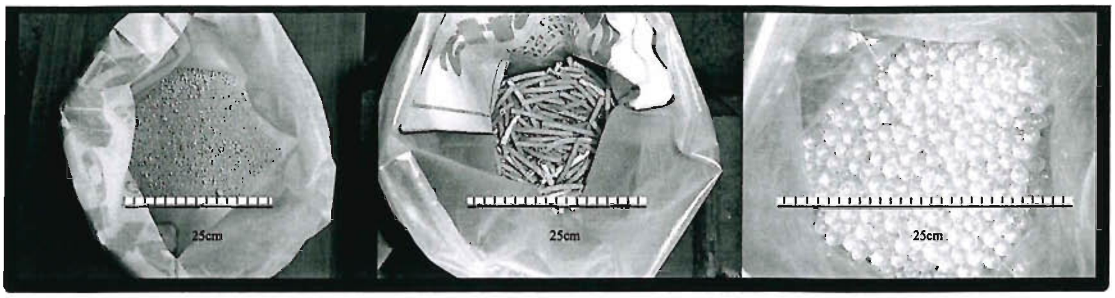
Components	Volatile solids (VS) % of total solids (TS)	Lignin content (LC), % of VS	Biodegradable fraction (BF)*
Food wastes	7-15	0.4	0.82
Newsprint	94.0	21.9	0.22
Office paper	96.4	0.4	0.82
Cardboard	94.0	12.9	0.47
Yard wastes	50-90	4.1	0.72

*Calculations based on the Equation (3.1)
Adapted from Tchobanoglous et al (1993) Table 4-7 pp 88

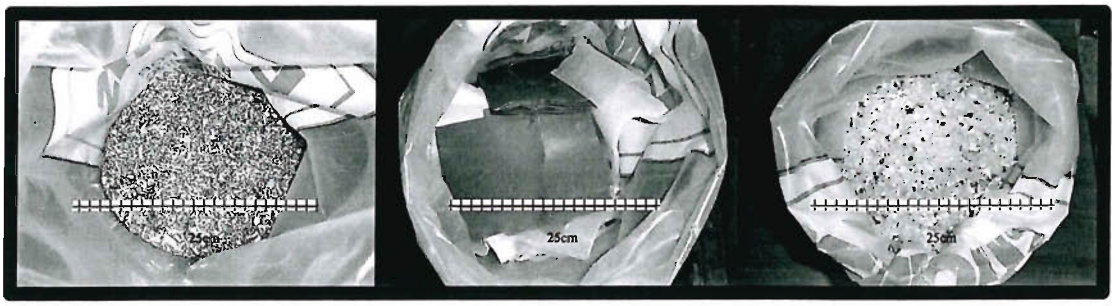
Table 3.2. Estimation of biodegradable fraction of waste components based on lignin contents.

According to Table 3.2, these two components (paper and wood) have a biodegradable fraction of 0.82 and 0.72 respectively despite their high biodegradable fractions. Considering the time scale of the experiments to be carried out in the laboratory, these components may be categorised as slowly degradable. Therefore, it is assumed that over the time scale of testing, degradation of the organic waste fraction does not occur or is insignificant.

The preparation of the components of the model waste is shown in the Figure 3.2.

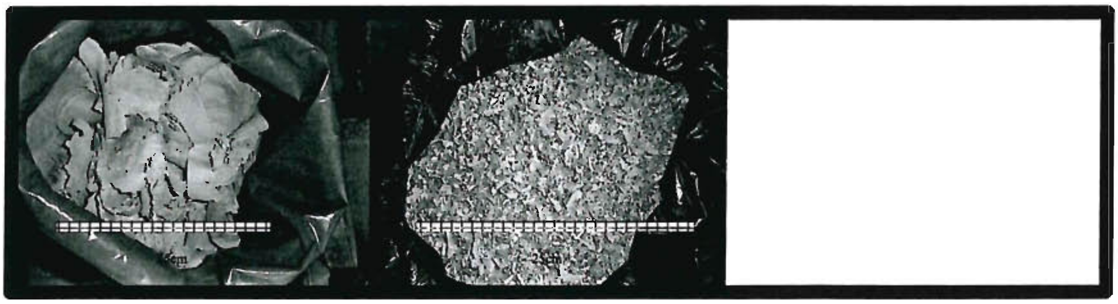


Absorbent granules Electric cables Glass beads



Metal shavings Polyethylene sheets Polyethylene bottles

Paper bags PVC sheets Rubber



Tissues Wood shavings

Figure 3.2. Preparation of various component of model waste

3.4. Experimental set up – test cell

The selection of appropriate particle sizes for different waste components was based on the size of the test cell or particularly the permeameter used for determining hydrogeological relationships in the model waste. Researchers have used different types and sizes of test cells for determining characteristic properties of real waste. A review of those test cells used in various studies is given in the following text.

Literature review – test cell

In comparison to conventional soil testing using test cells, the use of such cells for the study of waste characteristics in the laboratory is limited (Landva and Clark, 1990; Chen and Chynoweth, 1994; Beaven and Powrie, 1995; Beaven and Powrie, 1999; Kavazanjian, 1999; El-Fadel, et. al., 1999; Beaven, 2000; Oni, 2000). The size of the test cell used by the researchers varied according to the nature of the investigation carried out and the physical state of the waste. For example, Oni (2000) examined the hydrogeological characteristics of waste on a small-scale cell with a diameter of 240mm and a height of 230mm. The waste having a nominal size of 20 x 5mm was prepared which was less than $^1/_5$ of the diameter of the cell. Beaven (2000) experimented with a purpose built test cell of 2m diameter and 3m deep which could accommodate MSW taken in its in-situ state in order to minimise the experimental scale effects. Landva and Clark (1990) carried out laboratory investigations on geotechnical characteristics of landfill waste using a number of different types of test cells depending on the waste properties that were measured. The test cell, 250mm in diameter was used to determine the specific gravity, water-holding capacity, compressibility, permeability and degree of saturation of MSW. A 470mm diameter consolidometer and permeameter having 500-1000kN load capacity, a 434 x 287mm sample capacity direct shear and 240 x 124mm ring shear apparatus were also developed for these tests. Chen and Chynoweth (1995) used three test columns connected in parallel for determining the hydraulic conductivity of a simulated waste. Each plexiglass test cell (6mm wall thickness) was 1220mm long with an outer diameter of 381mm. Kavazanjian et al (1999) carried out large-diameter static and cyclic laboratory tests on reconstituted samples (having maximum particle diameter 100mm) of municipal waste using a purpose built oedometer ring 460mm in diameter and 460mm tall. The size of the ring for conducting direct and direct simple shear tests was 460mm in diameter.

El-Fadel et al (1999) used four steel cylindrical columns having dimensions 600mm in diameter and 1000mm height to study waste settlement characteristics with a provision for static load application on the waste. The waste composition varied in each of the test columns and biodegradation along with the subsequent settlement was observed. Gabr et al (1995) performed experiments on various geotechnical properties of aged municipal solid waste. For one dimensional consolidation test a 63mm diameter, 22mm thick circular consolidation rings was used. The particle size in the waste specimen was restricted to 6.3mm ($^1/_{10}$ of the diameter). Permeability and consolidated undrained triaxial compression tests were performed in 70.6mm diameter and 152mm long split mould type test cells. Particle sizes greater than $^1/_6$ of the diameter were not included in the waste specimen. A further set of consolidation tests with pore water measurements were carried out in 76mm diameter and 305mm long, transparent lucite cylinders in which waste particles up to 12.5mm in diameter were included. Direct shear testing of the waste specimen was conducted in a 63.5mm diameter, 23mm thick purpose built direct shear box. Jessberger and Kockel (1991) for the determination of waste shear strength parameter used large-scale triaxial compression cell with a height of 600mm and a sample diameter of 300mm. The compression tests on the municipal solid waste were carried out in a large-scale uniaxial compression test having a diameter of 1000mm in which the initial (pre-consolidation) height of the sample was 200mm.

On reviewing the test cell dimensions used in various studies for determining hydrological and geotechnical properties of waste, it is evident that the sizes of the test cells were selected in order to accommodate representative samples of the waste. However, it is noted that there was a practice to exclude large waste particles, in order to establish a similitude with the dimensions of the test cell. Hence in the investigations with waste, it is an acceptable practice to exercise a trade off between particle size and the test cell dimensions provided that the two parameters satisfy the pre-established criteria which are discussed in the following text.

3.4.1. Development of Test Cell

A test cell capable of holding a representative volume of waste was developed during the course of this research project. The principle criterion governing cell design was volume. It should be large enough to accommodate a representative waste but be of manageable size in order that it can be operated conveniently in a laboratory environment. It must be robust to withstand comparatively high radial stresses developed due to the applied axial loading necessary to simulate landfill overburden pressures. A transparent test cell is considered useful for visual observation of the sample.

3.4.2. Selection of test cell material

The volume of the test cell, apart from the limitations mentioned above, was dependent upon the material used for fabrication and its mechanical properties. The test cell must operate safely and be able to accommodate the axial loads and confining pressures in waste sample. The material conventionally used in tri-axial test cell apparatus and consolidation cells is Perspex. This material has good mechanical properties and is straight forward to work with. The transparency of the cell body is also a useful feature. See Appendix A for the mechanical properties of the Perspex material.

The large test cell fabricated for this project was designed to operate safely at maximum allowable axial compressive stress of 160kPa which required a cell wall thickness of 12mm (Figure 3.3). Details of the cell design and calculations are presented in Appendix A.

3.4.3. Diameter of the test cell

As discussed earlier, the volume of the cell was supposed to be adequate to accommodate a representative volume of the waste samples. A reduction in waste particle size was sometimes necessary to provide dimensional similitude between the linear dimensions of waste particles and the test cell.

In previous studies of this nature one of the considerations regarding compression cell diameter selection was the assumption that if the diameter is less than 10-20 times the particle size of the material being compressed then the particles may combine to form an arching structures that could resist compression (Beaven, 2000). This is more likely to occur in the case of soils where the particles are discrete and incompressible. However, in case of waste which is highly deformable, it may not be the case.

In the case of large test cell, the loading frame from which the compressive loads were applied was fabricated prior to the design of the test cell. A factor in the selection of the diameter for the compression cell was the lateral clearance available in the loading frame (Figure 3.4.) which was less than 600mm. This restriction and other practical aspects of the design i.e. free space and flange projections of the cell, the inner diameter of the large test cell was 500mm (Figure 3.3.).

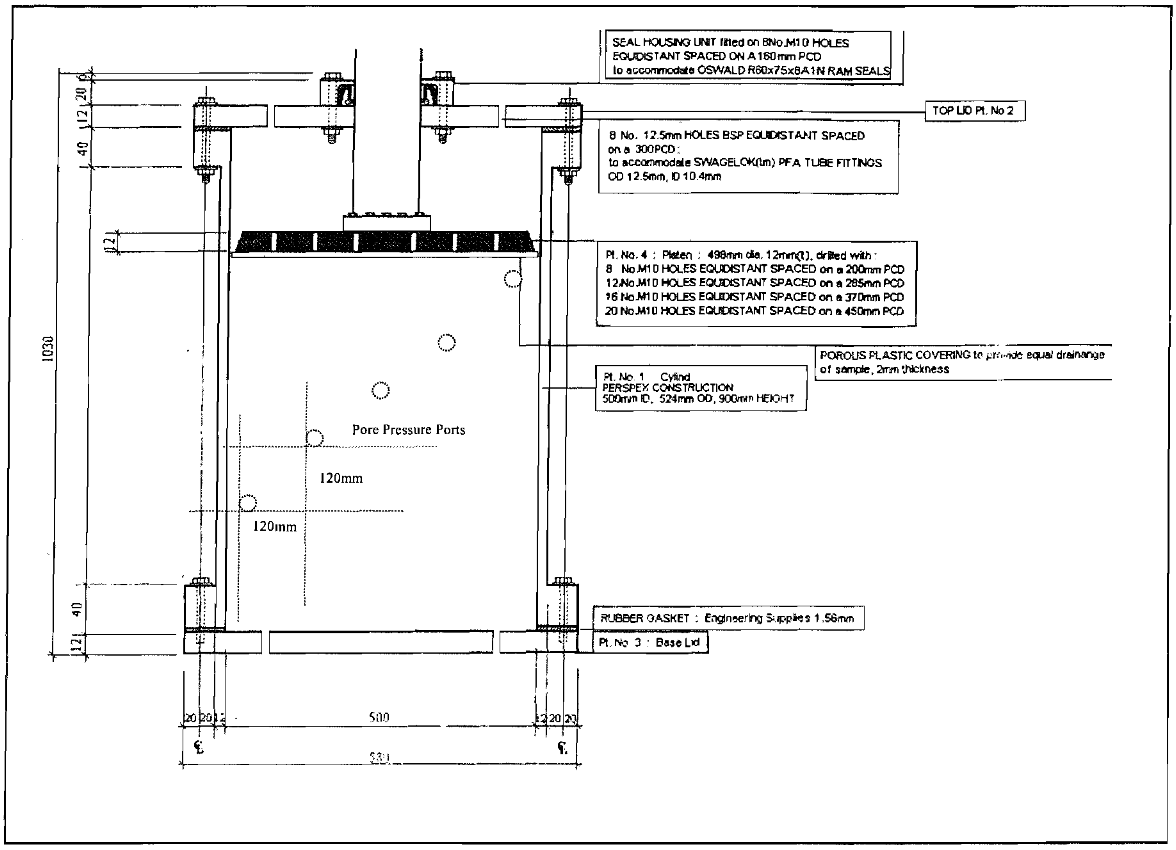


Figure 3.3. Design drawing of the Perspex test cell with loading platen assembly

3.4.4. Test cell height:

The vertical height (depth) of the compression cell was dependent on a number of factors:

a) the diameter of the cell

b) adequate height to measure hydraulic conductivity across specimen length

c) high compressible nature of the waste material

d) side wall friction effects

e) the available clearance within the consolidation machine's loading frame

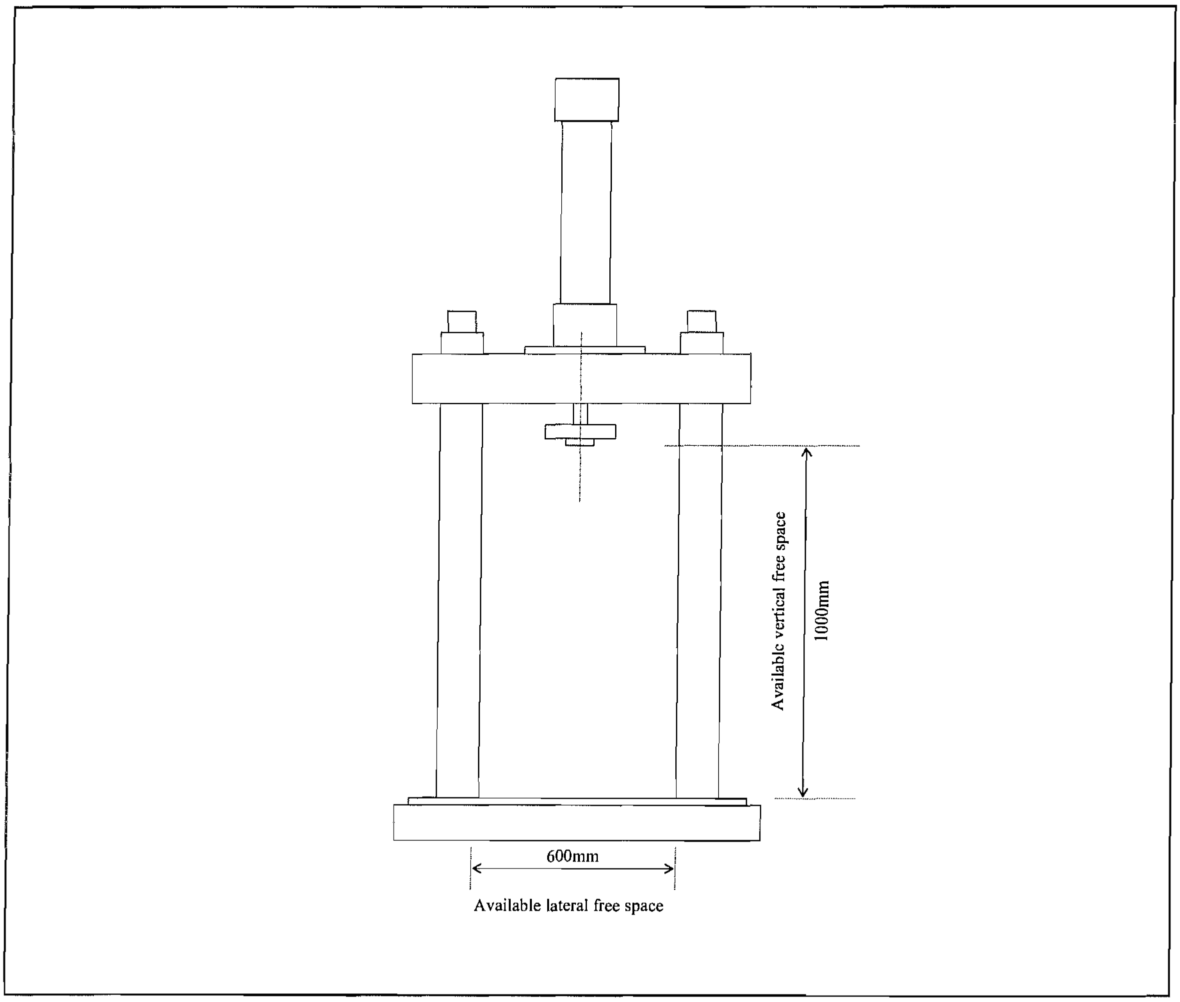


Figure 3.4. Elevation of the loading frame showing clear spacing available for accommodating the test cell

For a typical triaxial compression cell apparatus, typical diameter to height ratio is 1:2. Hence for the large test cell design with an internal diameter of 500mm diameter, a cell height of 1000mm would be required.

One of the primary functions of the large test cell was as a permeameter. Ideally, during downward flow hydraulic gradient should be determined between two points some reasonable distance apart, adequate enough to measure the head loss across waste specimen. This was much dependent upon the flow rates existing in the waste which could be fairly low resulting in a low head losses and hydraulic gradient.

Other criteria relating the height of the permeameter to the particle size have been reported by Daniel (1994) citing ASTM D2434 and D5084 which suggests that the cell height should be at least 6 times greater than the largest particle in the specimen. With highly compressible waste, individual waste particles tend to realign themselves perpendicular to the compressive load, termed as layering, i.e. in the lateral plane leaving the shortest dimension in the vertical plane (Beaven, 2000).

The highly compressible nature of waste may also require the cell height to be greater during sample preparation than is required during the test. Initial compression will cause such waste to consolidate, leaving the specimen height much less than the cell height i.e. the useful height may be up to $^1/_4$ of the original cell height (Beaven, 2000). Jessberger and Kockel (1991) suggested that to minimise the effects of side wall friction in the consolidation cell the ratio of sample height to its diameter should be around 1:5. Due to the constraints of the loading frame dimensions increase in diameter or the reduction of height of the test cell was not a feasible proposition to accommodate this recommendation.

The space available within the loading frame was therefore a decisive factor requiring the cell dimensions to be restricted to an internal diameter of 500mm, and 900mm vertical height. This gave an overall dimensional aspect ratio of 1:1.8 for the large test cell.

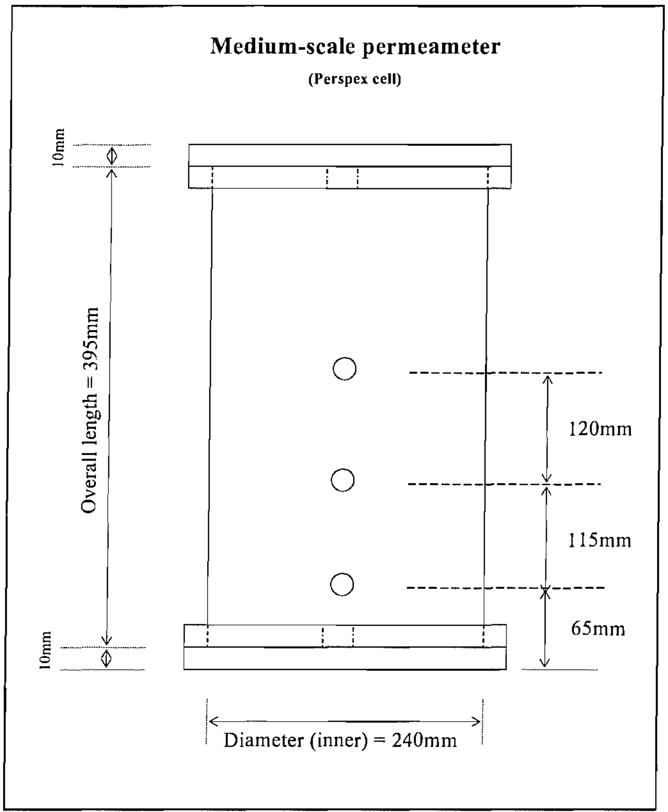
Tapping ports in the walls of the test cell to enable piezometric measurements were vertically spaced down the cell at 120mm intervals in a spiral configuration shown in the Figure 3.3.

3.4.5. Medium and small-scale test cells

In addition, two further (medium and small-scale) test cells were manufactured to assess the impact of particle scale effect on the key waste properties. In this study, in the case of medium and small-scale test cells there was no provision of external load application on the waste specimens. Waste density was controlled where appropriate, by consolidating the waste to desired volume by simple manual compaction. These test cells were designed to function solely as permeameters.

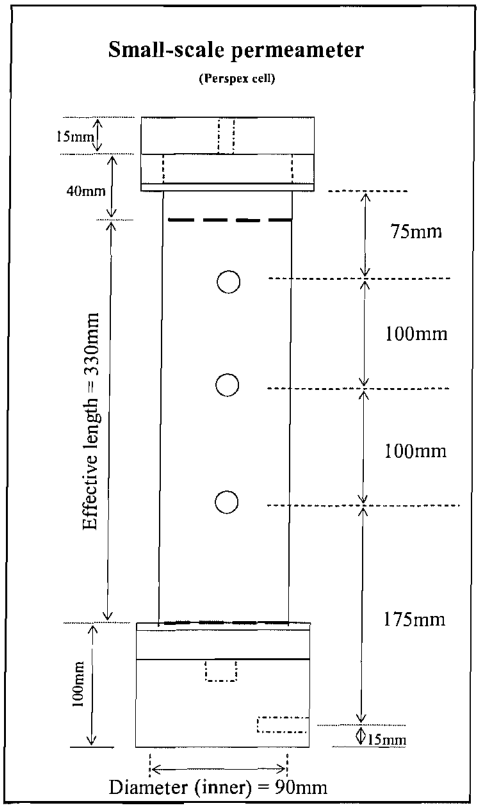
3.4.6. Dimensions of medium and small-scale permeameters

For the medium and small-scale testing, there was no constant compressive loading applied on the specimen during the test. Rather the density was controlled by consolidating the waste to a desired volume by simple manual compaction. The dimensions of small and medium test cells were selected arbitrarily (depending upon the available sizes) and the maximum particle size in the waste specimen was set accordingly to the criteria discussed earlier. For the medium and small scale permeameter the available / selected inner diameters were 240mm and 90mm, accommodating effective sample lengths of 395 and 330mm respectively. Tapping ports and other features of the test cells are shown in Figure 3.5 & 3.6.



Not to scale

Figure 3.5. Medium-scale permeameter



Not To Scale

Figure 3.6. Small-scale permeameter

3.5. Particle size and distribution

In case of soils, the particle size is the governing criterion in deciding the size of the test cell or laboratory permeameter (Lambe, 1951 and Head, 1994). For the model waste the particle size needed was to be selected accordingly in order to establish dimensional similitude. Lambe (1951) suggested that the ratio of the diameter of the confining cell or container to the diameter of largest particle should be approximately 15-20 times greater so as to decrease the chances of large void formations at the periphery of the permeameter. Head (1994) suggested (for triaxial cell specimens) that the largest particle size should not exceed one-fifth of the specimen diameter. After considering additional factors other than the dimensional similitude, such as the stiffness and compressibility of the waste particles, the largest particle size selected was 100mm for the large-scale test cell and 20mm for medium and small-scale test cells. Therefore, the corresponding aspect ratios (particle size to diameter of the test cell) for the three permeameters were:

- Large-scale = 0.2
- Medium-scale = 0.083
- Small-scale = 0.22

The particle size distribution (PSD) curves for the model waste prepared for the large, medium and small scale test cells are given in the Figures 3.7 and 3.8. These curves are projected by rough estimations obtained by the particle size information available for the preparation of the individual waste components and their given composition.

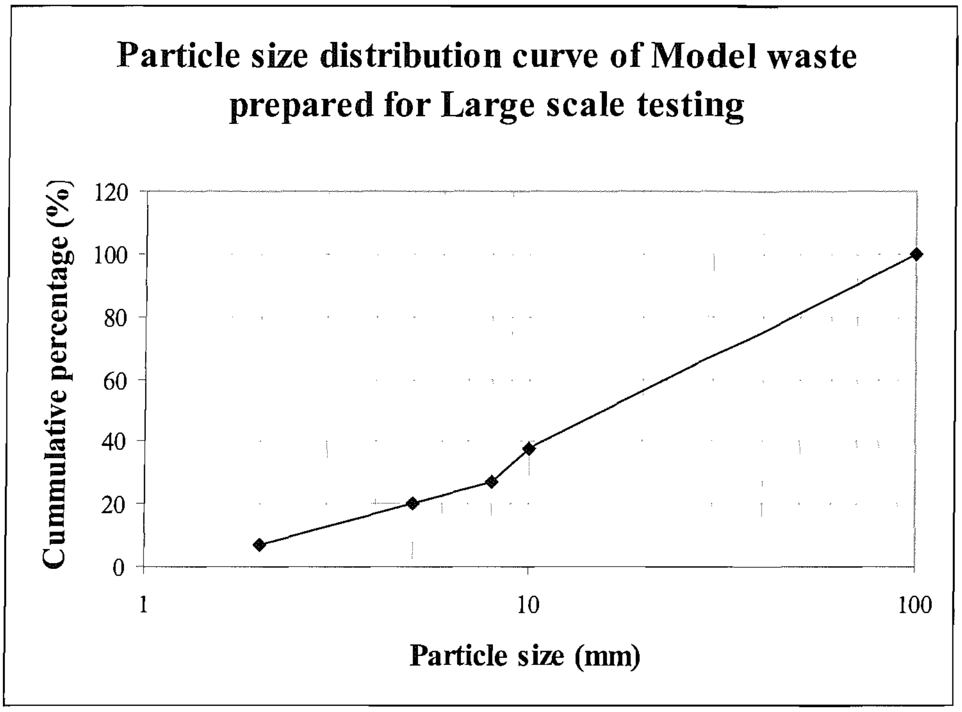


Figure 3.7. PSD curve of model waste for large scale test

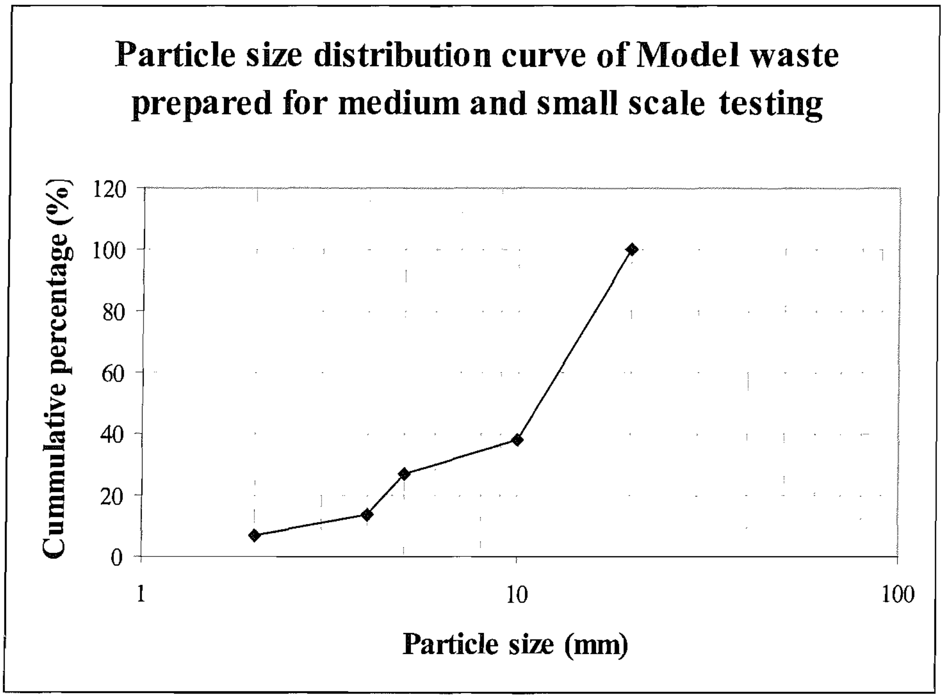


Figure 3.8. PSD curve of model waste for medium and small scale test

Table 3.3 shows the upper limits of particle sizes of the model waste components used in three permeameter tests.

Individual Waste Component	Max. Reduced Particle size (approximate)	Experiments
Tissue	~<100mm ~<20mm ~<20mm	Hydraulic conductivity (large scale) Hyd. cond. (med & small scale) Suction characteristics
Wood Shaving	<10mm	All experiments
Paper Sacks	~<100mm ~<20mm ~<20mm	Hydraulic conductivity (large scale) Hyd. cond. (med & small scale) Suction characteristics
Polyethylene Sac	~<100mm ~<20mm ~<20mm	Hydraulic conductivity (large scale) Hyd. cond. (med & small scale) Suction characteristics
Polyethylene Bottle	~<5mm	All experiments
PVC Sheeting	~<100mm ~<20mm ~<20mm	Hydraulic conductivity (large scale) Hyd. cond. (med & small scale) Suction characteristics
Rubber Gloves (neoprene waste cuttings)	~<100mm ~<20mm ~<20mm	Hydraulic conductivity (large scale) Hyd. cond. (med & small scale) Suction characteristics
Ferrous Metal Shaving	~10-15mm	All experiments
Electric Cable	~<100mm ~<20mm ~<20mm	Hydraulic conductivity (large scale) Hyd. cond. (med & small scale) Suction characteristics
Absorbent Granule	~2-4mm	All experiments
Glass Bead	~4-8mm	All experiments

Table 3.3. Model waste components particle size used in experiments

3.6. Simulation of overburden pressure in test cell:

In the large test cell, vertical compression of waste specimen was required to simulate over burden pressures experienced at various depths in landfill. The maximum allowable vertical stress in the case of large-scale test cell was not to exceed 160kPa. Assuming the average unit weight of waste in landfill is 10kN/m^3 (Beaven, 2000), the simulated depth of waste corresponding to the applied vertical stress would therefore be equivalent to 16m.

3.7. Effective stress application to waste

The cell was designed to fit within a constant load consolidation machine (Figure 3.4) having a maximum load rating of 225kN. A pressure transducer located within the hydraulic cylinder was calibrated to indicate the stress applied to the waste mass by the platen. Since the platen was fully perforated allowing the cell pressure to act uniformly across each face of the platen, the stress value indicated by the pressure transducer was also the effective stress applied to the waste mass.

3.8. Calibration of load cell and pressure transducer

The loading mechanism was originally designed to estimate vertical compression load directly by taking measurements from the load cell placed in between the ram and the load platen assembly. However this arrangement was found undesirable as the load cell was unable to withstand the corrosive fluid environment (leachate) present in the test cell. An alternative arrangement was adopted using a pressure transducer located within the hydraulic cylinder calibrated to measure hydraulic pressure. However, the load cell was calibrated by dead load calibration machine which was then used for the calibration of the pressure transducer. Hence the overall calibration process was a two-stepped indirect method. The two calibrations curves are shown in the Figures 3.9 and 3.10.

3.9. Back pressure mechanism – pore pressure simulation

The height of water table above the waste mass was simulated by pore water pressures (u_w). A standpipe arrangement representing the static pressure head for various depths of water was found simple and ideal for use. However, simulating large pore pressures as encountered in landfill waste required very high water columns or standpipes that were very difficult to maintain and link to the test cell. For the measurement of high pore water pressures, pressure transducers were used. An arrangement was especially designed and fabricated to provide constant 'back pressure' corresponding to various piezometric heads, however it was limited to the maximum confining pressures (160kPa). The application of back pressure was limited to a value of 120kPa, considering safe operational limits selected for the test cell.

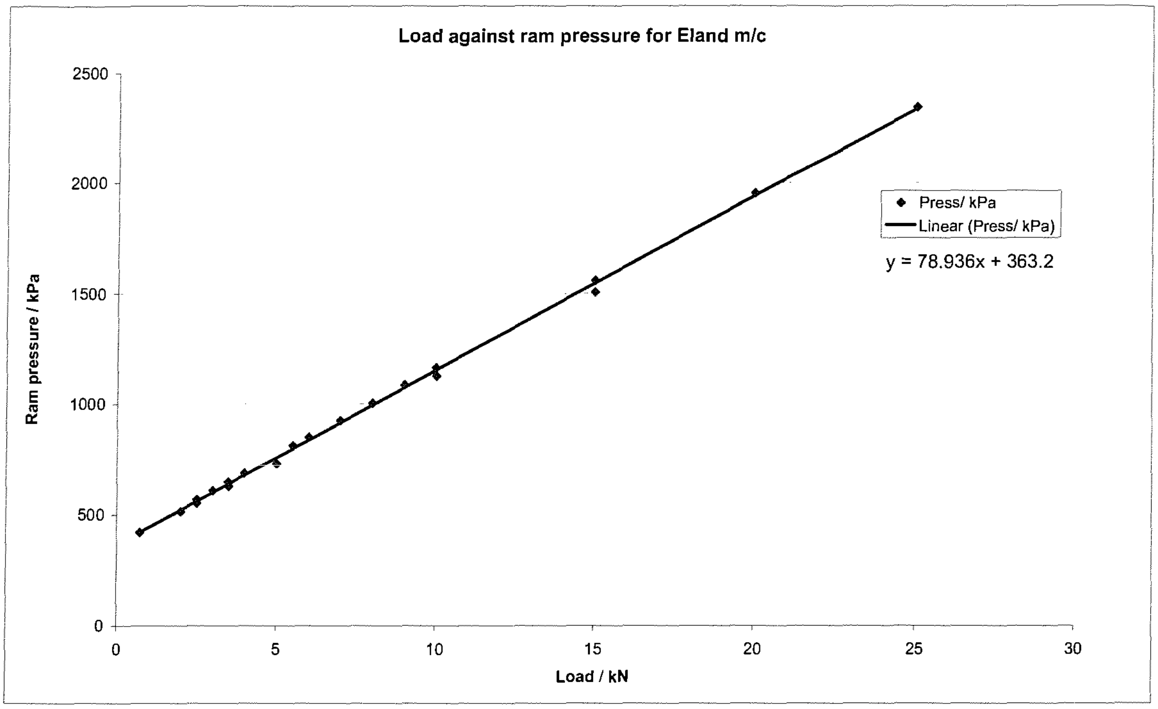


Figure 3.9. Load cell calibration followed by the ram pressure calibration by means of dead load calibration machine

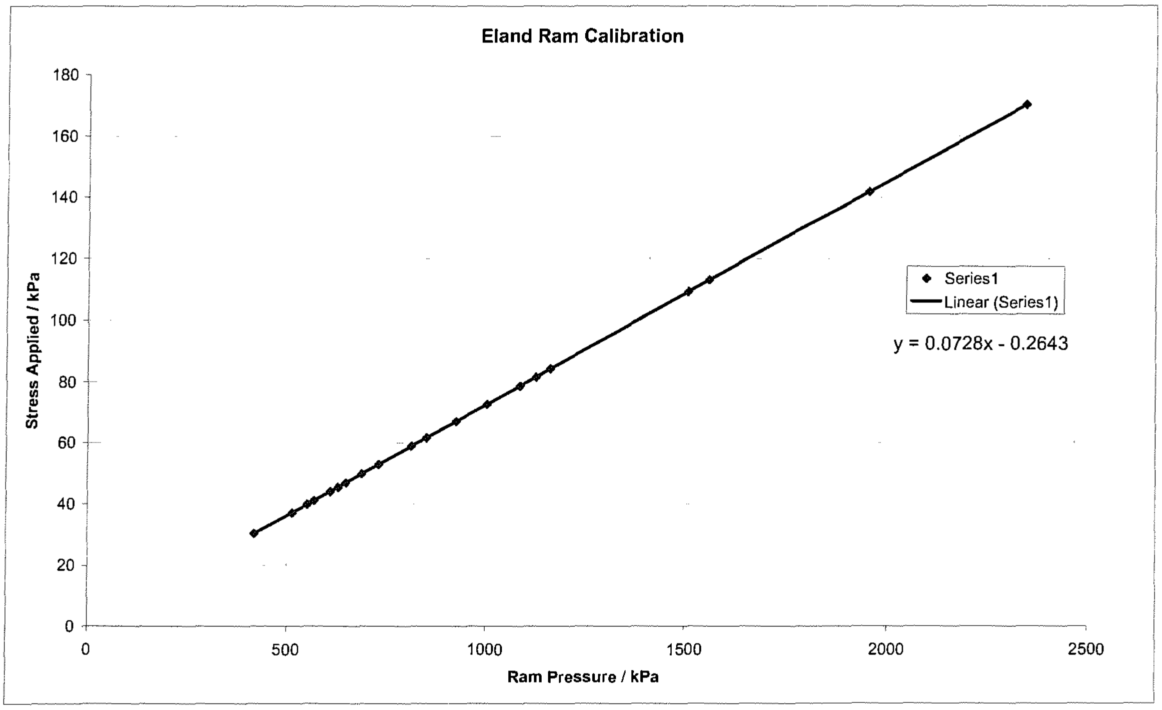


Figure 3.10. Ram pressure equivalence to the applied stress at the load platen

A number of systems were experimented with to provide a constant back pressure (pore pressure) within the waste mass. The most basic system involved constant header tank. Although accurate, it was limited in the pore pressure that it could provide due to height constraints. The maximum height achieved using a constant header tank was 2m which was equivalent to a pore water pressure of 19.6kPa.

A peristaltic pump arrangement was also tested to simulate any required pore pressures up to 120kPa. Though the system was successful in establishing and maintaining the pore pressures but while taking the hydraulic conductivity measurements due to its pulsating action a convective flow was observed in the entry zone of the test cell. This was indicated by the negative hydraulic gradients experienced in that particular zone of the waste sample.

Another arrangement comprising of two air-water interfaces (cells) that were linked together to operate sequentially to maintain a desired pressure in the test cell. The interfaces were operated by synchronised operation of 6 solenoid valves which were automated to function in a sequence to generate the cell pressures whilst maintaining flow through the test cell. The drawback of the system was that though the flow control was satisfactory at low pressures but at high pressures a significant drop in pressure was experienced before the system could regain the initial pressure while maintaining a constant flow within the cell. Hence, the mechanism failed to maintain steady flow with constant pore pressure. The mechanism was not used.

In both of the above cases some problems were encountered in maintaining the desired pressure and a steady flow condition simultaneously. Therefore, the study was limited to the use of stand pipe piezometers and the pore pressure being supplied by constant header tank. The entire arrangement could, therefore, only provide a maximum of 2 meters head.

Chapter 4

Hydraulic Conductivity Characteristics of Model Waste

4.1. Introduction

Determination of the hydraulic conductivity of waste is important for the modelling of certain aspects of its operational and post-closure behaviour. The movement of moisture or water inside has been shown to be important for optimising degradation processes (Blight, 1991), together with the transportation of leachates from the landfill to be either recycled or treated accordingly. Unrestricted fluid movement, i.e. percolation or infiltration is also necessary for nutrient transport to micro-organisms which are present in the waste and which are responsible for the biodegradation of waste. Hydraulic conductivity is influenced to a large extent by a number of waste characteristics and the prevailing hydrological conditions. Important landfill waste parameters from a geotechnical viewpoint are; waste hydraulic conductivity / density and the variation in hydraulic conductivity with density and overburden pressure (effective stress). Establishing these parameters for waste through application of soil mechanics principles will potentially increase our ability to predict the long term behaviour of landfill.

4.2. Application of constant head permeability test to model waste

From the review of literature (section 2.4.6), the hydraulic conductivity of landfill waste typically lies in the range of K=10^{-3} to 10^{-7} m/s. Therefore the constant head permeability test was considered to be a suitable method for determining the hydraulic conductivity of waste. It should be noted however, that the size of the permeameter should be scaled accordingly to accommodate the wide range of particle sizes typically encountered in landfill waste.

A number of difficulties or errors may be encountered during the measurement of hydraulic conductivity of waste. Such errors may increase as the applied stress is increased leading to denser waste samples and hence lower flow rates. A non-uniform compaction of the particulate material, may also affect the measured hydraulic gradient, particularly in case of waste which has a high degree of heterogeneity. Other errors may be caused by the 'piping' or the formation of preferential flow paths through the waste mass. In addition, a piezometer used to determine the pressure head at a certain point in the waste mass can easily be blocked by the waste material adjacent to the piezometric port.

4.2.1. Preparation of large-scale permeameter and hydraulic conductivity tests

Figure 4.1 and 4.2 details the general layout of the large scale cell which enabled the cell to function as a constant head permeameter. The model waste mix (section 3.3) was prepared having a maximum particle size of 100mm (an aspect ratio of 0.2). A high permeability gravel layer, approximately 150mm deep, was placed at the base of the cell on top of which was placed a coarse mesh geotextile separation layer. 50 kg (dry weight) of model waste was then carefully introduced into the permeameter in layers to ensure that only limited compaction of the waste could occur and that the as-placed waste density could be substantially at its lowest achievable value. A coarse mesh geotextile separation layer was placed on top of the waste and a 100mm gravel layer carefully placed over the geotextile layer. The permeameter was sealed (with the consolidation machine load platen positioned above the waste) and water was introduced from the bottom of the cell. The waste mass was allowed to saturate over a 24 hour period to ensure uniform wetting and to minimise air entrapment.

Ports located in the cell wall were connected to standpipes to determine head loss and hence hydraulic gradient across a measured depth of waste when flow was induced through the waste mass. A constant flow header tank arrangement that was fixed at a height of 2.0m from the permeameter base (datum level) supplied water to the top of the cell, providing a constant downward flow through the waste mass. An outlet at the base of the permeameter was connected to a hose which incorporated an in-line flow valve and was used to adjust the flow rate through the waste mass.

The initial hydraulic conductivity test was conducted with the waste mass in its less consolidated state. Prior to the start of each test the height of the waste within the cell was carefully measured at three locations and noted. The waste dry density was then determined from the known dry mass of waste used (50 kg) and the volume that the waste occupied within the cell. For each measured waste density, three volumetric flow rates (Q; m^3/s) were established by adjusting the in-line valve built into the outflow pipe, and the head loss across each tapings points were used to determine the hydraulic gradient (i). For the next dry density increment, the platen was used to compress the waste, followed by the establishment of three separate flow rates through the waste mass. Waste dry densities ranging from 400kg/m^3 – 750kg/m^3 were established in the large scale permeameter. Since the cross sectional area (A; m^2) of the permeameter was known, the hydraulic conductivity of the waste at a particular dry density could be calculated.

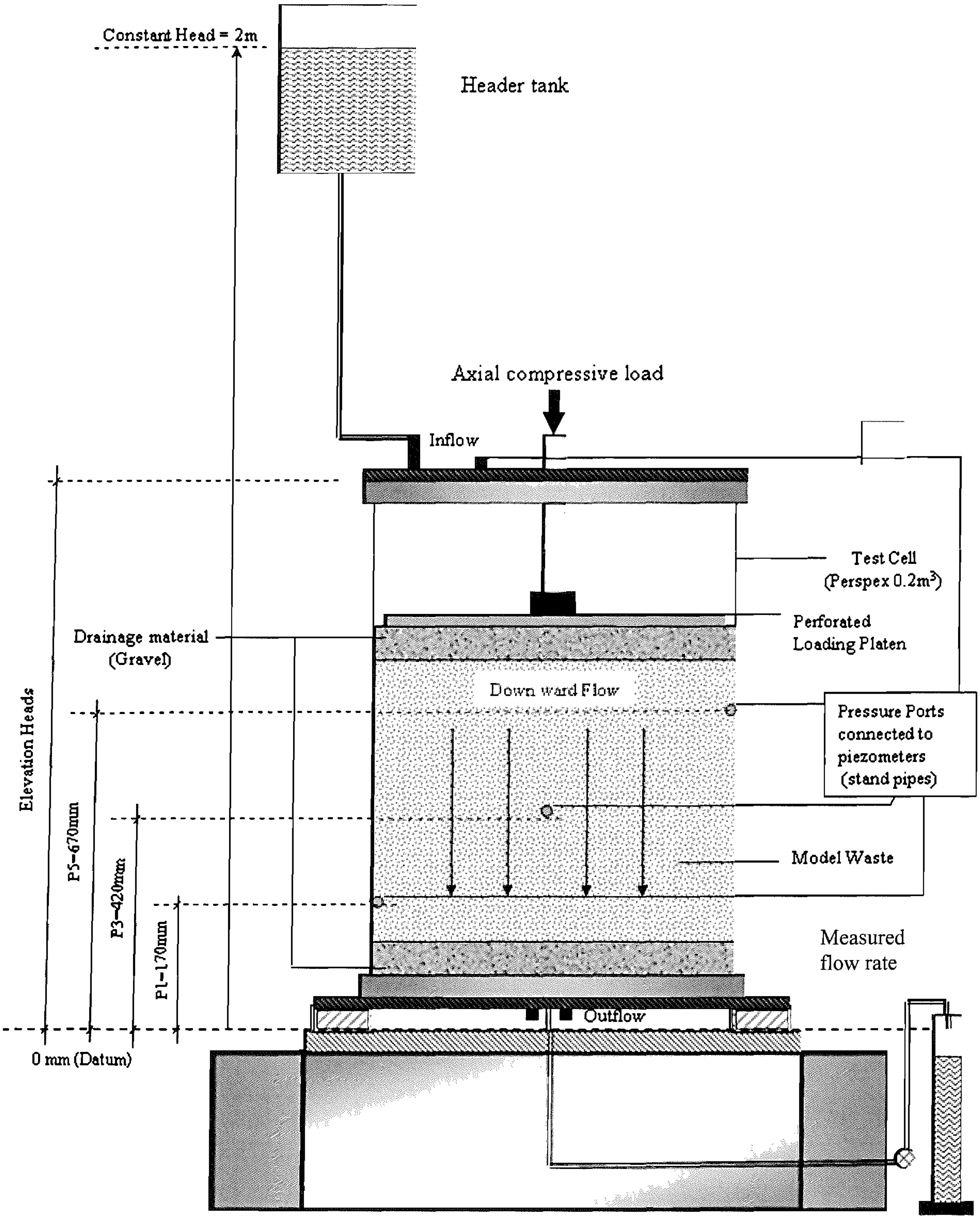


Figure 4.1. Constant head permeability test using large-scale permeameter

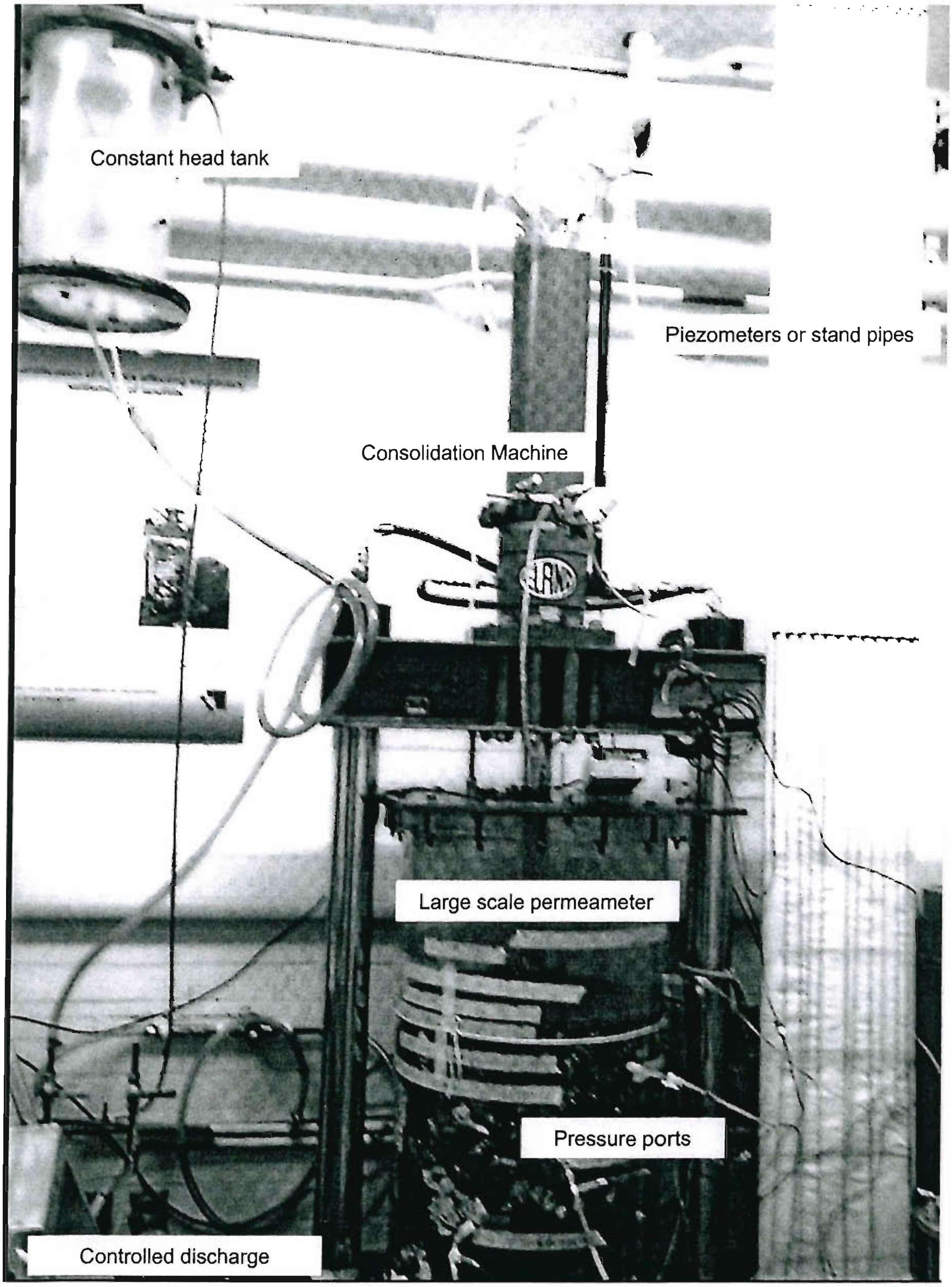


Figure 4.2. Large-scale permeameter setup – constant head permeability test

4.2.2. Medium-scale permeameter

A 240mm diameter × 395mm tall (Figure 3.5) constant head permeameter was used to assess further, the effects of particle size in relation to permeameter size on the hydraulic conductivity of model waste. Three tapping ports at 120mm centres were located down the depth of the permeameter and were connected to a standpipe arrangement to determine hydraulic gradient once downward flow had been induced through the waste mass. A constant head weir was used to maintain a constant head which was set at 1.6m above the base of the permeameter, and the flow rate was controlled by an in-line valve located in the tube connected to the bottom of the permeameter. The arrangement for constant head permeability test using medium-scale permeameter for model waste is shown in Figure 4.3 with its illustration in Figure 4.4.

The maximum waste particle size used was 20mm. The ratio of maximum particle size to permeameter diameter (aspect ratio) was 0.083.

Model waste was placed in the permeameter initially with the least attainable density (360kg/m^3). After successive measurements of hydraulic gradients for various flow rates, the dry density of waste was increased by adding appropriate amount of dry waste. The permeameter was emptied and refilled each time prior to starting with a new dry density setting. The permeameter was filled in layers by manual compaction using a brass rammer. It was tried to make sure that the waste was uniformly compacted and the density of waste stays uniform through out the length (depth) of waste sample in the permeameter. The highest dry density used in the medium-scale permeameter was 480kg/m^3.

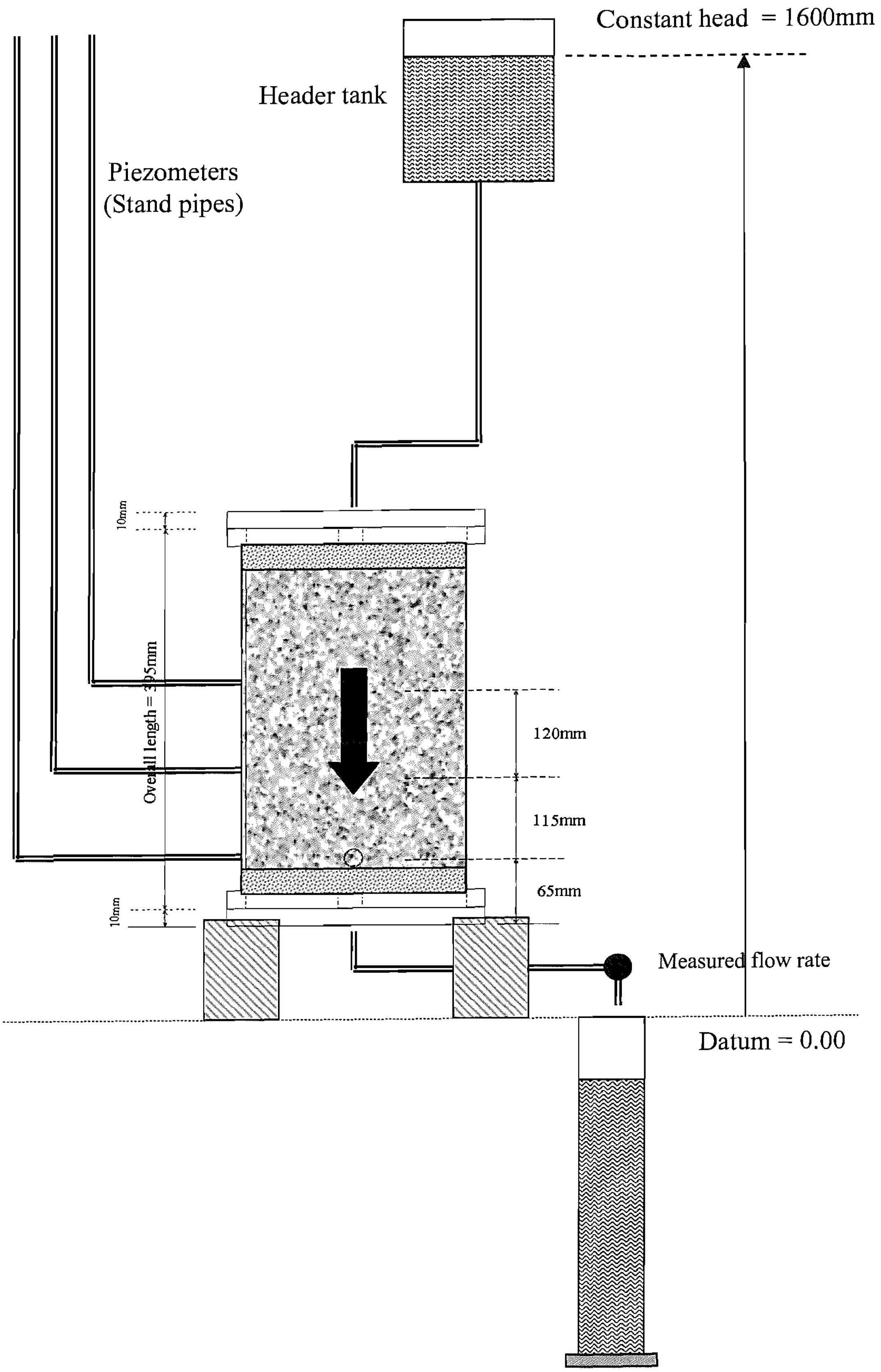


Figure 4.3. Constant head permeability test using medium-scale permeameter

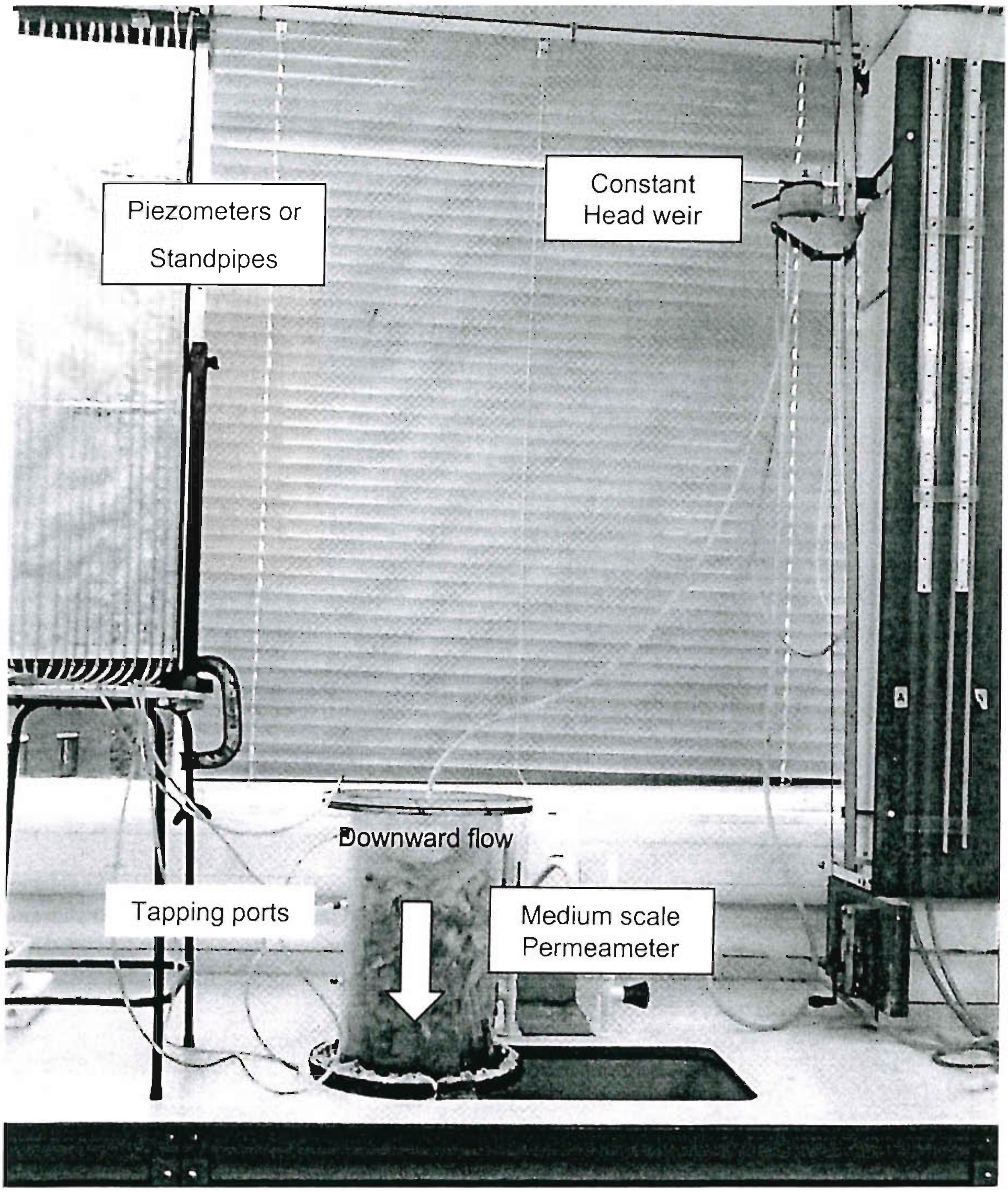


Figure 4.4. Medium-scale permeameter setup – constant head permeability test

4.2.3. Small-scale permeameter

The small scale permeameter (Figure 3.6) was substantially similar in operation and setup to the medium-scale permeameter arrangement described earlier in section 4.2.2. The maximum particle size was 20mm, giving an aspect ratio of particle size to permeameter diameter of 0.22. A constant head weir of 1.6m height above the base of the permeameter (datum level) provided the constant head downward flow through the waste mass. The flow rate was controlled by an in-line flow valve located in the tube exiting the permeameter at its bottom. Figure 4.5 shows the arrangement of the test and its illustration is given in Figure 4.6.

To achieve the required dry densities of model waste in the permeameter the same procedure was adopted as in earlier tests with the medium-scale permeameter. The minimum dry density in small-scale permeameter test was 275kg/m^3 which was increased to 350kg/m^3 and then finally to 425kg/m^3.

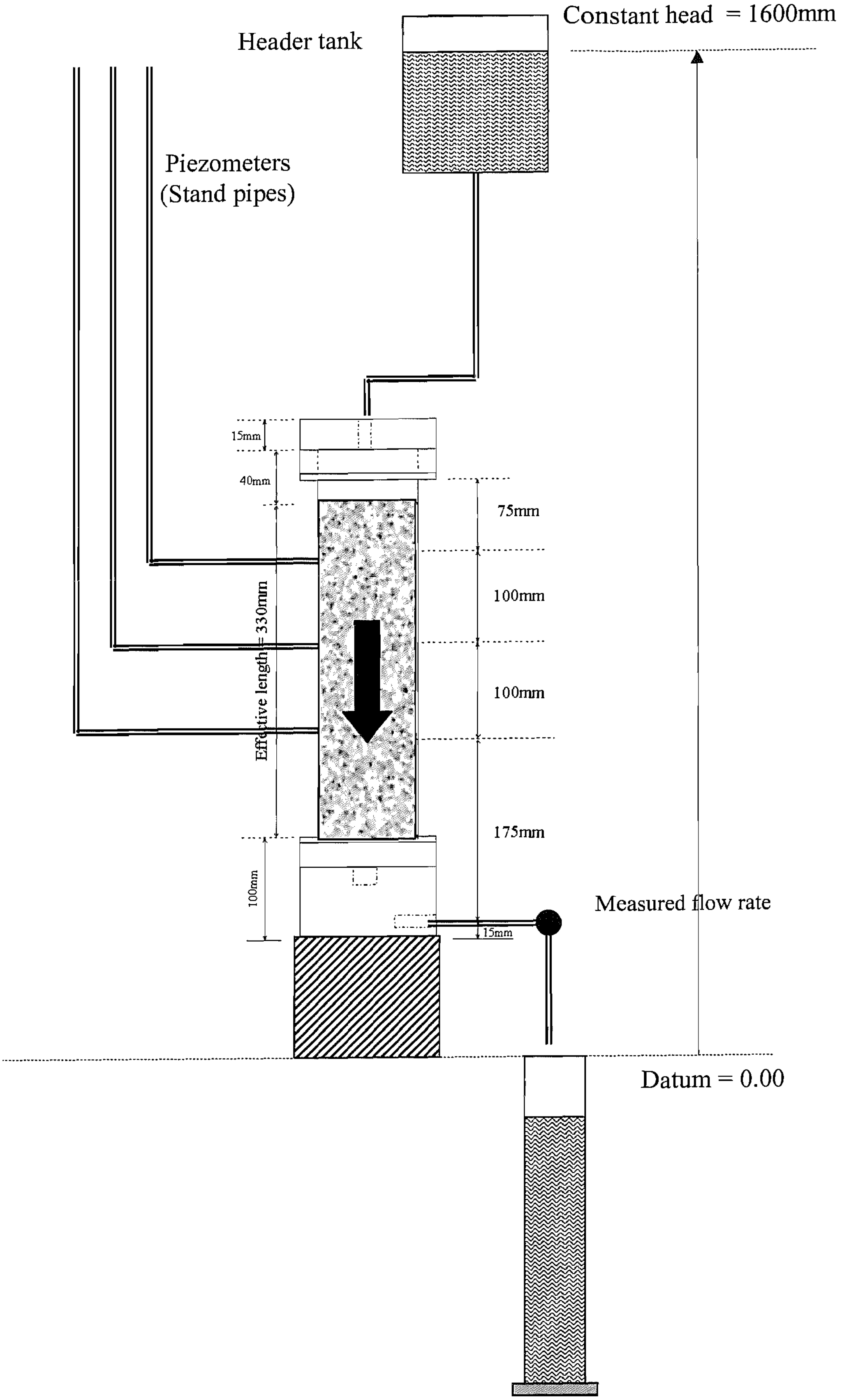


Figure 4.5. Constant head permeability test using small-scale permeameter

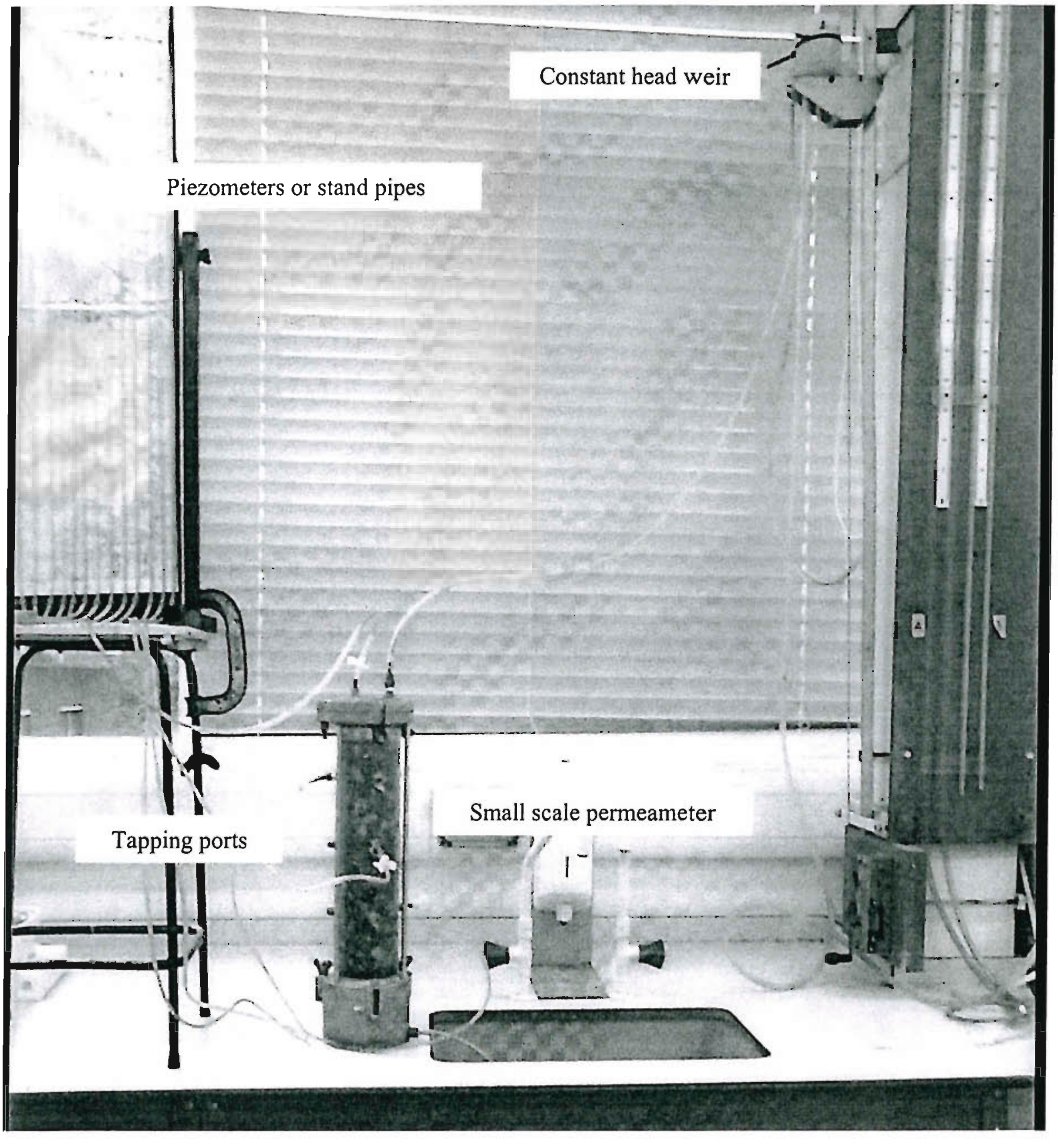


Figure 4.6. Small-scale permeameter setup – constant head permeability test

4.3. Dry density and hydraulic conductivity relationship

The constant head permeability tests carried out for determining the hydraulic conductivity of model waste on three different scales showed that in general the behaviour of model waste is in accordance to Darcy's law. The results for the individual scales of the tests are summarised in the subsequent sections.

It was observed that the model waste when fully saturated has hydraulic conductivity characteristics similar to soil. Particularly, a decrease in hydraulic conductivity is observed with the increase in dry density of the model waste which was common in all the three scales of the test. For each dry density, a minimum of 3 flow rates were established. Each time the established flow was laminar maintaining a steady state for a substantial period of time prior to reading. The hydraulic gradient was then measured for the established flow condition.

4.3.1. Large-scale permeability tests

The hydraulic gradient (i) and flow rate (Q) relationship obtained for varying dry density of model waste in large-scale permeameter is given in Table 4.1 and graphically in Figure 4.7. Hydraulic conductivity was determined in each segment of waste occurring between two successive ports (see tables in Appendix C). However, for the purpose of calculation of the hydraulic conductivity, the gradient between the initial and the final port covering the entire length of the sample was used, thus giving an overall estimation of hydraulic conductivity of the waste sample. The average hydraulic conductivity of the model waste for a given density was determined using three observations taken each time for three different flow rates. It was observed that hydraulic conductivity did not remain constant across the entire length / depth of the waste sample. This may be attributed to the heterogeneous nature of waste and partly to non-uniformity in the compaction of waste. It was indicated by the hydraulic conductivity values measured between any two successive piezometric ports which differ marginally showing that there was differential compactions i.e. waste was more compressed near the end of application of load i.e. in top zone of sample and the compactness decreased with depth of the sample. This differential compaction of waste may be attributed to friction offered by the walls of the test cell. To nullify the effect of differential compaction, the hydraulic conductivity was measured between the initial and final ports across the entire length of the sample. The (*K*) values on the graph (Figure 4.7) are the average values for the 3 sets of point obtained by establishing the flow rate and hydraulic gradient relationship. Each point on the curve for a particular dry density represents a hydraulic conductivity measured in the waste sample.

Large scale permeability test of Model waste
(aspect ratio = 0.2)

X-sectional Area of waste = 0.19635 m2

Dry density (kg/m3)	**Q** (m3/sec)	**Hyd Grad** (m/m)	**K** (m/sec)	**Avg K** (m/sec)
400	2.6300E-05	0.056	2.3930E-03	2.5238E-03
	2.3300E-05	0.048	2.4675E-03	
	1.8200E-05	0.038	2.4368E-03	
	1.4290E-05	0.026	2.7980E-03	
	0.0000E+00	0.000	0.0000E+00	
450	3.1300E-05	0.156	1.0202E-03	1.1002E-03
	2.2200E-05	0.106	1.0677E-03	
	1.4300E-05	0.060	1.2126E-03	
	0.0000E+00	0.000	0.0000E+00	
500	2.8600E-05	0.384	3.7894E-04	4.3103E-04
	2.3800E-05	0.308	4.7244E-04	
	1.5900E-05	0.190	4.2548E-04	
	1.2300E-05	0.148	4.2484E-04	
	8.5500E-06	0.096	4.5343E-04	
	0.0000E+00	0.000	0.0000E+00	
550	1.8900E-05	0.703	1.3675E-04	1.4055E-04
	1.3300E-05	0.481	1.4115E-04	
	8.6200E-06	0.305	1.4376E-04	
	0.0000E+00	0.000	0.0000E+00	
600	1.1500E-05	1.212	4.8300E-05	4.8708E-05
	8.2000E-06	0.896	4.6591E-05	
	4.3900E-06	0.436	5.1233E-05	
	0.0000E+00	0.000	0.0000E+00	
650	0.0000E+00	0.000	0.0000E+00	1.7988E-05
	1.1200E-06	0.288	1.9869E-05	
	5.1500E-06	1.560	1.6828E-05	
	6.2100E-06	1.832	1.7267E-05	
700	0.0000E+00	0.000	0.0000E+00	8.7195E-06
	3.0100E-06	1.520	1.0092E-05	
	5.4100E-06	3.060	8.9965E-06	
	7.4100E-06	4.820	7.8269E-06	
	7.6900E-06	4.920	7.9627E-06	
750	0.0000E+00	0.000	0.0000E+00	3.6540E-06
	9.0500E-07	1.300	3.5454E-06	
	1.4200E-06	1.920	3.7625E-06	

Dry Density (kg/m3)	Permeability (m/sec)	Summary of results
400	2.5238E-03	Dry density vs Hydraulic conductivity in Large-scale Permeameter
450	1.1002E-03	
500	4.3103E-04	
550	1.4055E-04	
650	1.7988E-05	
700	8.7195E-06	
750	3.6540E-06	

Table 4.1. Constant head permeability test results for model waste – large-scale permeameter

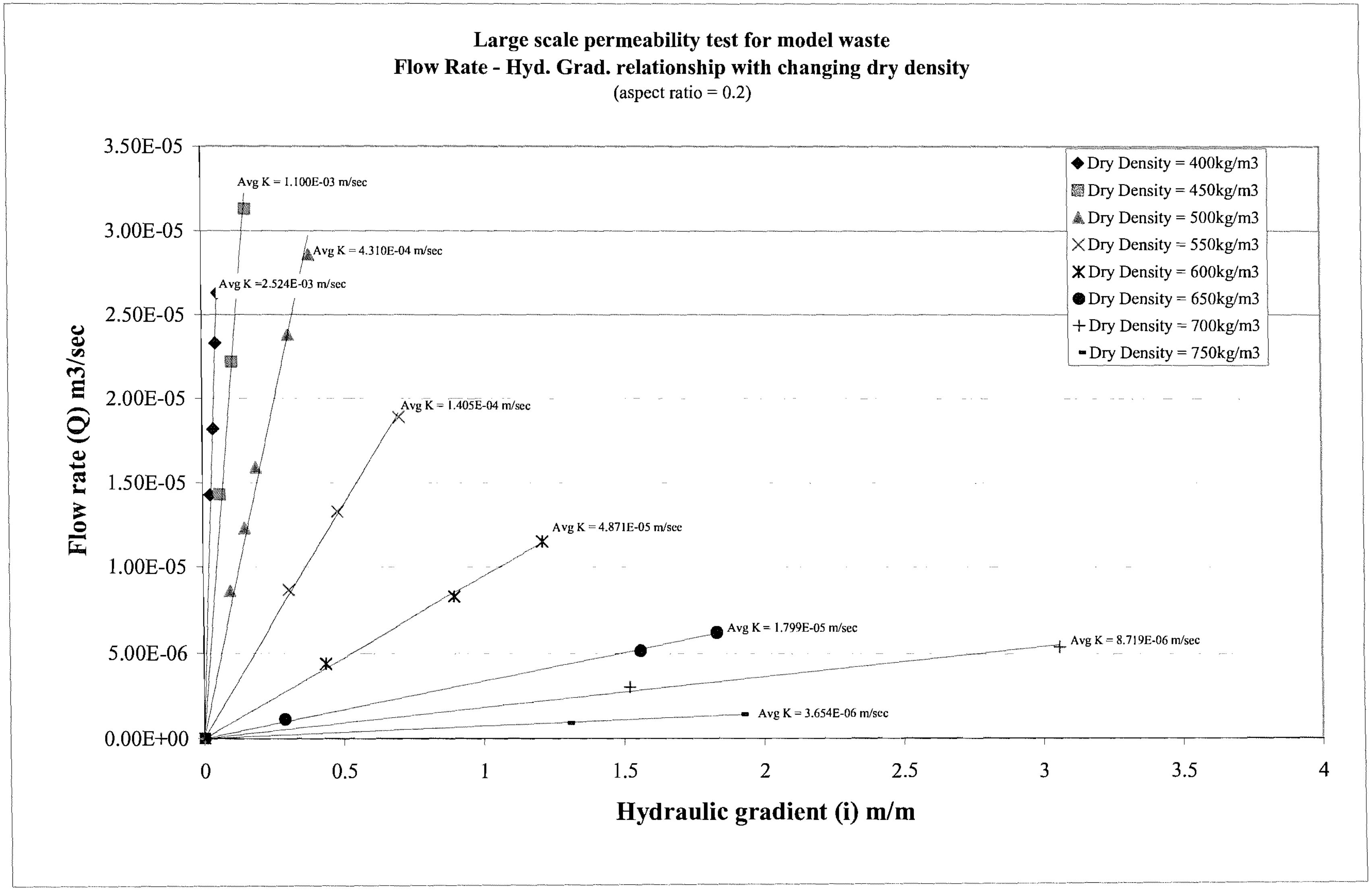


Figure 4.7. Darcy's relationship for model waste with changing dry density – large-scale permeameter test

The curves plotted on the graph shown in Figure 4.7 have been forced to pass through the origin. However, the data still supports Darcy's law and on allowing these curves to pass through the successive points the curve intercepts at more or less the origin.

4.3.2. Medium-scale permeability tests

The medium-scale and small scale permeameters were originally designed to investigate the effects of a change in particle diameter in relation to its experimental cell size (diameter), maintaining the dimensional similitude within acceptable limits. The effects of increase in dry density on the waste hydraulic conductivity characteristics were studied which could then be used for comparison of results.

As indicated in Table 4.2, the values of the hydraulic conductivity determined over the depth of the waste sample showed variations similar to the trend experienced in the large-scale permeameter tests. In the medium-scale test cell, where the dry density of the waste sample varied between 360-480 kg/m^3, the hydraulic conductivity was generally less in the upper half in comparison to its lower half showing a sign of differential compaction. This was experienced, as mentioned earlier in the case with the large-scale test cell, due to successive addition and compaction of waste mass from the top end. The general behaviour of the hydraulic conductivity of the model waste in the medium-scale permeameter remained similar to the large-scale permeameter, i.e. showing decrease in the hydraulic conductivity with the increase in the dry density.

The flow rate and hydraulic gradient relation curves (Figure 4.8) are almost linear and the hydraulic conductivity (flow rate and hydraulic gradient relationship) remains fairly constant for a particular dry density of the waste sample. Also the curves joining the data points intersect nearly at the origin.

Permeability test for Model waste in Medium scale permeameter - Constant Head

Observations & Calculations

For Low (dry) density of waste (360 kg/m3)

Length of Sample = 0.30 m
X Area of Sample = 0.0452 m^2

Test run No	Hp1 m	Hp2 m	Hp3 m	Hp4 m	P(H1-H2) m	P(H2-H3) m	P(H1-H3) m	Grad(12)	Grad(23)	Hgrad(13)	1 lit in min	sec	Q = (m^3/s)	k (1-2) (m/sec)	k (2-3) (m/sec)	k (1-3) (m/sec)	Q (m^3/s)	Hgrad(13)
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000
1	1.439	1.443	1.453	1.455	0.004	0.010	0.014	0.035	0.080	0.058	6	13	2.68E-06	1.7038E-03	7.4079E-04	1.0159E-03	2.68E-06	0.058
2	1.275	1.295	1.325	1.330	0.020	0.030	0.050	0.174	0.240	0.208	2	1	8.26E-06	1.0505E-03	7.6120E-04	8.7690E-04	8.26E-06	0.208
3	1.200	1.230	1.265	1.275	0.030	0.035	0.065	0.261	0.280	0.271	1	32	1.09E-05	9.2105E-04	8.5813E-04	8.8717E-04	1.09E-05	0.271
																	Avg k =	9.27E-04

m/sec

For Med-Low (dry) density of waste (400 kg/m3)

Length of Sample = 0.30 m
X Area of Sample = 0.04524 m^2

Test run No	Hp1 m	Hp2 m	Hp3 m	Hp4 m	P(H1-H2) m	P(H2-H3) m	P(H1-H3) m	Grad(12)	Grad(23)	Hgrad(13)	1 lit in min	sec	Q = (m^3/s)	k (1-2) (m/sec)	k (2-3) (m/sec)	k (1-3) (m/sec)	Q (m^3/s)	Hgrad(13)
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0	0.000
1	1.405	1.430	1.450	1.455	0.025	0.020	0.045	0.217	0.160	0.188	4	25	3.77E-06	3.8371E-04	5.2135E-04	4.4489E-04	3.77E-06	0.188
2	1.190	1.280	1.355	1.365	0.090	0.075	0.165	0.783	0.600	0.688	1	20	1.25E-05	3.5307E-04	4.6053E-04	4.0191E-04	1.25E-05	0.688
3	0.725	0.870	1.000	1.020	0.145	0.130	0.275	1.261	1.040	1.146	0	52	1.92E-05	3.3715E-04	4.0875E-04	3.7100E-04	1.92E-05	1.146
																	Avg k =	4.06E-04

m/sec

For Medium (dry) density of waste (440 kg/m3)

Length of Sample = 0.30 m
X Area of Sample = 0.0452 m^2

Test run No	Hp1 m	Hp2 m	Hp3 m	Hp4 m	P(H1-H2) m	P(H2-H3) m	P(H1-H3) m	Grad(12)	Grad(23)	Hgrad(13)	1 lit in min	sec	Q = (m^3/s)	k (1-2) (m/sec)	k (2-3) (m/sec)	k (1-3) (m/sec)	Q (m^3/s)	Hgrad(13)
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0	0.000
1	1.358	1.375	1.435	1.440	0.017	0.060	0.077	0.148	0.480	0.321	5	39	2.95E-06	4.4111E-04	1.3585E-04	2.0324E-04	2.95E-06	0.321
2	1.275	1.305	1.415	1.423	0.030	0.110	0.140	0.261	0.880	0.583	3	9	5.29E-06	4.4834E-04	1.3291E-04	2.0050E-04	5.29E-06	0.583
3	1.070	1.125	1.335	1.345	0.055	0.210	0.265	0.478	1.680	1.104	1	47	9.35E-06	4.3196E-04	1.2297E-04	1.8710E-04	9.35E-06	1.104
																	Avg k =	1.97E-04

m/sec

For High (dry) density of waste (480 kg/m3)

Length of Sample = 0.29 m
X Area of Sample = 0.0452 m^2

Test run No	Hp1 m	Hp2 m	Hp3 m	Hp4 m	P(H1-H2) m	P(H2-H3) m	P(H1-H3) m	Grad(12)	Grad(23)	Hgrad(13)	1 lit in min	sec	Q = (m^3/s)	k (1-2) (m/sec)	k (2-3) (m/sec)	k (1-3) (m/sec)	Q (m^3/s)	Hgrad(13)
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000
1	1.375	1.400	1.455	1.475	0.025	0.055	0.080	0.217	0.440	0.333	8	8	2.05E-06	2.0837E-04	1.0295E-04	1.3589E-04	2.05E-06	0.333
2	1.105	1.180	1.370	1.420	0.075	0.190	0.265	0.652	1.520	1.104	2	46	6.02E-06	2.0419E-04	8.7608E-05	1.2060E-04	6.02E-06	1.104
3	0.860	0.970	1.265	1.350	0.110	0.295	0.405	0.957	2.360	1.688	1	52	8.93E-06	2.0634E-04	8.3631E-05	1.1696E-04	8.93E-06	1.688
																	Avg k =	1.24E-04

Table 4.2. Constant head permeability test results for model waste – medium-scale permeameter

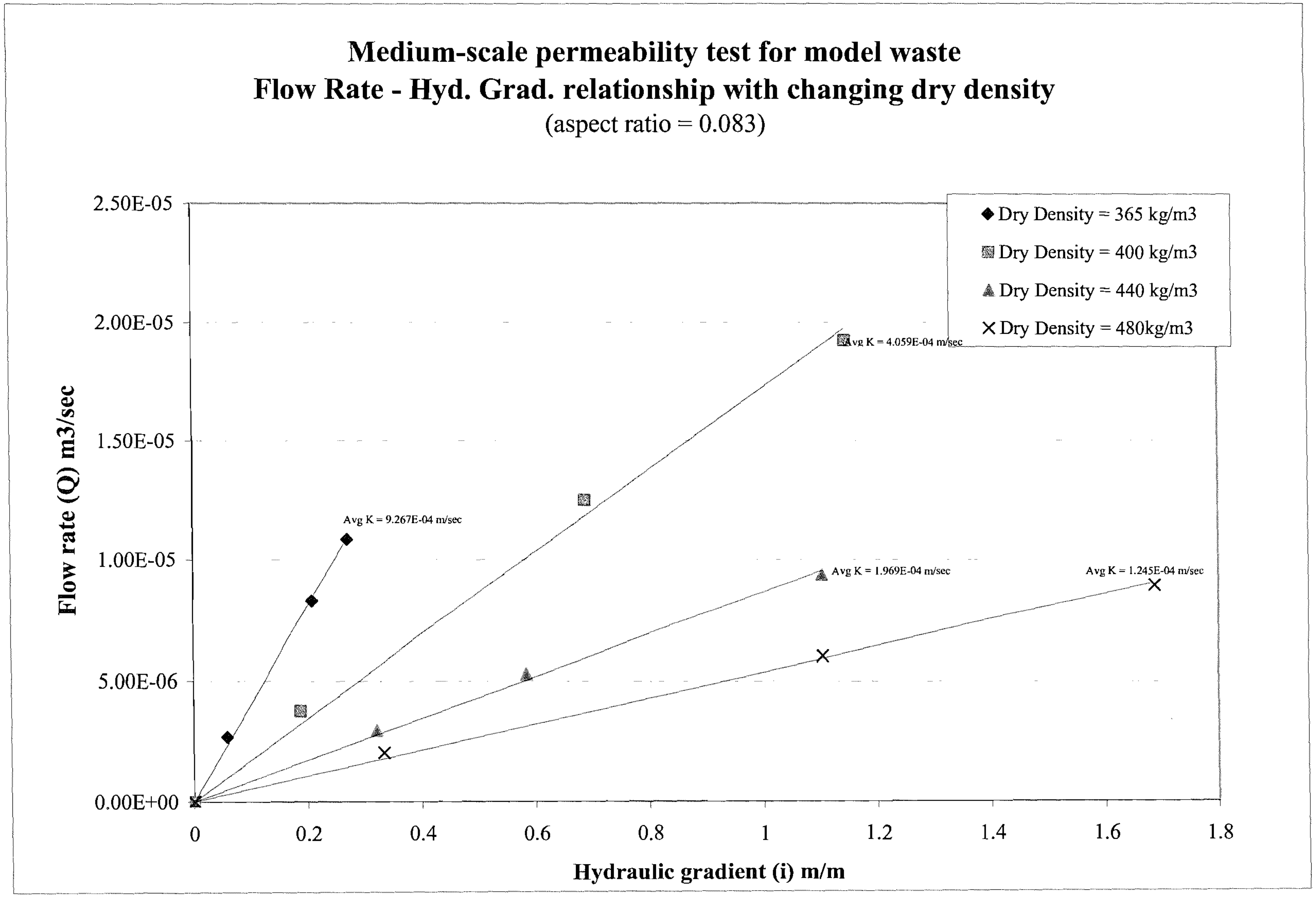


Figure 4.8. Darcy's relationship for model waste with changing dry density – medium-scale permeameter

4.3.3. Small-scale permeability tests

The dry density in small-scale permeameter achieved through manual compaction was in the range of 275 - 425 kg/m^3. Table 4.3 indicates the similar trend in variation of hydraulic conductivity with dry density as observed in the previous two scales of test. Hydraulic conductivity remains a function of dry density which may vary in the test cell according to the degree of compaction (more compacted at the top and less compacted at the bottom due to effects of side wall friction). Side wall friction becomes more pronounced as the diameter of the confining vessel decreases. It was established that an attempt to increase the density by applying compaction (pressure) at one end i.e. top of the waste sample, results in non-uniform density distribution of waste mass in the test cell. The layers closer to the point of application of pressure (top) are denser than those farther away in the bottom half. This non-uniform distribution of density in the waste caused variation in the hydraulic conductivity over the length of the sample.

It was observed (Figure 4.9) that hydraulic gradient variations are more sensitive to changes in flow rate as the scale of the permeameter is reduced. Hence for an increase in the flow rate the corresponding change in the hydraulic gradient is not linear. In other words, a non-linear change in hydraulic gradient may indicate a change from laminar to turbulent flow. This effect is however less prominent in the medium and large-scale permeameters.

The curve joining the data points in case of small-scale test do not pass through the origin which signifies that the flow rate and hydraulic gradient relationship becomes non-linear.

Determination of Hydraulic conductivity of Model waste using Small-scale permeameter - Constant Head Test

Dry density of waste = 425kg/m3

Observations & Calculations

											1 lit in									
Test run No	Hp1	Hp2	Hp3	Hp4	P(H1-H2)	P(H2-H3)	P(H1-H3)	Grad(12)	Grad(23)	Hgrad(13)	min	sec	Q = (m^3/s)	K (1-2) (m/sec)	K (2-3) (m/sec)	K (1-3) (m/sec)	Q (m^3/s)	K (m/sec)	Hgrad(13)
	m	m	m	m	m	m	m												
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.830	1.095	1.440	1.520	0.265	0.345	0.610	2.650	3.450	3.050	2	11	7.63E-06	4.5292E-04	3.4790E-04	3.9352E-04	7.63E-06	3.9352E-04	3.050
2	1.205	1.330	1.510	1.550	0.125	0.180	0.305	1.250	1.800	1.525	3	38	4.59E-06	5.7700E-04	4.0069E-04	4.7295E-04	4.59E-06	4.7295E-04	1.525
3	1.390	1.450	1.545	1.570	0.060	0.095	0.155	0.600	0.950	0.775	6	15	2.67E-06	6.9881E-04	4.4135E-04	5.4102E-04	2.67E-06	5.4102E-04	0.775
																	Avg k =	4.6916E-04	m/sec

Dry density of waste = 355kg/m3

Observations & Calculations

											1 lit in								
Test run No	Hp1	Hp2	Hp3	Hp4	P(H1-H2)	P(H2-H3)	P(H1-H3)	Grad(12)	Grad(23)	Hgrad(13)	min	sec	Q = (m^3/s)	K (1-2) (m/scc)	K (2-3) (m/sec)	K (1-3) (m/sec)	Q (m^3/s)	K (m/sec)	Hgrad(13)
	m	m	m	m	m	m	m												
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	1.475	1.555	1.585	1.590	0.080	0.030	0.110	0.800	0.300	0.550	4	38	3.60E-06	7.0698E-04	1.8853E-03	1.0283E-03	3.60E-06	1.0283E-03	0.550
2	1.250	1.465	1.545	1.550	0.215	0.080	0.295	2.150	0.800	1.475	2	10	7.69E-06	5.6255E-04	1.5119E-03	8.1999E-04	7.69E-06	8.1999E-04	1.475
3	0.950	1.330	1.470	1.475	0.380	0.140	0.520	3.800	1.400	2.600	1	19	1.27E-05	5.2376E-04	1.4216E-03	7.6550E-04	1.27E-05	7.6550E-04	2.600
																	Avg k =	8.7127E-04	m/scc

Dry density of waste = 275kg/m3

Observations & Calculations

											1 lit in								
Test run No	Hp1	Hp2	Hp3	Hp4	P(H1-H2)	P(H2-H3)	P(H1-H3)	Grad(12)	Grad(23)	Hgrad(13)	min	sec	Q = (m^3/s)	K (1-2) (m/sec)	K (2-3) (m/sec)	K (1-3) (m/sec)	Q (m^3/s)	K (m/sec)	Hgrad(13)
	m	m	m	m	m	m	m												
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	1.490	1.530	1.550	1.560	0.040	0.020	0.060	0.400	0.200	0.300	4	9	4.02E-06	1.5786E-03	3.1573E-03	2.1049E-03	4.02E-06	2.1049E-03	0.300
2	1.420	1.495	1.525	1.535	0.075	0.030	0.105	0.750	0.300	0.525	2	36	6.41E-06	1.3439E-03	3.3597E-03	1.9198E-03	6.41E-06	1.9198E-03	0.525
3	1.160	1.315	1.410	1.418	0.155	0.095	0.250	1.550	0.950	1.250	1	13	1.37E-05	1.3896E-03	2.2672E-03	1.7231E-03	1.37E-05	1.7231E-03	1.250
																	Avg k =	1.9159E-03	m/sec

Table 4.3. Constant head permeability test results for model waste – small-scale permeameter

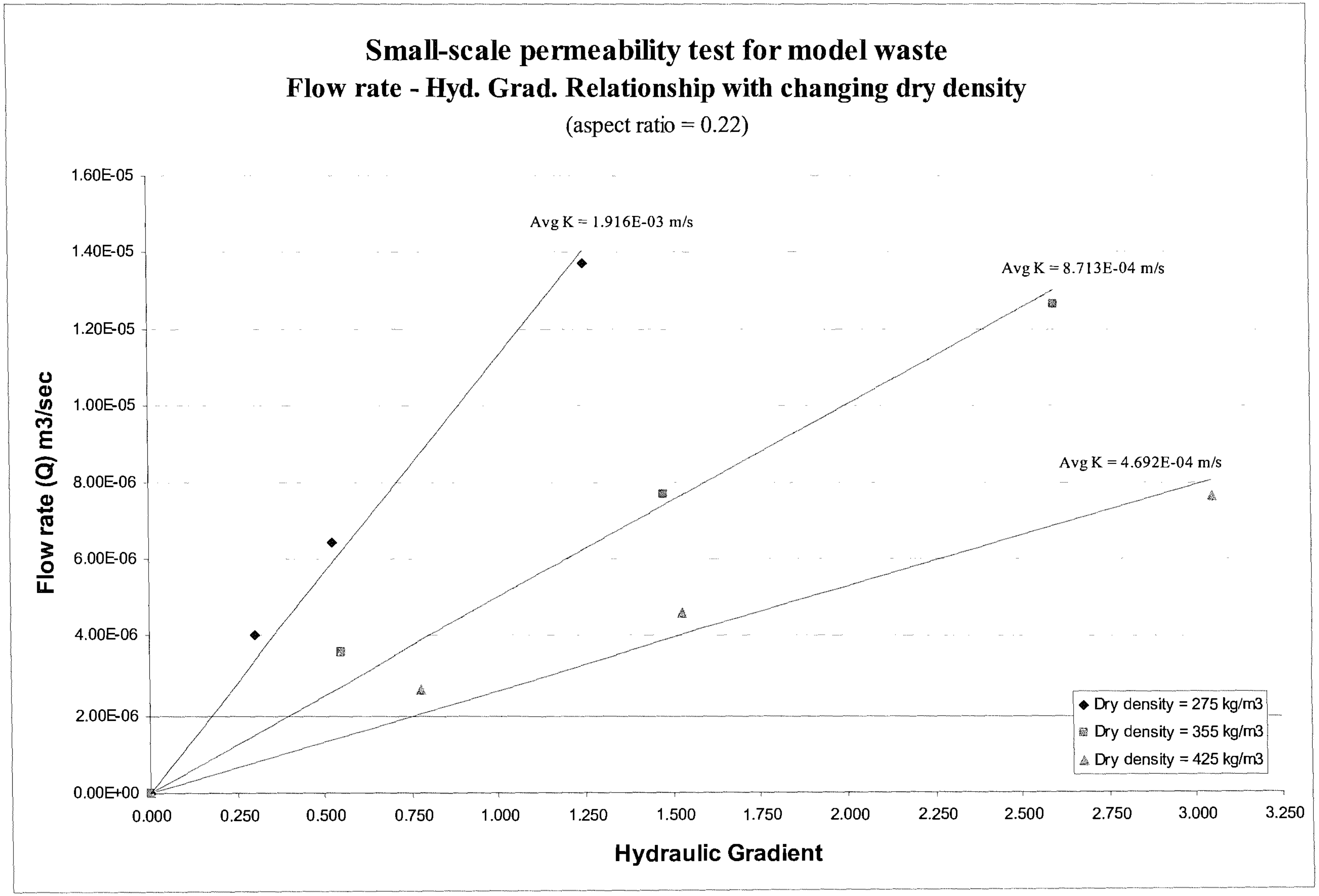


Figure 4.9. Darcy's relationship for model waste with changing dry density – small-scale permeameter

4.3.4. Variation in total head with elevation head

In the large-scale test, the variation in the total head with respect to the elevation head was measured in order to demonstrate whether the loss of head is proportional or directly related to the height of the waste column. This would in turn help identify any differential compaction occurring within the waste layers. The relationship observed for different dry densities of model waste is shown in the Figure 4.10. For low densities in model waste the head loss with respect to depth is marginal. With an increase in the dry density of the model waste it becomes more pronounced as the magnitude of loss of total head increases. A non-linearity in the observed trend (curve) signifies some differential compaction but not to any significant extent.

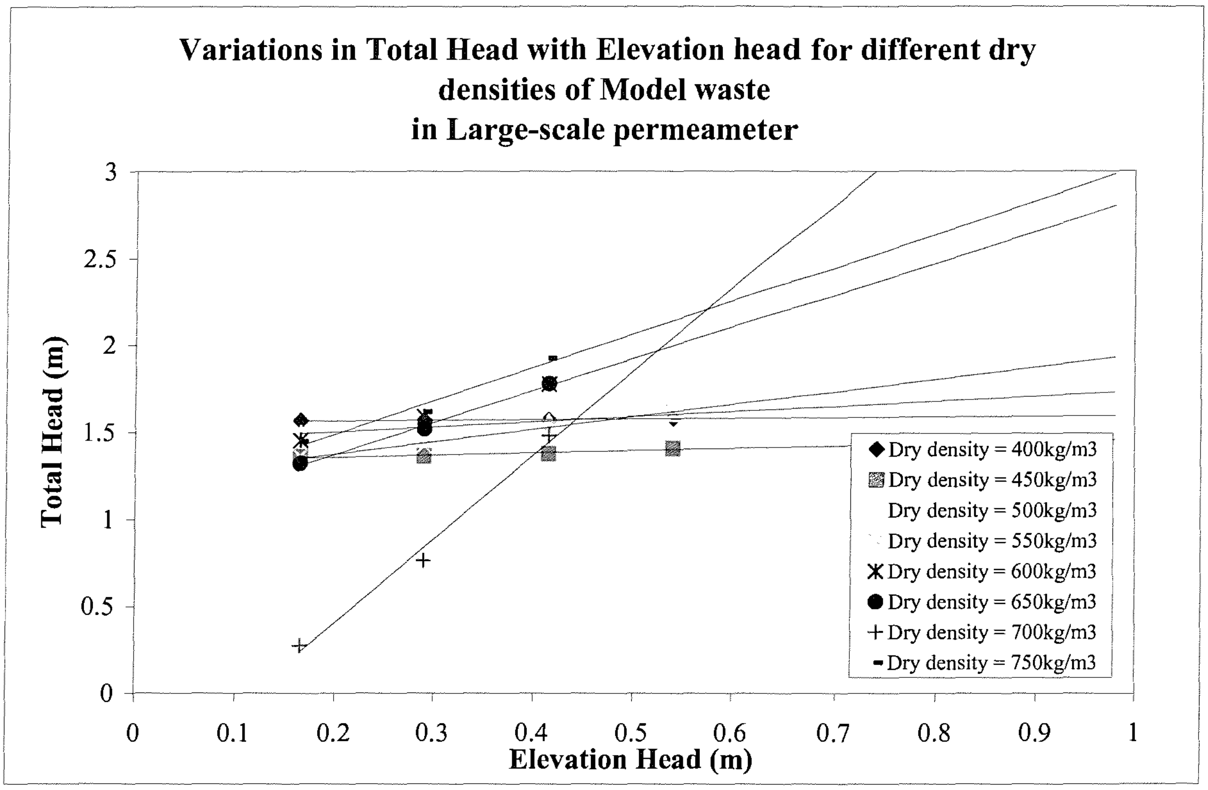


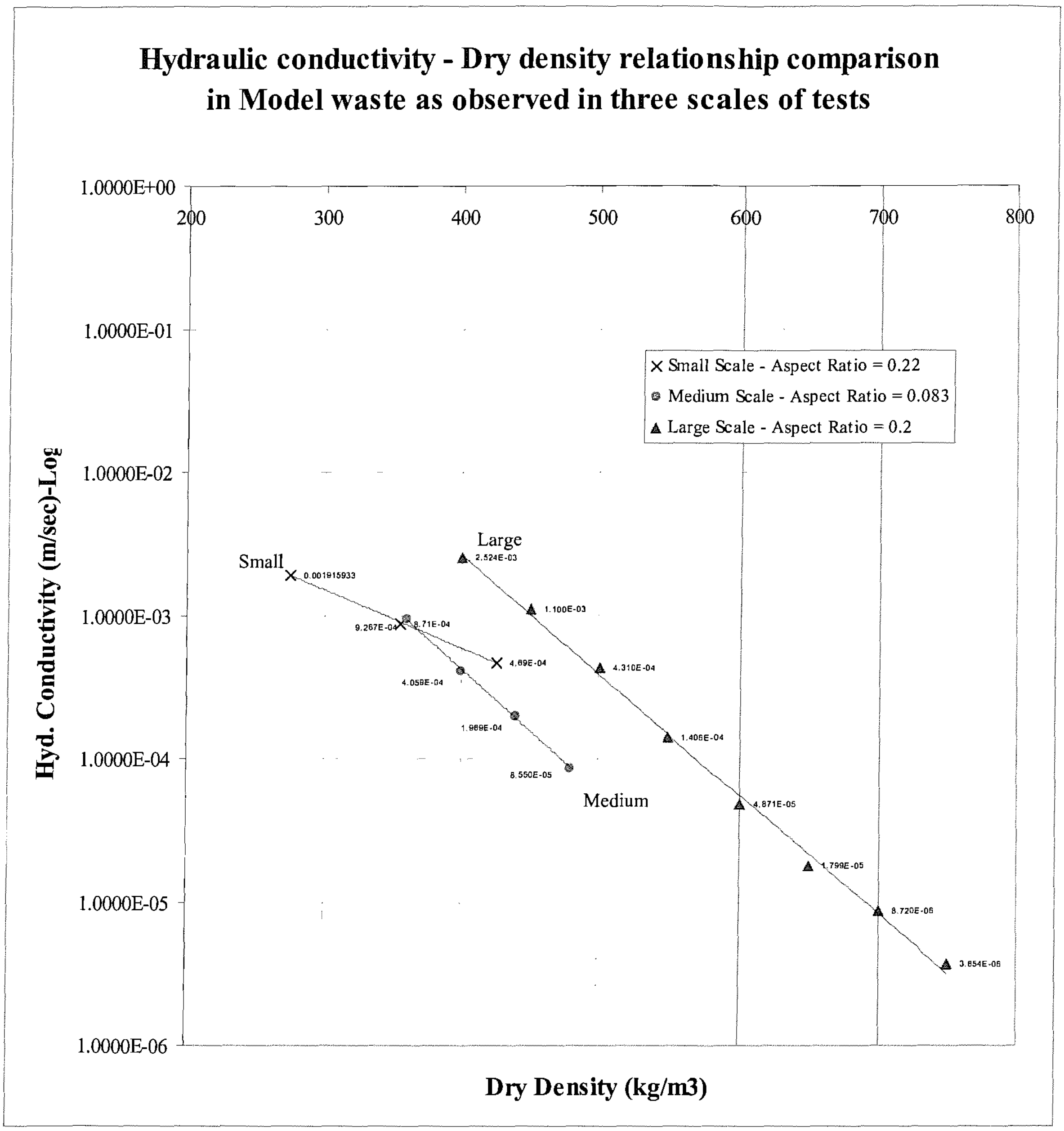
Figure 4.10. Variations in total head vs elevation head in large-scale test cell

4.3.5. Discussion

All the three scales of tests show that Darcy's law holds valid for the model waste. In each case hydraulic conductivity, decreased with the increase in the dry density of the waste.

It was also interesting to note (Table 4.1, 4.2, 4.3) that the hydraulic conductivity for a given dry density was sensitive to flow rate (Q, m^3/s). The hydraulic conductivity (K) increased with the decrease in the flow rate. This behaviour may be associated with the resistance offered by the waste matrix once the continuous flow is established. Increasing the flow rate is likely to gather increased resistance to flow (incompressibility of water) and therefore the net effect is a decrease in the hydraulic conductivity.

A comparison of measured hydraulic conductivity for the three scales of model waste relationship to dry density investigated is shown in the Figure 4.11. Some consideration was given to highlight the effect of the aspect ratio on the hydraulic conductivity characteristics of model waste. From the three curves of large, medium and small-scale tests it is clear that it is not the aspect ratio rather the particle size which clearly distinguishes the three scales of test. It can be suggested that that the medium and small-scale test which were conducted with the model waste having particle size not greater than 20mm are more or less same whereas the large-scale test using particle size less than 100mm behaves differently. Hence, the particle size as would be expected is significant in determining the hydraulic conductivity of the model waste. Secondly, the comparison of small and medium-scale with the large-scale permeameter tests shows that for a given dry density the hydraulic conductivity of model waste increases with the increase in the particle size.



Hydraulic conductivity - Dry density relationship comparison in Model waste as observed in three scales of tests

Note: Error bars obtained by analysing the data in each case lie within the symbol size

Figure 4.11. Dry density and hydraulic conductivity relationship observed in small, medium and large-scale permeameters

4.4. Comparison of the measured hydraulic conductivity with the previous work

It is relevant to compare the measured hydraulic conductivity of the model waste (large-scale permeameter) with the previous studies involving actual landfill wastes. This is presented graphically in the Figure 4.12.

A description of some of the waste used in previous studies is as follows;

DM3: Fresh crude domestic refuse obtained directly from a landfill tipping face. 39% of the sample had an average particle size greater than 160mm which predominantly comprised cardboard and paper. The compression / hydraulic conductivity tests reported were undertaken at the 'as placed' water content of 51% (dry weight).

PV1: Processed (pulverized) refuse. Following pulverization, the refuse was passed through a 150mm filter which removed some heavy fines. The bulk of the sample comprised fines between 160-40mm in size (68.5%) with cardboard and paper forming the largest waste category (49%).

AG1: Aged municipal solid waste obtained from the Rainham landfill, Essex in July 1995. The waste dated from the late 1960's and contained a mixture of soil, crude and pulverised municipal solid waste.

The type of waste used by Chen (1977) was milled municipal refuse. Blieker (1993) used refuse recovered from a borehole of a municipal landfill, majority of the sample were taken from the bottom of the landfill. These two studies were conducted in the laboratory using constant head as well as for some samples in falling head permeability apparatus in the latter study to determine their respective hydraulic conductivity characteristics.

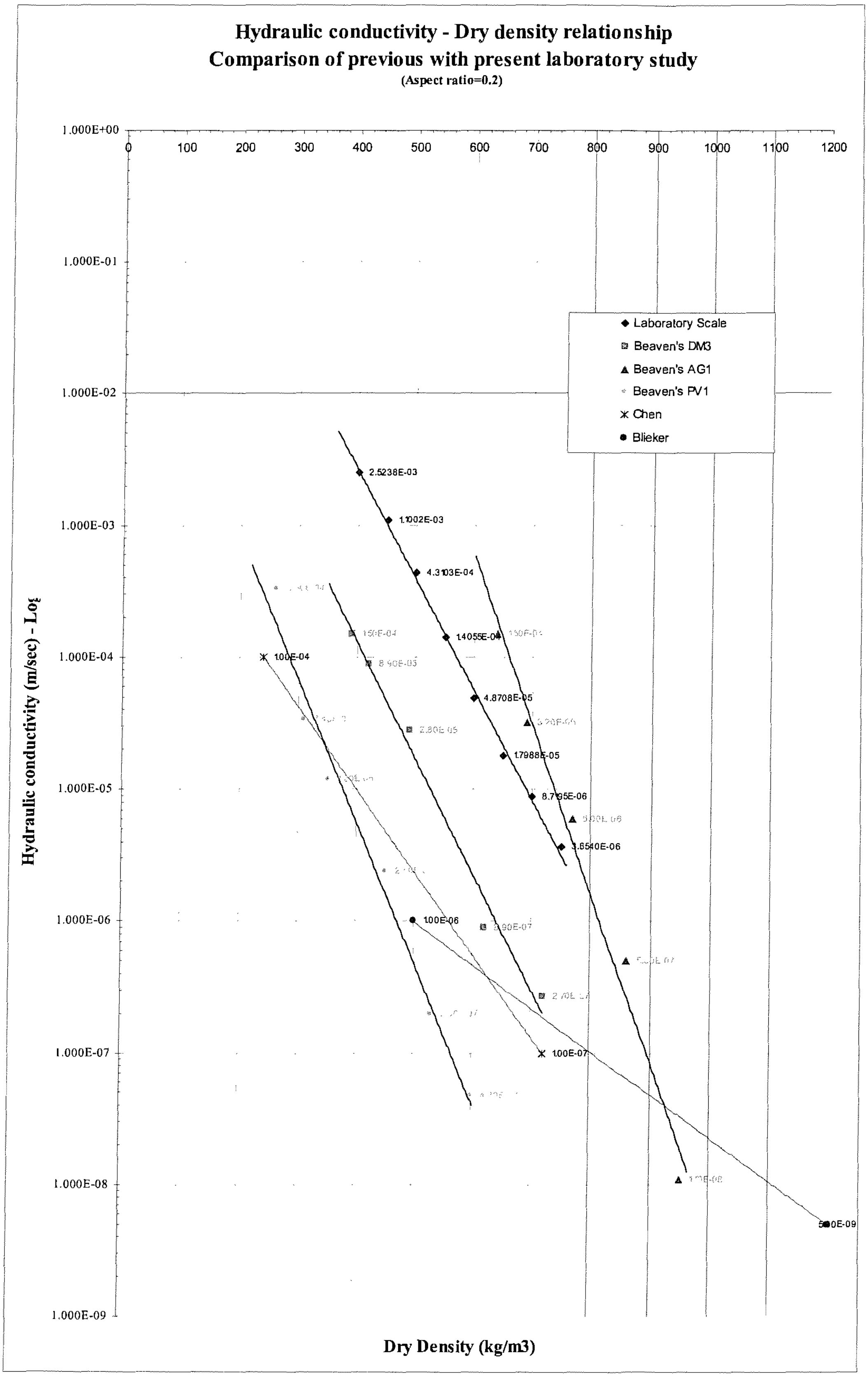


Figure 4.12. Comparison of hydraulic conductivity and density relationship of earlier studies with the present (large-scale permeability test)

Figure 4.12 shows the behaviour of hydraulic conductivity characteristics with respect to density for different landfill wastes and their comparison with the model waste. It is observed that in general, model waste behaves similarly to landfill wastes particularly to the wastes studied by Beaven (2000). The waste studied by Chen (1977) also falls within the comparable limits and shows similar hydraulic conductivity characteristics. However, the waste used by Blieker (1993) does not fall within the comparable limits and covers a wide range of densities with low hydraulic conductivity values. This may be due to the particular consideration in sampling which involved a contaminated waste i.e. mixed with liner material, obtained from the bottom of the landfill.

In all the cases it was observed that increase in waste density has an inverse effect on the hydraulic conductivity characteristics i.e. hydraulic conductivity decreases. The relationship between the two parameters is linear when presented on a semi-log scale. It can be further suggested that density-hydraulic conductivity relationship is unique for a particular waste provided that there is no substantial change in the characteristic property of the waste due to processes such as biodegradation, gas production and occlusion, clogging with time etc.

4.5. Hydraulic conductivity and dry density relationship – effects of biodegradation

The model waste remained in the large-scale permeameter in a saturated state for nearly 18 months. This prolonged saturation period was not in the proposed experimental regime. Despite the model waste comprising predominantly of inert material, the lingo-cellulose fractions which account for approximately 33% of the model waste mass, due to saturation sustained for considerable period in the test cell found favourable conditions started to show signs of degradation. Some measurable amount of methane (CH_4) and carbon dioxide (CO_2) gases was produced. The dry density-hydraulic conductivity relationship for the 'degrading' model waste was investigated further by 'fluidising' and 're-fluidising' the compacted waste. The fluidisation process allowed the waste to regain its initial volume that was set at the beginning of the original experiment. Here the term 'fluidisation' is not used in the strictest sense of its meaning rather it is used to describe the process of decompressing the waste to regain its original volume which was achieved by the expansion of the waste mass by the introduction of water at high pressure from the bottom of the cell. However, the fluidised waste failed to acquire the original density values.

In order to check whether fluidising the waste was capable of showing repeatable results, the experiment was carried out twice. The density-hydraulic conductivity relationship for fluidised and re-fluidised waste is given in the Figure 4.13.

Despite the evidence of degradation the waste characteristics remained significantly unchanged. It was only the fluidisation process which resulted in the formation of preferential flow paths, reduced tortuosity and re-orientation of the waste particles that caused a physical change in the waste mass leading to changes in hydraulic conductivity characteristic of the waste sample to be observed. The term 'degrading' waste therefore, may be regarded as mere distinction between the two phases of experiments carried out and to show any changes to the hydraulic conductivity characteristics of the model waste. The fluidising and re-fluidising of the waste gave more or less the same results indicating that fluidising process was itself repeatable.

In Figure 4.13, the two curves are more or less parallel to each other showing that shift in hydraulic conductivity is comparable. It is observed that for a given dry density in the waste the value of hydraulic conductivity increased after fluidising most likely for the reasons discussed above. Therefore, it remained inconclusive whether the apparent increase in the hydraulic conductivity was merely due to the fluidising action alone or there was also an element of degradation involved. Beaven (2002) has suggested that it has remained inconclusive that whether the hydraulic conductivity increases or decreases with the degradation of waste.

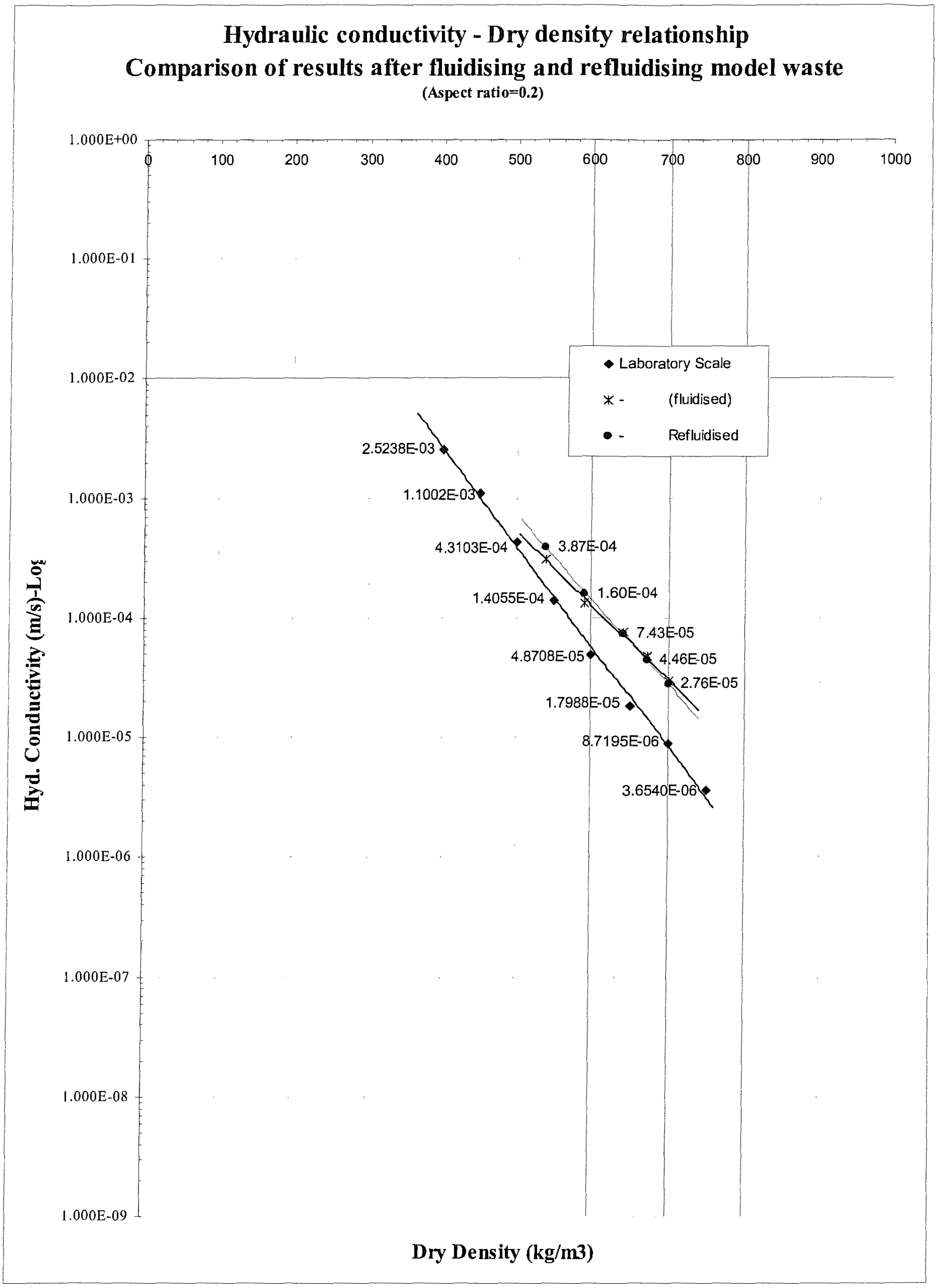


Figure 4.13. Comparison of dry density-hydraulic conductivity relationship for large scale tests after fluidising and re-fluidising model waste

4.6. Effective stress and hydraulic conductivity relationship

The large-scale permeameter had a provision for simulating an overburden pressure by applying load normally to the waste sample. The applied load may then be used to calculate the effective stress generated at various depths in the waste column. A preliminary assessment of the overburden pressure and hydraulic conductivity relationship was undertaken for the model waste.

4.6.1. Overburden pressure and effective stress

The overburden pressure (σ_o) may be defined as the load per unit area experienced at a certain depth in the waste due to the overlying self weight of the waste. It is a function of the waste unit weight (γ) and its variation over the depth (z). The unit weight of waste varies due to changes in the density of waste over the landfill depth. However, for simplicity, when calculating the over burden pressure in a test cell, it may be assumed constant over the entire depth of waste sample:

$$\sigma_o = \int \gamma dz \qquad \text{Equation 4.1}$$

The effective vertical stress (σ_v') in a consolidation test cell developed at a certain depth (z) due to the application of an external pressure (P) i.e. the ram pressure is a function of the internal angle of friction of waste (ϕ) and the angle of friction (δ) between the waste and cell wall together with the internal diameter (d) of the cell. Beaven (2000) developed a generalised equation to describe the vertical stress in waste at certain depth due to the application of an overburden pressure which may be simulated by the external pressure applied on the surface of the waste in a test cell. The following expression (Equation 4.2) defines the relationship between the external (applied) pressure (P) and the resulting effective stress given as:

$$\sigma'_v = \frac{\gamma}{B}(1 - e^{-Bz}) + P.e^{-Bz} \qquad \text{Equation 4.2}$$

Where

$$B = \frac{4(1 - \sin\phi')\tan\delta}{d} \qquad \text{Equation 4.2(a)}$$

It is assumed that there pore pressure is zero hence the applied external pressure is equivalent to the effective vertical stress at the surface of the waste specimen. In the

Equation 4.2a suggest the value of parameter B which has a unit m^{-1} defining the particle to particle and particle to wall interaction measured in terms of the linear dimension of the cell.

Assuming a unit weight of waste as $10kN/m^3$ in landfill, in order to simulate a depth of 10m the overburden pressure applied at the surface of the waste in the cell is $100kN/m^2$ or 100kPa which is equivalent to ~20kN (for d = 500mm).

4.6.2. Experimental setup

The cell was located centrally onto the base of the consolidation machine, a 100mm thick layer of washed gravel was placed at the base of the cell and a plastic separation mesh was placed on top of the gravel to prevent waste migration into the gravel. The waste mix was then carefully placed to minimize compaction, into the Perspex cell. A further separation mesh and gravel layer was placed on top of the waste. A downward flow was provided through the waste cell to maintain a constant head through out the experiment. The outlet to the permeameter was connected to a four-way manifold having a flow regulating valve connected to it which controlled the discharge as required. Refer Figures 4.1 and 4.2.

The load platen was lowered onto the top granular layer and a small load applied to contain the waste sample. With top valve open to expel air, the cell was then filled with water (introduced through the base of cell at mains pressure to minimize air entrapment with the waste mass). When the cell was full, the bottom valve was closed and the flow of water was reversed by connecting the constant head tank to the top (inlet) valve and allowing water to discharge from the bottom through the outlet valve. The pressure head was remained constant by maintaining the inflow and outflow balance in the header tank and the fluid flow was induced through the waste mass through the continued introduction of water into the cell.

The volume of water exiting the cell through the bottom valve was measured over a timed period to determine the volumetric flow rate (Q; m^3/s) through the waste mass. Stand pipes / piezometers located within the waste sample length were used to measure the head loss due to the induced flow.

4.6.3. Effective stress simulation in the test cell

The loading platen (Figure 4.14) was perforated to allow free movement of water across the waste sample and load platen interface which allowed the simulation of effective stress with the application of external pressure by the load platen.

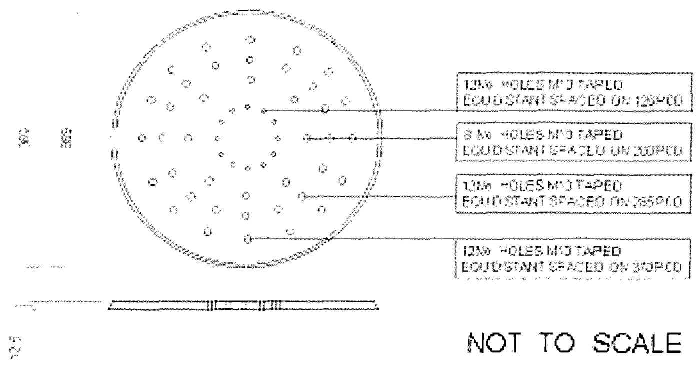


Figure 4.14. The perforated circular load platen

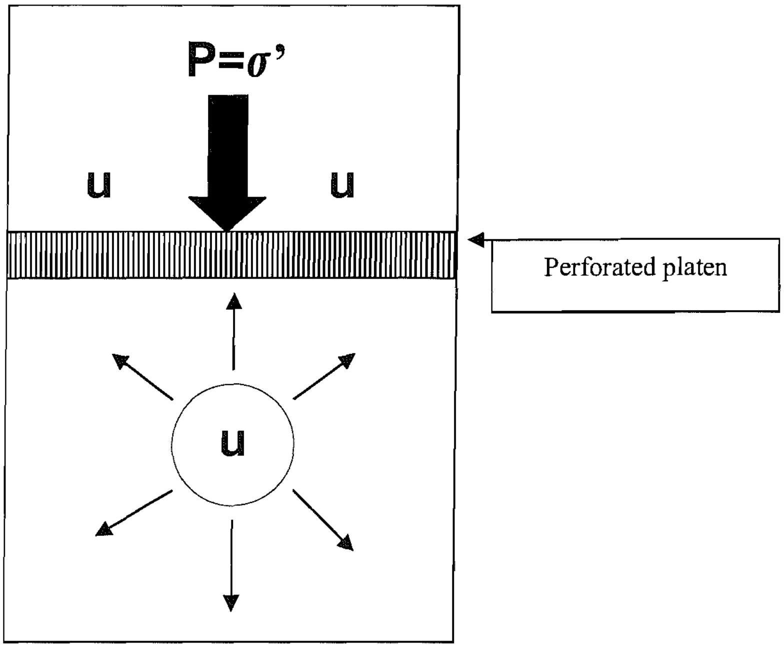
There was no appreciable change in pore pressure in response to an increase in the over burden pressure due to the provision of perforations in the load platen. It was assumed that the total stress is taken up by the waste matrix and any increment in the stress has a negligible effect on the pore pressures (Figure 4.15) such that:

$$\text{Overburden pressure} = \text{Effective stress}$$

or

$$P = \sigma'$$

The effective stresses developed due to the applied overburden pressure were calculated at various depths in waste by the Equation 4.2. The overburden increments of 0, 40, 80, 120 and 160kPa were used. For each overburden pressure increment, hydraulic gradients were measured by varying the flow rates.



Pore water pressure (u) is equal above and below the load platen ⇒ P=σ'

Figure 4.15. Pore water pressure distribution across the perforated load platen

4.6.4. Hydraulic conductivity measurements

At each stage of an increment in the overburden pressure, a steady volumetric flow rate was established through the measurement of the cell outflow (Q; m^3/sec) across a constant cross section of waste (A; m^2), a constant head loss was recorded between two absolute gauge points, thus giving the measure of the hydraulic gradient (i; m/m). Using Darcy's equation it was then possible to determine the coefficient of permeability (K; m/sec) for the model waste sample.

4.6.5. Determination of internal angle of friction (ϕ)

The internal angle of friction for the model waste was determined from the observed angle of repose. A mass of waste allowed to heap up and then slumped on a levelled surface forming a stable slope. The angle of the slope to the horizontal was measured for the model waste was 31° which was found to be in the limits reported by Kockel (1991) i.e. in between 20° to 40°for domestic refuse.

4.6.6. Determination of side wall friction angle (δ)

The angle of friction between the two surfaces, i.e. the wall of the permeameter and the waste material had to be determined. The waste was placed on a level surface made up of the similar material as the wall of the test cell (Perspex) and then the surface was raised gradually inclined until the waste started to slide. The value of the angle of friction determined for wet and dry model waste was found out to be similar at 27° to the horizontal. Beaven (2000) indicated that it is not possible for an angle of friction (δ) to be greater than the value of internal angle of friction ($\acute{\phi}$) as observed in the case of model waste.

Reduction in effective stress over the depth of waste column occurs due to side wall friction which may be estimated by the Equation 4.2. The estimated loss in the effective stress over the depth of waste was up to 50% of the external pressure applied. Beaven (2000) showed using different combination of values of internal angle of friction ($\acute{\phi}$) and angle of side wall friction (δ) the reduction in effective stress value experienced during the compression of waste in a test cell may reach up to 80%.

4.6.7. Effective stress versus hydraulic conductivity

The relationship between hydraulic gradient and the flow rate was determined for increase in the overburden pressure, hence the effective stress in the waste. The results are presented in Table 4.4. The Darcian relationship for various effective stresses in model waste is presented in the Figure 4.16. The effective stress variations over the depth of waste (top, middle and bottom) are also calculated using the Equation 4.2. These values for different overburden pressures resulting in effective stresses varying with the depth of waste in the test cell are tabulated in Table 4.5. The effective stress-hydraulic conductivity relationship for the model waste when subjected to overburden pressure at the surface ($z = 0$, $\sigma = P$) is presented in Figure 4.17.

Effective stress - Hydraulic conductivity relationship in model waste

Large scale permeameter (aspect ratio = 0.2)

Overburden Pressure (P) kPa	Flow Rate (Q) m3/sec	Hyd Grad. (i) m/m	Hydraulic conductivity (K) m/sec	
	2.0408E-05	4.060	2.5600E-05	
	1.6807E-05	3.140	2.7260E-05	Avg K (m/s)
160	1.4184E-05	2.480	2.9129E-05	2.8230E-05
	1.0811E-05	1.780	3.0932E-05	
	7.0423E-06	1.080	3.3209E-05	
	0.0000E+00	0.000		

Overburden Pressure (P) kPa	Flow Rate (Q) m3/sec	Hyd Grad. (i) m/m	Hydraulic conductivity (K) m/sec	
	2.5000E-05	3.200	3.9789E-05	
	2.3256E-05	2.800	4.2300E-05	
	2.0408E-05	2.320	4.4801E-05	Avg K (m/s)
120	1.7857E-05	1.920	4.7367E-05	4.7148E-05
	1.4925E-05	1.540	4.9360E-05	
	1.2903E-05	1.260	5.2155E-05	
	8.0972E-06	0.760	5.4261E-05	
	0.0000E+00	0.000		

Overburden Pressure (P) kPa	Flow Rate (Q) m3/sec	Hyd Grad. (i) m/m	Hydraulic conductivity (K) m/sec	
	3.1250E-05	2.100	7.5807E-05	
	2.7778E-05	1.880	7.5270E-05	
	2.1053E-05	1.440	7.4477E-05	Avg K (m/s)
80	1.7241E-05	1.140	7.7045E-05	7.4571E-05
	1.3158E-05	0.880	7.6170E-05	
	7.5472E-06	0.560	6.8656E-05	
	0.0000E+00	0.000		

Overburden Pressure (P) kPa	Flow Rate (Q) m3/sec	Hyd Grad. (i) m/m	Hydraulic conductivity (K) m/sec	
	3.3898E-05	1.330	1.2951E-04	
	2.5000E-05	0.960	1.3266E-04	
	2.2727E-05	0.867	1.3359E-04	
40	1.8868E-05	0.693	1.3863E-04	Avg K (m/s)
	1.3889E-05	0.506	1.3964E-04	1.3370E-04
	9.8522E-06	0.373	1.3444E-04	
	6.1350E-06	0.245	1.2739E-04	
	0.0000E+00	0.000		

Overburden Pressure (P) kPa	Flow Rate (Q) m3/sec	Hyd Grad. (i) m/m	Hydraulic conductivity (K) m/sec	
	1.6393E-05	0.290	2.8797E-04	
Zero	1.1364E-05	0.180	3.2161E-04	Avg K (m/s)
	6.1728E-06	0.100	3.1446E-04	3.0801E-04
	0.0000E+00	0.000		

Table 4.4. Effective stress and hydraulic conductivity relationship for model waste

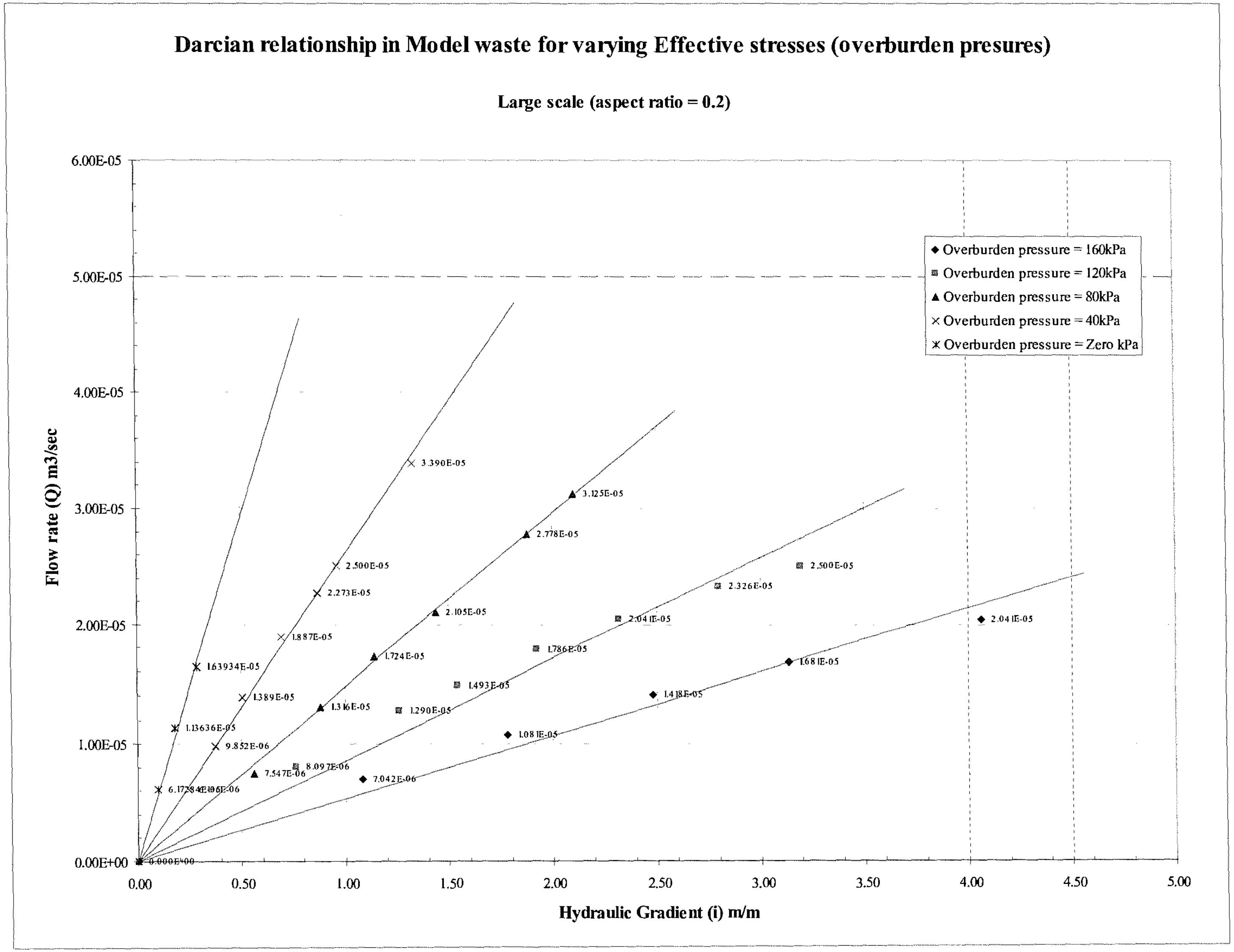


Figure 4.16. Darcian relationship in model waste for varying effective stresses (overburden pressures)

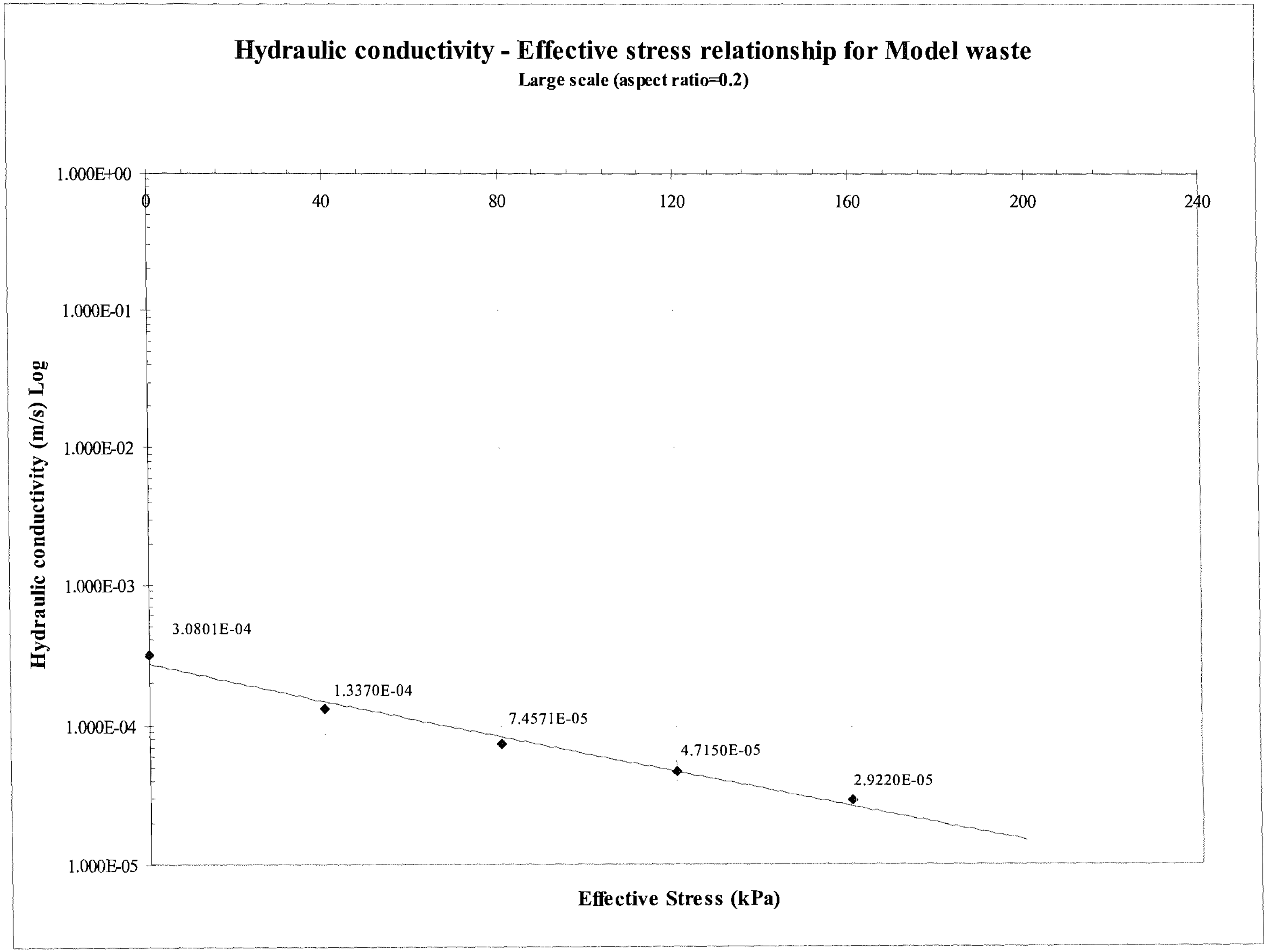


Figure 4.17. Hydraulic conductivity and Effective stress relationship for model waste

Values of effective stress over depth of waste in test cell

ρ(dry) =	700 kg/m3	γ(dry) =	6.864 kN/m3	Internal angle of friction (ø) =		31 degree =	0.541 rad
	Sample length (L) =		0.365 m	Angle of Sliding (wall) friction (δ) =		27 degree =	0.471 rad
Avg K =	2.92E-05 m/sec			Depth (z)=	0.1825 m		
		Overburden pressure = 160kPa		B value = 4(1-sin ø) tan δ / (d)			
Depth (z) = (Sample L / 2)		0.1825 m		B =	1.9768045 per meter		
Effective Stress at depth (z) =		112.5943 kPa		-Bz=	-0.360767		
				Exp(-Bz)=	0.6971415		
Depth (z) = (Sample L) =		0.365 m		1- Exp(-Bz)	0.3028585		
Effective Stress at depth (z) =		79.5478 kPa		γ / B =	3.4723717		

ρ(dry) =	670 kg/m3	γ(dry) =	6.57 kN/m3	Internal angle of friction (ø) =		31 degree =	0.541 rad
	Sample length (L) =		0.38 m	Angle of Sliding (wall) friction (δ) =		27 degree =	0.471 rad
Avg K =	4.71E-05 m/sec			Depth (z)=	0.19 m		
				B value = 4(1-sin ø) tan δ / (d)			
		Overburden pressure = 120kPa		B =	1.9768045 per meter		
Depth (z) = (Sample L / 2) =		0.19 m		-Bz=	-0.375593		
Effective Stress at depth (z) =		83.4665 kPa		Exp(-Bz)=	0.6868819		
				1- Exp(-Bz)	0.3131181		
Depth (z) = (Sample L) =		0.38 m		γ / B =	3.3235558		
Effective Stress at depth (z) =		58.3723 kPa					

ρ(dry) =	640 kg/m3	γ(dry) =	6.276 kN/m3	Internal angle of friction (ø) =		31 degree =	0.541 rad
	Sample length (L) =		0.4 m	Angle of Sliding (wall) friction (δ) =		27 degree =	0.471 rad
Avg K =	7.46E-05 m/sec			Depth (z)=	0.2 m		
				B value = 4(1-sin ø) tan δ / (d)			
		Overburden pressure = 80kPa		B =	1.9768045 per meter		
Depth (z) = (Sample L / 2) =		0.2 m		-Bz=	-0.395361		
Effective Stress at depth (z) =		54.91171 kPa		Exp(-Bz)=	0.673437		
				1- Exp(-Bz)	0.326563		
Depth (z) = (Sample L) =		0.4 m		γ / B =	3.1747398		
Effective Stress at depth (z) =		38.0163 kPa					

ρ(dry) =	595 kg/m3	γ(dry) =	5.835 kN/m3	Internal angle of friction (ø) =		31 degree =	0.541 rad
	Sample length (L) =		0.43 m	Angle of Sliding (wall) friction (δ) =		27 degree =	0.471 rad
Avg K =	1.34E-04 m/sec			Depth (z)=	0.215 m		
				B value = 4(1-sin ø) tan δ / (d)			
		Overburden pressure = 40kPa		B =	1.9768045 per meter		
Depth (z) = (Sample L / 2) =		0.215 m		-Bz=	-0.425013		
Effective Stress at depth (z) =		27.17238 kPa		Exp(-Bz)=	0.6537613		
				1- Exp(-Bz)	0.3462387		
Depth (z) = (Sample L) =		0.43 m		γ / B =	2.9515159		
Effective Stress at depth (z) =		18.7861 kPa					

ρ(dry) =	540 kg/m3	γ(dry) =	5.295 kN/m3	Internal angle of friction (ø) =		31 degree =	0.541 rad
	Sample length (L) =		0.47 m	Angle of Sliding (wall) friction (δ) =		27 degree =	0.471 rad
Avg K =	3.08E-04 m/sec			Depth (z)=	0.235 m		
				B value = 4(1-sin ø) tan δ / (d)			
		Overburden pressure = Zero kPa		B =	1.9768045 per meter		
Depth (z) = (Sample L / 2)		0.235 m		-Bz=	-0.464549		
Effective Stress at depth (z) =		0.995351 kPa		Exp(-Bz)=	0.6284184		
				1- Exp(-Bz)	0.3715816		
Depth (z) = (Sample L) =		0.47 m		γ / B =	2.6786867		
Effective Stress at depth (z) =		1.6208 kPa					

Table 4.5. Values of effective stress over the depth of waste in the test cell for the applied stresses

It was observed that the relationship between the two parameters; overburden pressure (effective stress) and hydraulic conductivity, in the model waste was similar to the dry density-hydraulic conductivity relationship i.e. with an increase in the overburden pressure (effective stress) the hydraulic conductivity decreases.

It was observed that linearity of hydraulic gradient and flow rate relationship is affected by the overburden pressure (effective stress). As the overburden pressure is increased the curve starts becoming non-linear (Figure 4.16). The flow rates involved are very low and the corresponding hydraulic gradients become increasingly high with the increase in the overburden pressure particularly beyond 80kPa, i.e. for 120 and 160kPa. This may be associated with the increase in compactness of the waste and increased resistance to flow. In general, the model waste obeys Darcy's law in the context of hydraulic conductivity and overburden pressure (effective stress) relationship.

It is again emphasised that the determination of effective stress and its relationship to hydraulic conductivity could not be assessed directly. Rather it was possible to interpret the relationship in terms of overburden pressure due to some of the following issues associated with the effective stress which are:

- The compressibility of the waste particle, whereas the concept of effective stress suggests and consider the particles to be discrete and incompressible.

- The occlusion of gas and development of pore air pressure causing errors in the pore pressure estimation, etc.

- The specific area of refuse at high refuse density is not small because many of the macro voids in the refuse would collapse due to the relatively high compressibility of some components of waste e.g. paper and plastic (Beaven 2000).

Overall, the effective stress / hydraulic conductivity characteristics of model waste have been determined for only small flow rates. As discussed earlier, there were several problems associated with the flow and pore pressure control mechanisms. Further development of apparatus capable of establishing variations in hydraulic conductivity with effective stress and hence depth in a landfill is needed to provide further investigations into the performance of leachate collection (extraction) system as discussed by Powrie and Beaven (1999).

Chapter 5

Determination of Waste Suction Characteristics

5.1. Introduction

Suction characteristics have been studied for various soils, either directly in the field or in a controlled laboratory environment (Gardener, 1937; Fawcett and Collis-George, 1967; McQueen and Miller, 1968; Al-Khafaf and Hank, 1974; McKeen, 1980; Hamblin, 1981; Chandler and Gutierrez, 1986; Sibley and Williams, 1990; Ridely, 1999). The importance of suction and its dominance in governing the stress behaviour has been established for soils, particularly in unsaturated conditions where effective stress may not be determined empirically. Understanding the unsaturated behaviour of municipal solid waste in a well managed landfill site may provide an overall comprehension of landfill waste modelling. Thus the suction characteristic which is far more dominant in unsaturated condition is likely to depict the in situ stress-state in the waste. Suction characteristics are dependent upon the waste's water content and therefore may be expressed in terms of either the volumetric water content, degree of saturation or storage capacity.

There are a number of methods for determining suction both in the field and the laboratory. These methods may be regarded as either 'direct' or 'indirect' measurement techniques depending upon the correlation used in the determination of suction. In the present study, an indirect technique – the filter paper method, is assessed for its suitability in determining the suction characteristics of model landfill waste.

5.2. Determination of the suction characteristics by filter paper method

A number of methods for determining soil suction have been already described in the literature review (Chapter 2). The following is a description of the methodology developed for this study and used to further characterise the waste-suction relationship for a model waste.

5.2.1. Background

Gardener (1937) described the use of filter paper for the first time in determining suction in soil samples and studied the soil-water release characteristics. Williams and Sedgley (1965) employed the method for measuring soil-water potential. Fawcett and Collis-George (1967) developed a modified method which used Whatman No. 42 filter papers for determining soil suctions. McQueen and Miller (1968) used an alternative type of filter paper, Schleicher and Schuell No. 589 and observed that when the filter paper was placed in close physical contact with the soil, a measure of matric potential was acquired. Also, when the filter paper was placed away from the soil in a closed chamber, the total (matric and osmotic) potential was measured. Al Khafaf and Hanks (1974) described a method capable of measuring both the components of suction; matric and osmotic, simultaneously from the same sample.

Despite its relatively simple test procedures, the filter paper technique has not proved successful in finding favour with the mainstream geotechnical community for the measurement of soil suctions. A limited number of applications have been reported e.g., successful application of the method reported by McKeen (1981) for determining total suction profiles in clay. Similarly Ching and Fredlund (1984) obtained measurements of total suction on high plasticity clay. Chandler and Gutierrez (1986) used the filter paper technique to estimate the in situ stress state of London clay with reasonable success.

A possible reason that the filter paper method has not been widely adopted is the limited published data available to verify both the accuracy and repeatability of this technique. Such data that does exist is limited to individual single applications of this method. Despite this, the filter paper method has many advantages over other methods viz, suction probes, tensiometers, psychrometers, and thermal conductivity sensors, high air-entry disks etc. in its simplicity, economy and versatility allowing the measurement of suctions up to 10^6 kPa. Also due to the heterogeneous particulate nature of waste material in which large variations in the shape, size and physical form of the constituent components exist, other methods were not found suitable for laboratory scale suction measurements. For these reasons the filter paper method was considered to have potential in providing a method to determine the suction characteristics of a model waste.

5.2.2. The filter paper method

A filter paper may be used as a 'sensor' that can measure either matric or total suction of a particulate medium (Fredlund and Rahardjo, 1993) such as soil or waste, etc. The filter paper method is an indirect method of measuring suction which requires a reference, i.e. a unique calibration curve for the filter paper which allow determination of suction values by interpolation.

Richards (1974) discussed the relationship between the total suction of a porous media and its temperature, humidity and vapour pressure at equilibrium. The method is based on the assumption of attaining equilibrium of relative humidity among the two separated porous media (the filter paper and soil / waste sample) when the two materials are held in contact or are sufficiently close to each other in a confined space. Equilibrium of moisture is achieved either due to the transfer of liquid (when in contact) or in the form of vapours (when separated) across the exposed physical boundaries of the two media. At equilibrium, the suctions of the two media are supposedly equal and the moisture transferred to the recording medium i.e. the filter paper which is comparatively drier than the sample has a unique value of suction for that particular moisture content. This suction-moisture relationship is established with reference to a calibration curve which is unique to the specific type / grade of filter paper used. The moisture content of the sample is determined by conventional means and the suction value is interpolated accordingly.

5.2.3. Calibration curves of filter paper

The typical relationship of moisture to suction i.e. the calibration curve, for a specific type of filter paper is unique, irrespective of the calibration technique used. There are two commonly available filter paper types that have been calibrated and used for measuring suction values in soils. Fawcett and Collis-George (1967) obtained the calibration curve for Whatman No. 42 type filter paper and McQueen and Miller (1968), determined the calibration curve for Schliecher and Schuell No. 589 filter paper. The calibration curves for these filter papers are shown in Figure 5.1.

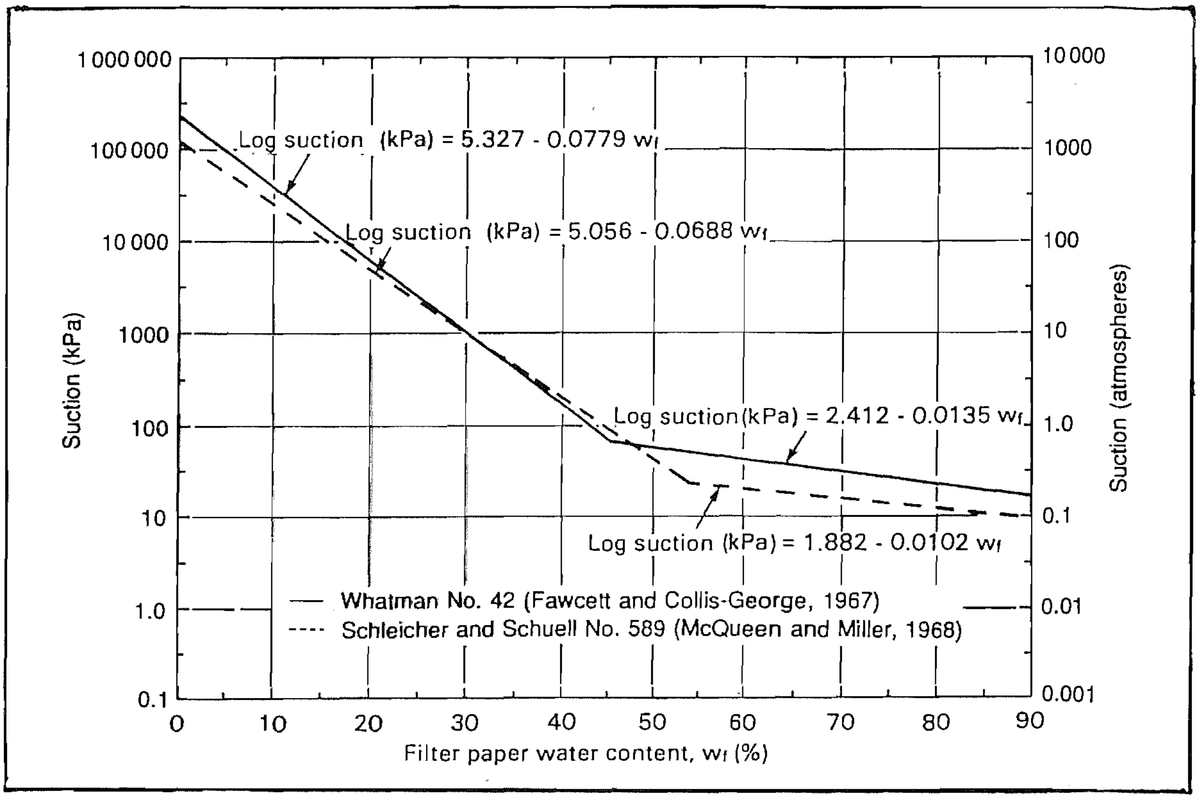


Figure 5.1. Calibration curves for filter papers used for determining suction in soil

Whatman No. 42 filter paper (50mm ø) is the more widely used filter paper and is the type used by Fawcett and Collis-George (1967), Hamblin (1981), Chandler and Gutierrez (1986), Deka et al. (1995), Swarbrick (1995). In the present study, the calibration curve developed by Swarbrick (1995) has been used for determining the suction characteristics of model waste (Figure 5.2). The reproducibility of the calibration curve for the Whatman No. 42 filter paper has been found very consistent over the years regardless of potential anomalies that may be introduced during manufacture, to the point that Whatman No. 42 filter paper can be considered to have a standard calibration curve. Calibration curves obtained by Fawcett and Collis-George (1967) and a number of additional calibrations undertaken by Hamblin (1981) over a two year period found very little variation in the calibration characteristics of the filter paper. Additional calibrations by Chandler and Gutierrez (1986) and Swarbrick (1992) again showed only minor deviations from the original calibration work of Fawcett and Collis-George (Swarbrick, 1995). Hence, it is considered that for any Whatman No. 42 type filter paper, the calibration curve may be used with a satisfactory level of confidence

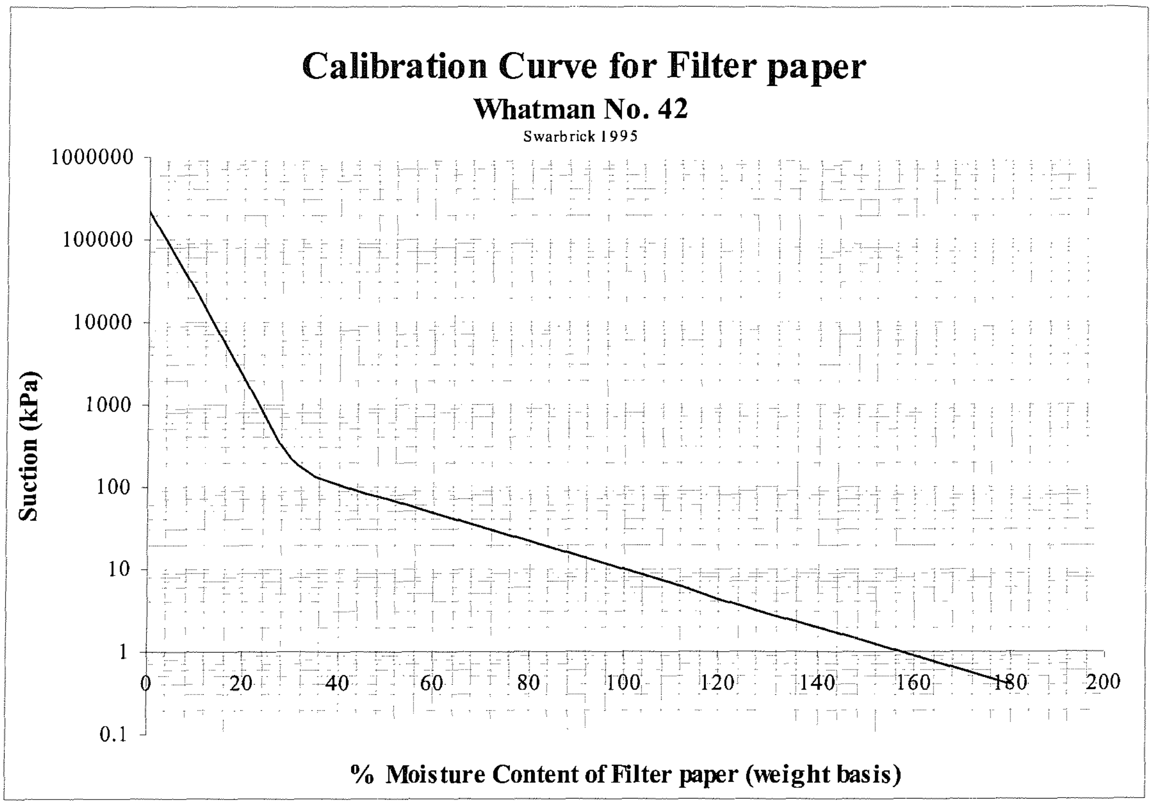


Figure 5.2. Filter paper calibration curve for Whatman No. 42. by Swarbrick ,1995

5.2.4. The standard filter paper method

The filter paper technique has been formally standardised by the American Society for Testing and Materials (ASTM) Committee D18 on Soil and Rock, in 1992, designated ASTM D 5298 – 92 under the title of, 'Standard Test Method for Measurement of Soil Potential (Suction) using Filter Paper'. The procedures and the standard method of ASTM D5298 – 92 are appended in Appendix B, however, the method adopted for determining suctions in waste, is described in the following section.

5.2.5. Suction measurements in waste

The filter paper method can be used to determine total and matric suction depending upon its placement technique. The contact technique measures matric suction where as total suction is determined by non-contact technique. As the names suggest, in the contact method the filter paper is placed in full physical contact with the sample, whereas the non-contact method requires a separation i.e. free air space between the specimen and the filter paper. Apart from the difference in the filter paper placement, the remainder of the experimental procedure for the two techniques remains essentially the same and is described in the following text.

1- It is advisable to oven dry the filter paper prior to each test. However, filter paper taken from a sealed pack may be used without prior oven drying.

2- Approximately 200g of a representative waste sample is measured into a pre-weighed sampling container. The sample and container weight is noted. The sampling container volume should be in proportion to the mass of the sample such that a minimal free space could be maintained above the sample. The containers must be airtight, and made of inert material, so that no noticeable gain or loss in tare weight occurs on heating. Add specific quantity of water to waste sample and mix thoroughly to acquire samples of desired moisture content.

3- Adjust sample mass and volume in order to achieve the required dry density in the waste sample. Maintain the volume and hence dry density by placing a constraining plate (perforated plate) on top of the specimen.

4- If the total suction needs to be determined filter papers are placed on top of the perforated plate (non-contact method). Two filter papers should be used to check the consistency in moisture transfer to the filter papers during the test. The head space above the filter papers should be kept to a minimum to minimise the equilibration time required by water vapours which saturate the free space above the sample (Figure 5.3a).

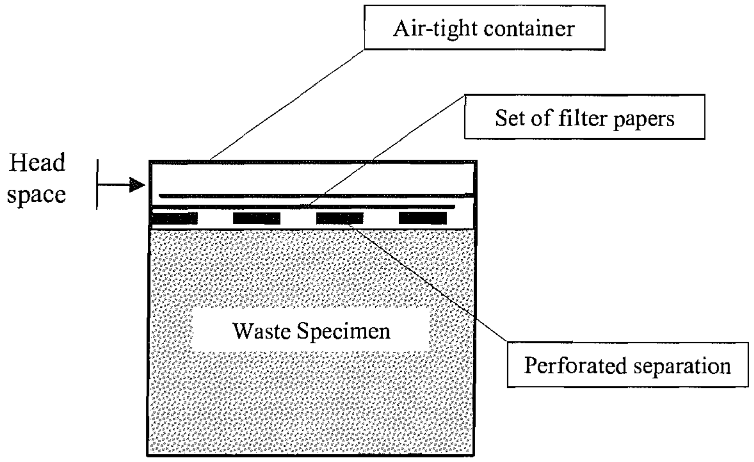
5- To determine the matric suction (contact method), a filter paper acting as a 'sensor' is placed within the waste mass, either in the middle or at the bottom of the waste sample. The filter paper that is supposed to measure the moisture retention (and subsequently the suction) is placed between two similar filter papers in order to protect it against dirt and possible contamination with waste particles (Figure 5.3b).

These two methods can either be employed simultaneously or independently to a sample provided that the moisture acquired by the filter papers during the equilibration process does not significantly alter the moisture content of the waste specimen.

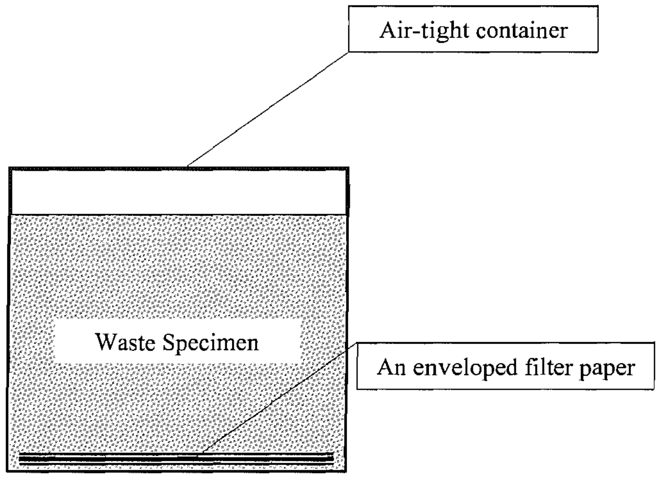
Immediately after placing the filter papers, the container is sealed with masking tape.

6- By following the procedure described in 1 to 5, samples were prepared for a specific set of moisture contents for a specific set of dry density values.

7- The prepared samples were stored in an incubator keeping the temperature variations to minimum. The equilibration temperature was maintained at 20°C, with temperature fluctuations controlled to ±1°C.



a) Filter paper method – non-contact technique



b) Filter paper method – contact technique

Figure 5.3. Arrangement of filter papers in contact and non-contact techniques

8- The equilibration period observed was a minimum of 7 days allowing sufficient time for the filter papers to absorb moisture from the sample until the suction is equalised.

9- After the completion of the equilibration period, the filter papers were required to be taken out for the measurement of moisture gained during the equilibration process. While weighing the filter paper, extreme care must be taken to minimise any change in its moisture content. Immediate transfer of each filter paper to a small pre-weighed airtight metal container followed by weighing within shortest possible time is required. The containers must be adequately light such that the weight of the wet and dry filter papers can be measured accurately.

10- The filter papers were then oven dried at 105°C ±5°C for at least 6 hours (recommended 12 hours) prior to determining the moisture content. The metal containers are kept in the oven with their lids slightly open for drying.

11- When the filter paper is dry, the container lid is replaced and the containers are re-sealed with electrical insulation tape and left inside the oven for a further 15 minutes (to facilitate equalisation of the container's inner space air temperature with the outside oven temperature).

12- The hot containers are removed from the oven sequentially and allowed to cool down to ambient temperature before determining the dry weight of the filter paper and the container. Rapid cooling is achieved by placing the container on a metal block for say 30 seconds. On cooling, the gross weight and tare cold weight of the container is quickly noted. The gravimetric measurement is quite critical and requires precision. A precision balance of resolution 0.0001g is recommended. However, it was suggested that a precision up to 0.001g may be adequate with reasonable accuracy.

13- The filter paper moisture contents were determined followed by the determination of moisture content of the waste sample. A sample observation and calculation sheet is appended in Appendix B.

14- With the help of the calibration curve (Figure 5.2) the various measured filter paper moisture content values were correlated to suction values. These interpolated suction values were then reported against the pre-determined (known) moisture contents of the waste samples for the development of waste-moisture characteristic curve for a known dry density.

The values of suction can also be determined by using the following set of equations formulated by Swarbrick (1995) for the calibration curve of Whatman No. 42, filter paper.

When moisture content (Mc) of the filter paper ≤ 0.3172 then,

$$\text{Suction (total or matric) kPa} = 10^{(5.35-10.00\mathrm{Mc})} \qquad \text{Equation 5.1}$$

When moisture content (Mc) of the filter paper > 0.3172 then,

$$\text{Suction (total or matric) kPa} = 10^{(2.729-1.736\mathrm{Mc})} \qquad \text{Equation 5.2}$$

5.3. Critical considerations in the filter paper method for suction determination

Certain considerations are necessary when following the procedure outlined above regardless of the nature of specimen used in the experiment. These considerations are listed below:

5.3.1. Sample size

The method restricts the use of large sample volumes (recommended volume range 115-230g). In order to establish representative waste sampling, considerably larger volumes of waste samples are required owing to extensive and uncontrolled variation in the particle size. In measuring total suction the sample size becomes more critical due to the restricted minimum head space in the closed container required for attaining equilibrium of suction between the sample and the filter paper, in the shortest possible period of time.

5.3.2. Wetting or drying sequences for calibration and measurement

Like many other porous media, filter paper exhibits hysteresis, over a number of wetting and drying cycles. Therefore, filter paper has different wetting and drying characteristic curves. Calibration of the filter papers should therefore follow either wetting or drying sequence and similarly the particular sequence should be observed while measuring the suction in samples (Fredlund and Rahardjo, 1993; Swarbrick, 1995). To minimise the effects of hysteresis, filter papers should be used for recording moisture and suction according to the sequence adopted during the calibration method (Swarbrick, 1995). Deka *et al.* (1995) performed calibrations of filter paper using both wetting and drying curves and discovered that calibration on a drying curve would lead to an underestimate when applying the standard technique for determining matric potential.

Chandler and Gutierrez (1986) advocated the importance of using only the wetting sequence with the filter paper initially dry. ASTM D 5298-92 does also recommend that the wetting sequence should be followed using oven dried filter papers for equilibration with the wet specimens. Swarbrick (1995) observed that when using dry filter papers, with relative humidity greater than 80%, the filter paper should be oven dried prior to the experiment in order to remove the excessive moisture.

5.3.3. Degree of contact while measuring matric suction

When determining matric suction it is necessary to place the filter paper in full / complete contact with the specimen. However, care must be taken to ensure that the filter paper is not compressed to an extent that its tendency to absorb moisture is affected. Otherwise restriction in the uptake of water may result in an overestimation of suction by approximately 200-300kPa, depending upon the degree of compaction (Chandler and Gutierrez, 1986). Al-Khafaf and Hanks (1974) investigated the influence of contact between the filter paper and sample on suction values and showed that the effect is pronounced in wet samples. Since as experienced with soils, it is rather difficult to attain good contact between the waste sample and the filter paper, instead of matric suction total suction is more likely to be measured (Fredlund and Rahardjo, 1993) when using the filter paper method as described in Section 5.2.5.

5.3.4. Equilibration period

The measurement of suction depends to a great extent on the time allowed for the filter papers to reach equilibrium in terms of moisture flow. At equilibrium, the suction in the filter paper and the sample are equal, therefore, it is important to allow sufficient time for attaining complete equilibrium. The equilibration process depends upon the initial moisture (suction) within the sample, relative humidity of air, sample mass, and the container free space. The recommended equilibration period is 7 days (ASTM D 5298-92). It was reported by Hamblin (1981) that the time taken for a single paper to equilibrate varied from a few minutes when soils were near to saturation, to ~36 hours in dry soils of fine texture provided that a good contact between paper and soil exists. Al-Khafaf and Hanks (1974) suggested 2 days; Chandler and Gutierrez (1986) allowed 3-5 days; William and Sedgley (1965), Fawcett and Collis-George (1967) and McQueen and Miller (1968) all suggested 7 day calibration periods; Sibbley and Williams (1990) recommended 10 days for the process. Deka *et al.* (1995) observed that for suction less than 2.5 MPa, filter papers required 6 days for equilibration and at lower potentials longer periods were required. Using initially dry filter paper in non-contact with the wetter sample takes a longer time to equilibrate. However, in the contact method using dry filter papers with wetter samples may take less time to reach equilibrium due to better flow path contact (Swarbrick, 1995).

5.3.5. Temperature fluctuations

ASTM D 5298-92 recommends that during the equilibration process, all samples should be placed in a controlled temperature environment of 20°C. Thermostatic control (less than ± 3°C as recommended in the standard method) is necessary to avoid condensation within the head space which is likely to occur due to thermal fluctuations. Chandler and Gutierrez (1986) used a controlled temperature of 21°C with a variation of ± 2°C. Deka *et al.* (1995) conducted suction measurements by maintaining 21±1°C temperature during the equilibration process to avoid thermal distillation.

5.3.6. Precision in gravimetric measurement

The ASTM procedure recommends that the mass of the filter papers and their containers should be determined to the nearest 0.0001g. However, experience shows that it is difficult to obtain a stable / constant reading during the weighing process when using such precision balance. Swarbrick (1995) showed that the filter paper weighed immediately to at least 3 decimal places give reasonably accurate results. Deka *et al.* (1995) indicated that weighing to an accuracy of ± 0.2mg, the maximum random error in the water content determination is approximately 0.002 g/g (0.2%). The weighing measurements by Deka *et al.* (1995) were performed to a precision of ± 0.001g.

5.3.7. Instant weighing and measurement

The procedure presented in section 5.2.5 demands quick transfer of the filter paper to container followed by immediate weighing so as to avoid drying or wetting of the filter paper that may occur due to ambient disturbances once the filter paper is exposed. The ASTM method requires that this process must be completed in 3 to 5 seconds. It has been noted that a delay of 5-10 seconds can result in 5% or more loss of mass when exposed to room atmosphere having a relative humidity of 30 to 50% (ASTM D 5298-92). Chandler and Gutierrez (1986) suggested that a period of 30 seconds may be acceptable when weighing the paper following removal of the filter paper from the equilibration containers. Deka *et al.* (1995) were able to undertake this procedure within 20 to 30 seconds.

5.4. Preliminary experiments

Waste suction characteristics determined by the filter paper method are presented. The preliminary experiments were carried out using the model waste. In the later experiments, actual landfill waste was used to investigate further the applicability of the filter paper method.

5.4.1. Suction characteristics of model waste mix

The filter paper (non-contact) method was used with a model waste to determine its suction characteristics and hence its total suction was measured. Total suction measurement was preferred over the matric suction measurement as there was a concern regarding the establishment a of good physical contact between the waste and the filter paper essential for contact method to provide accurate results. As identified by Fredlund and Rahardjo (1993), the contact method may record either total or matric suction depending upon the degree of contact between the filter paper and the particles.

The model waste composition was mixed with fine sand in the proportion of 2:3, i.e. having 60% sand in the mix based on dry weight. The addition of sand was required to simulate the fine fragments found in waste and also to represent the daily cover used in the landfill. The waste composition derived from the waste obtained from a landfill site (Section 3.3) identified the use of sand with the model waste in this proportion. With the addition of the sand to model waste, the 'model waste mix' was able to attain higher dry density values and hence, substantial variations in the dry density of the waste were possible. The suction-moisture relationships (represented by WMC curves) for the model waste mix were developed for a range of dry densities; 500kg/m^3, 750 kg/m^3 and 1000kg/ m^3. The non-contact filter paper technique was used during the preliminary tests and total suction measurements were obtained.

The waste moisture characteristic curves for the 500kg/m^3, 750 kg/m^3 and 1000kg/ m^3 model waste mix were developed using the experimental data with van Genuchten (1980) Equation 5.3 and following a curve-fitting exercise. Equation 5.3 defines the relationship between the volumetric water content (θ) and suction head (h). The other parameters in the equation are characterised as 'soil parameters' which are α, m and n. θ_r and θ_s being the moisture characteristics representing residual and saturated volumetric water content, respectively.

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{\left[1 + (\alpha h)^n\right]^m} \qquad \text{Equation 5.3.}$$

The waste moisture characteristic (WMC) curves for the model waste mix with varying densities are shown in the following figures.

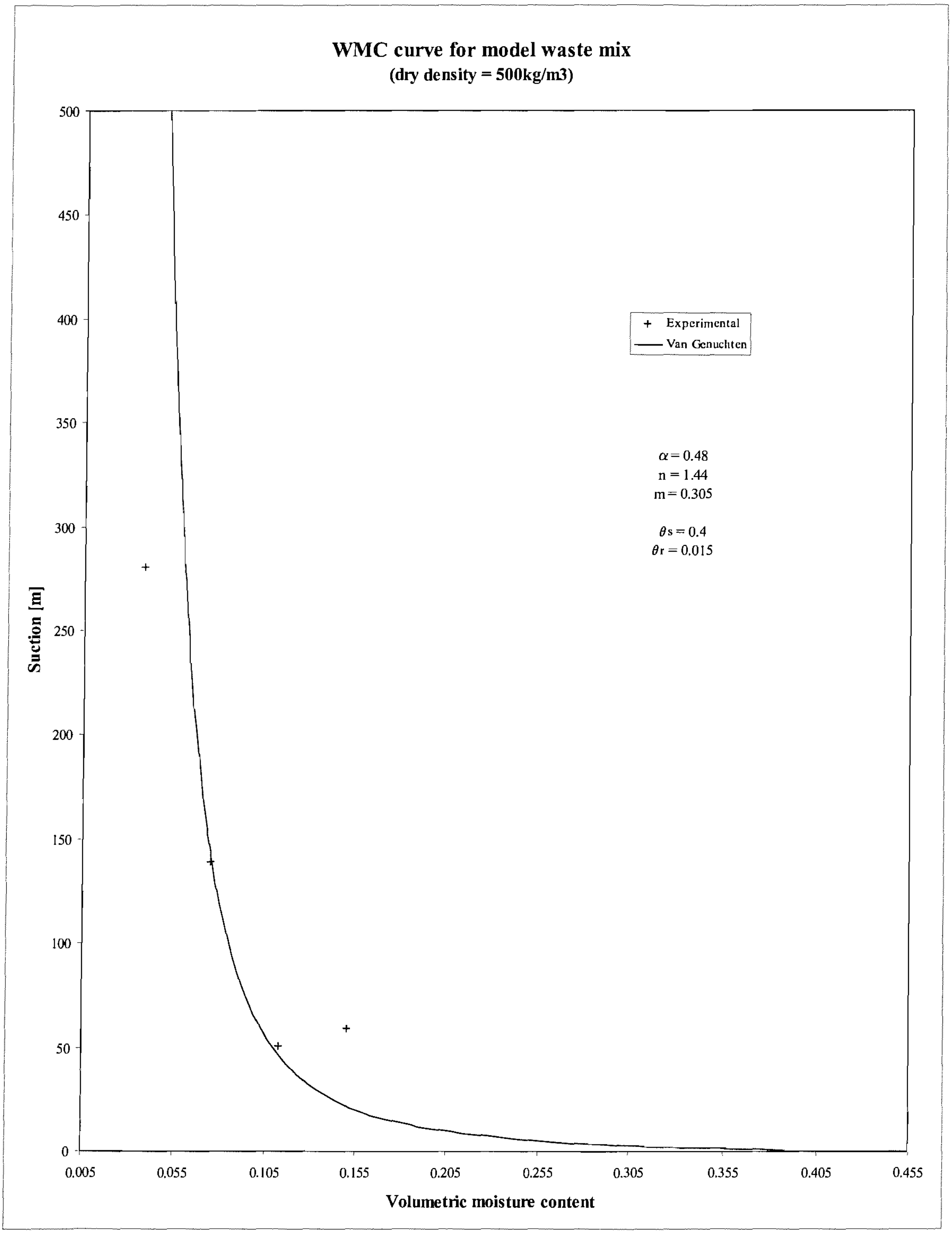


Figure 5.4. WMC curve for model waste mix ($\rho_{dry} = 500kg/m^3$)

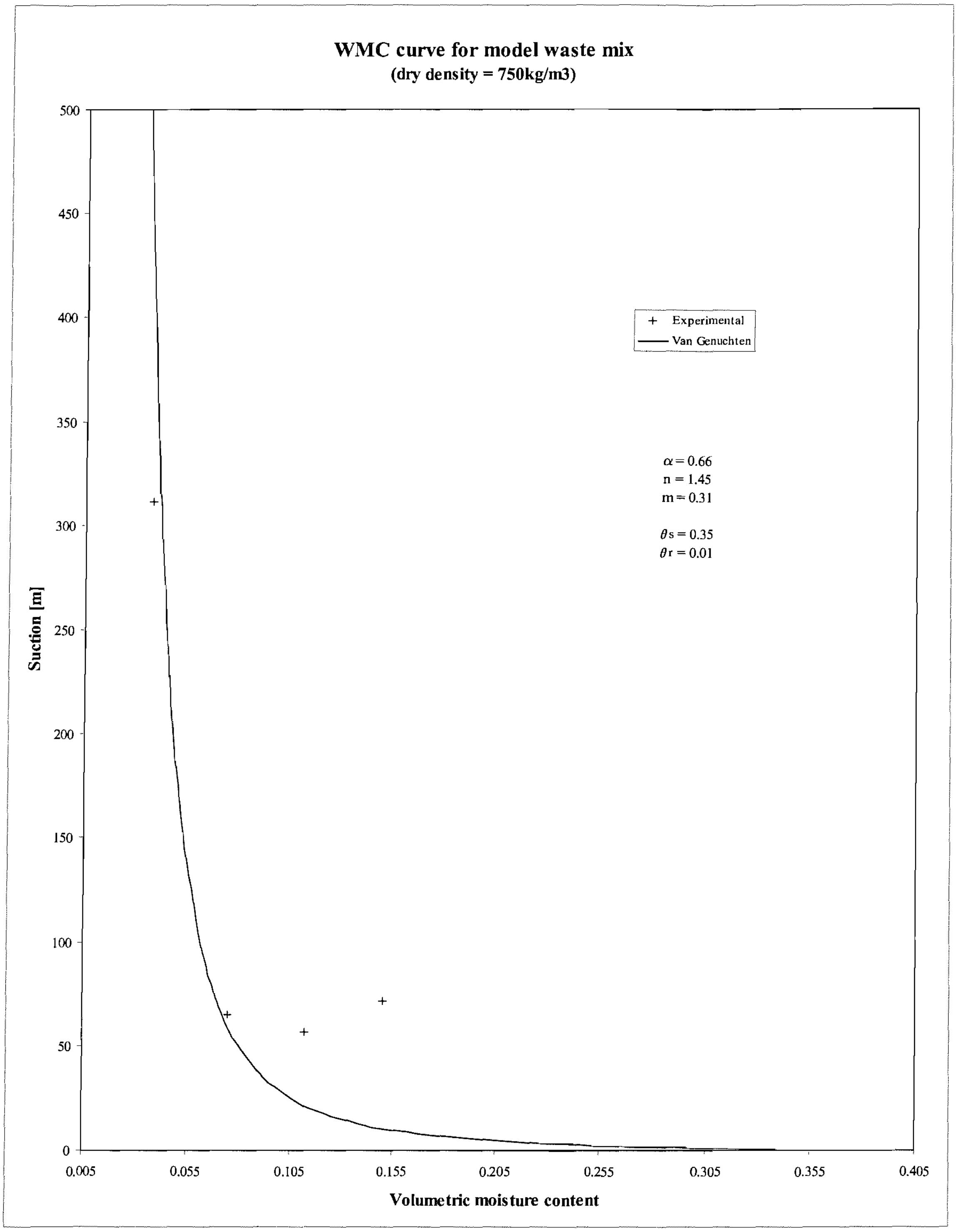


Figure 5.5. WMC curve for model waste mix ($\rho_{dry} = 750kg/m^3$)

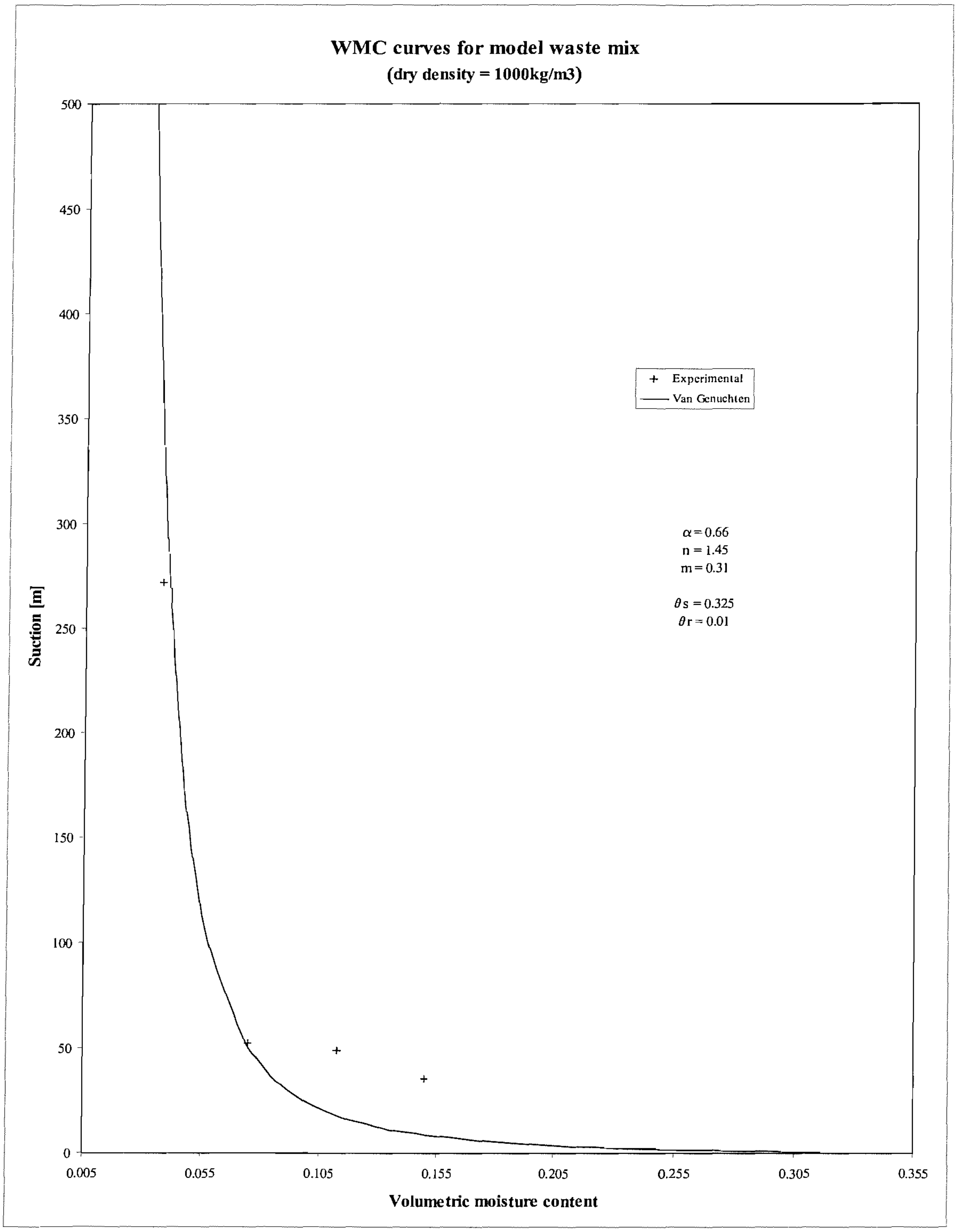


Figure 5.6. WMC curve for model waste mix (ρ_{dry} = 1000kg/m^3)

5.4.2. Application of filter paper method to actual landfill waste

A waste sample from a municipal landfill site was obtained in order to determine its suction characteristics using the filter paper method. The waste is referred to as Dano waste (Hudson et al., 2001) and has undergone processing (screening and sorting) prior to landfill. The composition and particle size distribution data for the Dano waste is given in Table 5.1 and Table 5.2, respectively.

No.	Components	Wt Comp %
1	Paper & Cardboard	42.3
2	Dense Plastics	5.3
3	Plastic Films	7.9
4	Textile	3.5
5	Glass	4.5
6	Ferrous Metal	2.2
7	Non-Ferrous Metal	0.8
8	Biodegradable organics	2.0
9	Fines	24.7
10	Misc. Combustibles	4.9
11	Misc. Non-Combustibles	2.0
	Total Percentage	100.1

Table 5.1. Percentage weight composition of Dano waste (May 1999)

The waste composition was modified by restricting the particle size in the sample. In order to have a fairly representative sample, particle size for the larger fraction was reduced or separated from the waste as required in the filter paper method while using non-contact technique. The modified composition of Dano waste having particle size less than 20mm used in the suction determination experiments is given in the Table 5.3.

Waste components	Particle Size ,mm Distribution %						Total %
	>165 mm	>80 mm	>40 mm	>20 mm	>10 mm	<10 mm	
Paper & Cardboard	15.3	57.9	19.0	7.0	0.8	0.0	100.0
Dense Plastics	8.9	66.5	18.1	6.5	0.0	0.0	100.0
Plastic Films	11.7	61.8	20.5	6.1	0.0	0.0	100.1
Textile	23.9	51.0	15.2	4.9	5.0	0.0	100.0
Glass	6.1	5.2	25.6	47.5	15.5	0.0	99.9
Ferrous Metal	6.3	60.8	27.9	5.1	0.0	0.0	100.1
Non-Ferrous Metal	5.7	45.6	39.0	9.7	0.0	0.0	100.0
Organics ,Biodegradable	0.0	13.7	18.4	50.4	17.5	0.0	100.0
Fines	0.0	0.0	0.0	0.0	0.0	100.0	100.0
Misc. Combustibles	0.0	52.8	38.9	8.2	0.0	0.0	99.9
Misc. Non-combustibles	0.0	2.5	45.9	25.1	26.4	0.0	99.9

Table 5.2. Particle size distribution found in Dano waste as determined at site

Waste components	**Comprising**	**Wt. %age composition dry basis**
Paper	Paper and Cardboard	20
Plastics	HDPE and LDPE	10
Metals	Ferrous and Non-Ferrous	3
Glass	General – broken	4.5
Textile	Cloth / fabric	2.5
Fines	Fine waste particles <3.5mm	30
Other	Coarse particles >10 < 20mm	30
Total		100

Table 5.3. Modified Dano waste composition

The waste moisture characteristic curve for the modified Dano waste is shown in the Figure 5.7. The curve shows the relationship between the gravimetric moisture content and suction. The van Genuchten equation could not be applied due to limited experimental data on the volumetric water content and dry density values. However, the moisture characteristic curve implies that landfill waste can also be characterised and the filter paper method is equally applicable. Since it was necessary to restrict the particle size in the preparation of landfill waste samples there may be a significant effect on the measured suction values typical for in-situ waste.

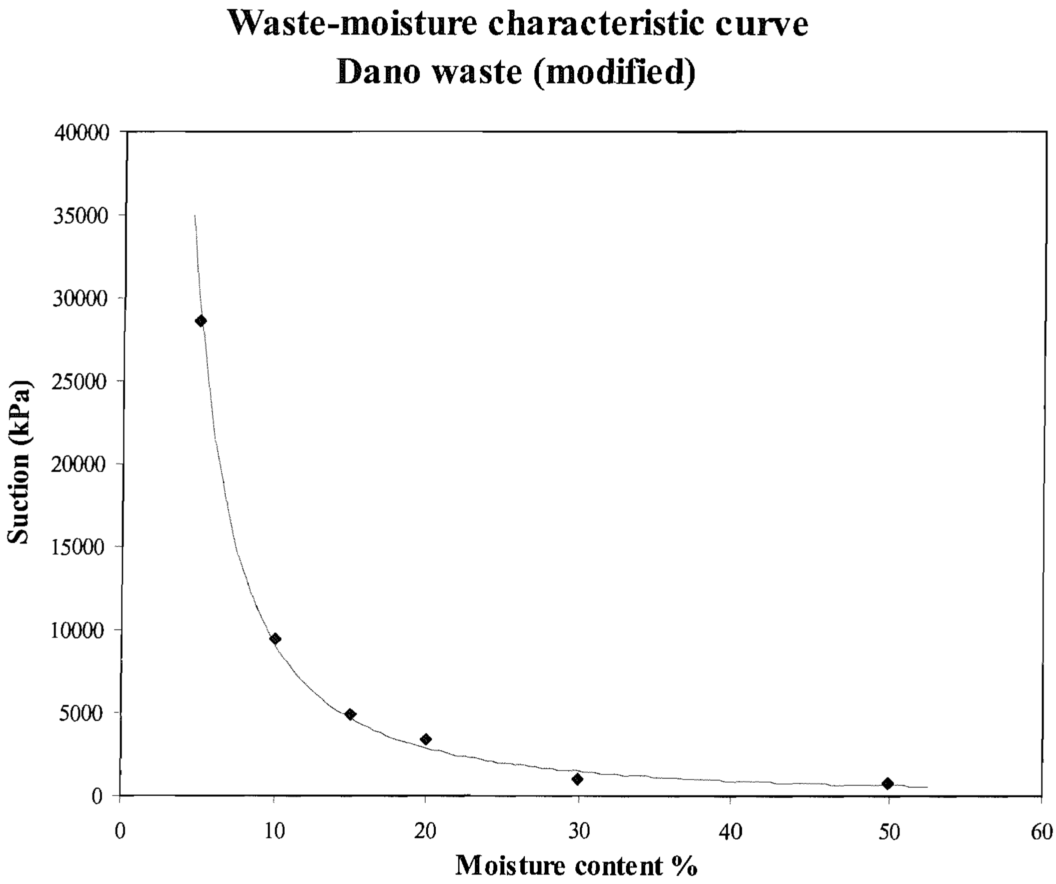


Figure 5.7. WMC curve for landfill waste (ρ_{dry} = not measured)

5.4.3. Waste-moisture characteristic (WMC) curves for the model waste

The method described in section 5.5.5 was repeated using model waste with a particle size less than 20mm and using the non-contact technique to obtain total suction values. The experiments were repeated for 3 dry densities, 300, 350 and 400 kg/m^3. As mentioned earlier, preliminary experiments were performed with dry densities of 500, 750 and 1000 kg/m^3. Such high dry density values were possible in the model waste mix where sand was used in the ratio of 2:3. In the later experiments samples were prepared without sand using solely the model waste composition, therefore the maximum dry density attained in the specimens by hand mixing and manual compaction did not exceed 400kg/m^3.

The waste moisture characteristic curves for the model waste using the experimental data and van Genuchten Equation (5.3) by curve fitting are given in Figures 5.8, 5.9 and 5.10, respectively.

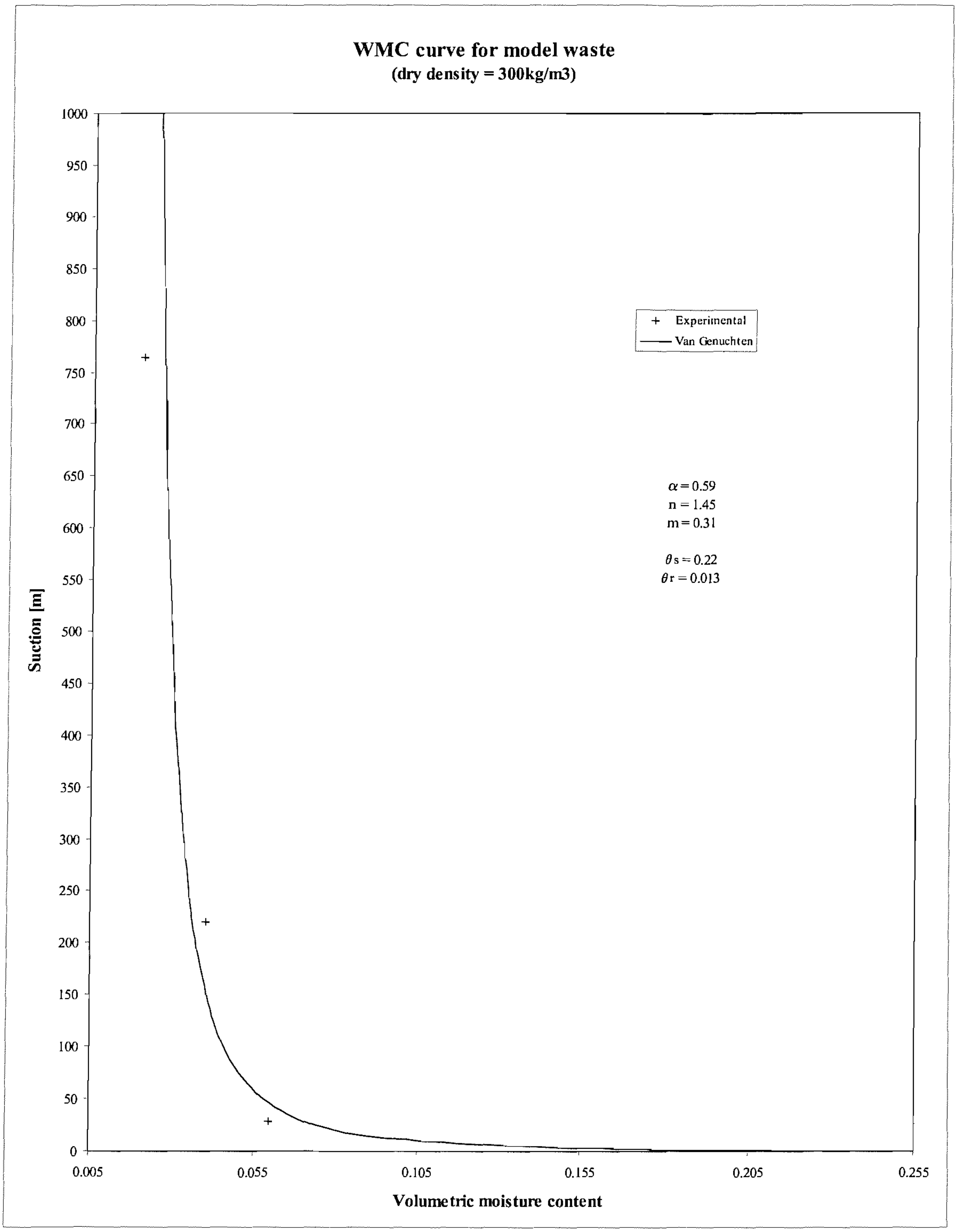


Figure 5.8. WMC curve for the model waste ($\rho_{dry} = 300kg/m^3$)

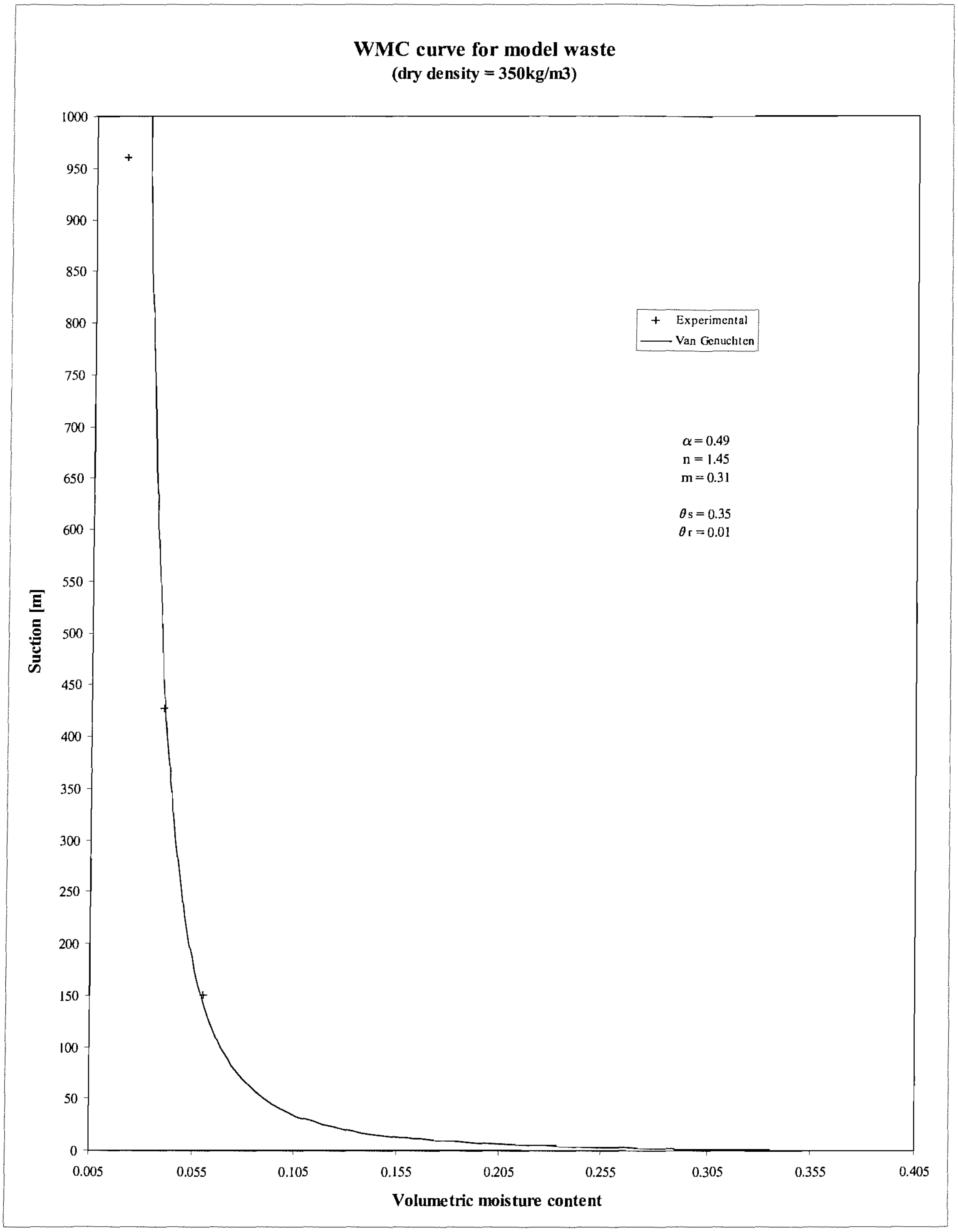


Figure 5.9. WMC curve for the model waste ($\rho_{dry} = 350kg/m^3$)

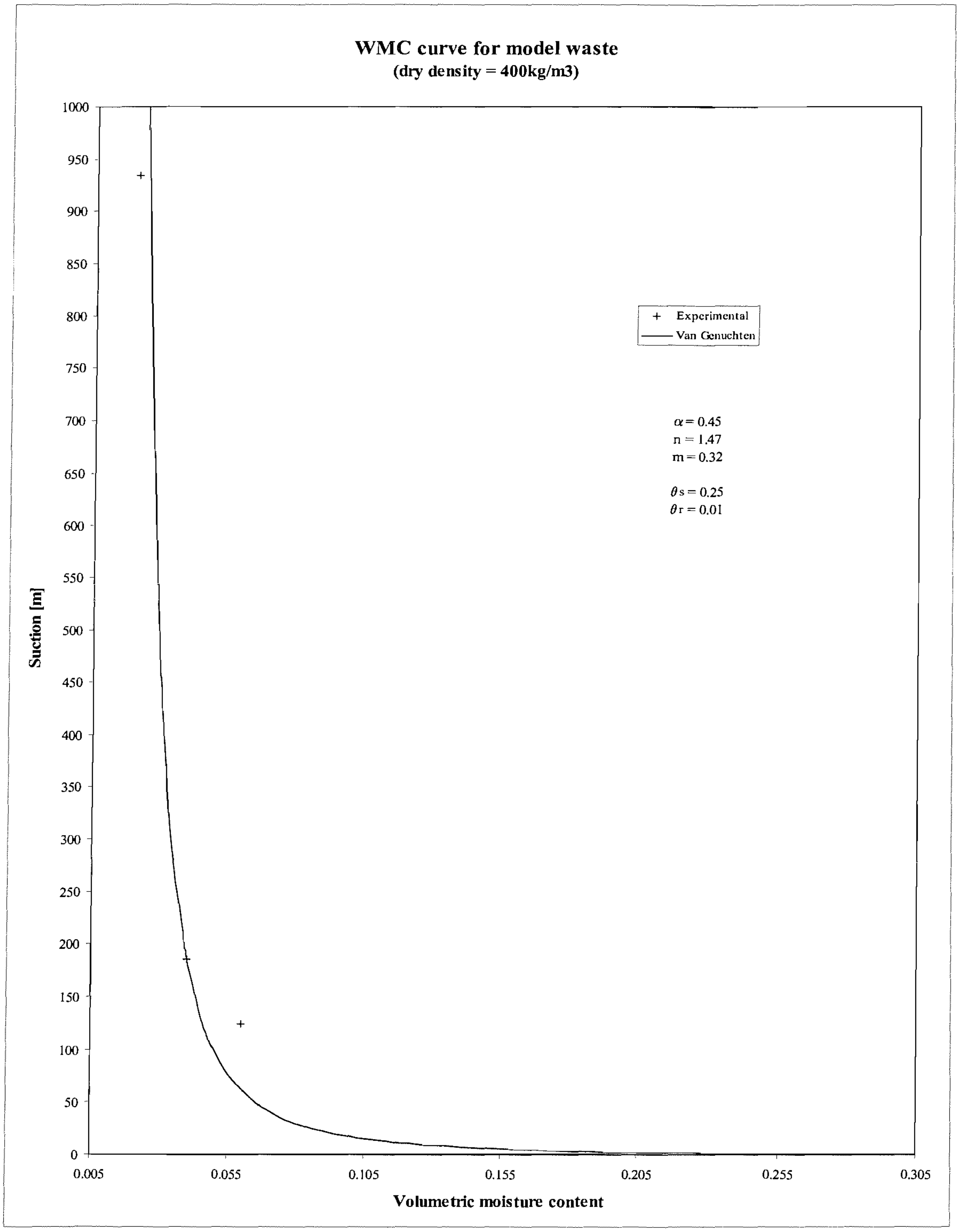


Figure 5.10. WMC curve for the model waste ($\rho_{dry} = 400kg/m^3$)

A summary of the parameters obtained by using experimental data and the van Genuchten model is given in Table 5.4.

Model waste mix & Model waste Dry density (kg/m^3)	**Residual volumetric water content (θ_r)**	**Saturation volumetric water content (θ_s)**	**Soil parameter (α) m^{-1}**	**Soil parameter (n)**	**Soil parameter (m)** [$m = 1 - 1/n$]
1000	0.01	0.325	0.66	1.45	0.31
750	0.01	0.35	0.66	1.45	0.31
500	0.015	0.4	0.48	1.44	0.305
400	0.01	0.25	0.45	1.47	0.32
350	0.01	0.35	0.49	1.45	0.310
300	0.013	0.22	0.59	1.45	0.310

Table 5.4. Summary of soil parameters described in van Genuchten equation obtained for model waste mix and model waste

Two of the soil parameters α and n of some of the soils along with there moisture characteristics reported by van Genuchten, are presented in the Table 5.5.

Soil	(θ_r)	(θ_s)	α (m^{-1})	n
Hygiene sandstone	0.153	0.25	0.79	10.4
Touchet silt loam G.E.3	0.19	0.469	0.50	7.09
Silt loam G.E.3	0.131	0.396	0.423	2.06
Guelph loam (drying)	0.218	0.52	1.15	2.03
(wetting)	0.218	0.434	2.00	2.76
Beit Netofa clay	0.0	0.446	0.152	1.17

Source: modified Table 1, van Gunechten (1980)

Table 5.5. Soil-physical parameters for some of the soils

The comparison of the soil-physical properties that are represented by parameters of van Genuchten Equation (5.3) of the model waste and natural soils indicate that model waste, in the context of its suction and moisture retention characteristics, behaves similar to soil. Its low residual volumetric water content (θ_r) in comparison to clay soils

(Table 5.5) indicates that waste behaves as a coarse soil. The value of α which represents the suction characteristic of soil is found to lie within the range for sandstone and silt loam. The parameter n represents the slope of the characteristic curve and it is the increasing function of the slope. In the case of the model waste, n is low and more or less constant

In general, model waste suction-moisture characteristics are typical of coarse soils. Repeatedly obtained values of soil-physical properties (parameters) indicate that model waste behaves as a consistent material. The effect of changes in dry density is also reflected in the curves and their soil parameters. Saturation volumetric water content (θ_s) is observed to increase with the decrease in dry density, particularly in the model waste mix where sand was used in the preparation of samples. This trend is however, not very clear in the model waste samples. The parameter α does not seem to vary consistently in model waste mix however there is a gradual increase in α value with the decrease in dry density of model waste. Parameter n remains more or less constant and since m being dependent on n does not vary either.

5.5. Discussion

The experiments using filter paper for the determination of suction in the model waste highlighted some of the observations which are discussed below.

5.5.1. Sensitivity of the filter paper in recording moisture

It was observed that filter papers are very sensitive to changes in moisture occurring within the waste specimen (contact method) as well as to the changes in humidity in the free space above the waste specimen (non contact method). Slight variations in moisture retention of the filter paper may have a significant effect on the measured suction. The calibration curve defining the suction-moisture relationship is a logarithmic function hence, a small error in the measurement of moisture is likely to cause a substantial change in the interpreted suction value.

5.5.2. Effect of increase in fine particles on suction measurement

It was noted for the non-contact tests that samples having the same moisture content and dry density showed a significant difference in the measured suction values. This may be attributed to the sample preparation practice which involved accumulation of finer particles on the top of the waste sample where the filter paper was placed. The other possibility may be the non-uniform distribution of moisture in the samples particularly in the proximity to filter paper. In either of the cases, the suction recorded was not consistent though the moisture content was same. Due to ravelling and mixing action while preparing moist waste samples, the particle size of some of the waste components such as paper, wood and granules etc. was reduced and since the waste was reused each time the particle size and its distribution was changing successively. Also an increase in the finer fragments was observed due to repeated drying and re-use of the samples. It was therefore concluded that the method is sensitive to sample preparation.

5.5.3. Effect of particle size and its distribution on suction in waste

The development of suction is substantially influenced by the average particle size and their relative distribution within the waste mass. So far experimental method used was not capable of accommodating a large range of particle sizes due to restriction of the sample volume required by the method. In order to quantify the effect of particle size on suction characteristics, a similar experiment (non contact filter paper method) was performed using (Dano) waste samples having definite particle size ranges. Table 5.6 shows the particle size (Ø) and the range, passing through successive sieves used in the experiment. The moisture content was kept constant (~10% dry weight basis) in all samples so that the determined suction values would be independent of the moisture content. The suction characteristic curve (Figure 5.11.) with respect to the particle size range shows that suction bears an inverse relationship to particle size. The observed behaviour suggested that the application of filter paper method to real landfill waste required a modification that would incorporate the use of in-situ landfill waste.

Sample No.	**Particle size ranges**	**Total suction (kPa)**
1	Ø < 1.18mm	16952
2	1.18mm < Ø < 2.36mm	9896
3	2.36mm < Ø < 5mm	5475
4	5mm < Ø < 10mm	2634

Table 5.6. Effect of particle size on suction characteristics - particle size ranges and measured suction values

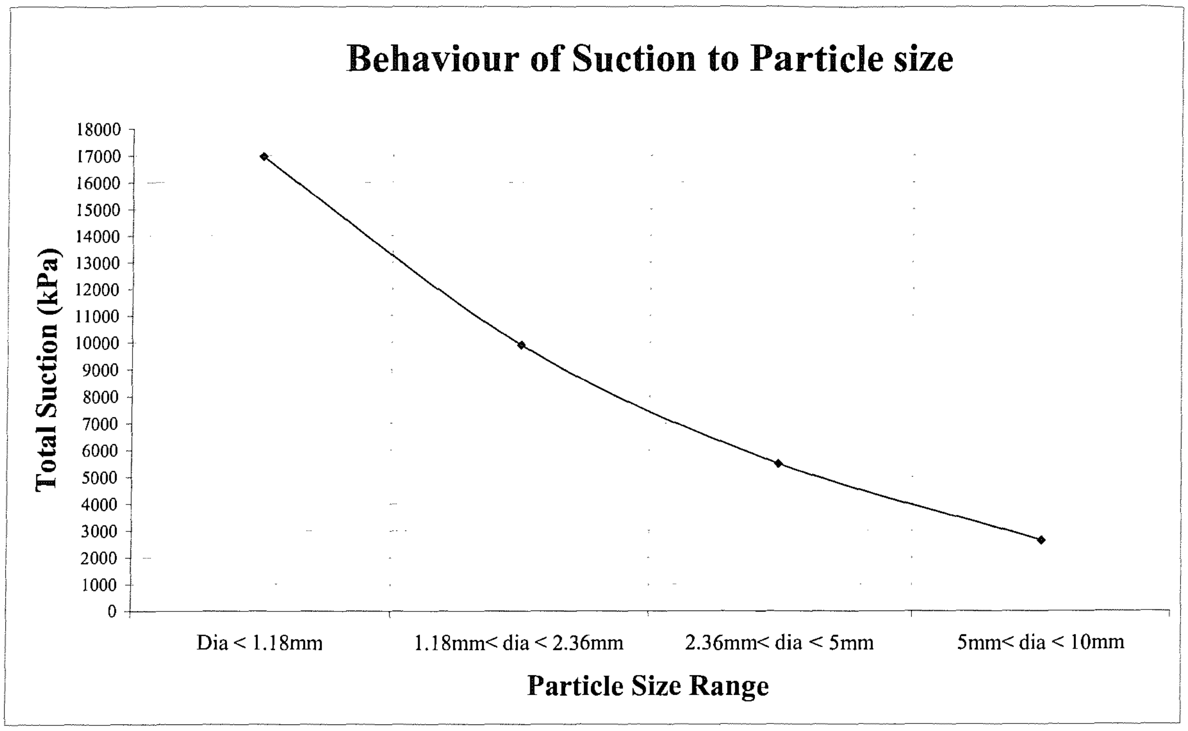


Figure 5.11. Effect of particle size on suction characteristics in waste

5.6. Proposed method for determining in situ suction

As discussed above, variation in the particle size of waste has significant effect on its suction characteristics. The standard filter paper method (ASTM D5298-92) specifically for soils excludes large particle from the sample due to limitation of the volume / size of the specimen. Therefore, a revised sampling methodology was proposed and investigated to overcome the present limitation of the method. A representative sample should therefore be large enough to accommodate the different ranges of particle sizes typically encountered in landfill waste. Hence, the non-contact technique became inapplicable and the use of the contact technique measuring matric suction was experimented to investigate into the in-situ behaviour of waste. Suction values determined using this method depends to a considerable extent upon the degree of contact between the filter papers and the waste particles. Fredlund and Rahardjo (1993) suggest that since it is particularly difficult to estimate the extent of contact between the soil and the filter paper, for in-situ experiments total suction is determined rather than the matric suction.

5.6.1. In-situ application of the contact filter paper method to landfill waste

Representative sample of landfill waste (with no adjustment to the particle size) was placed in large container. Certain key hydrological properties such as bulk density, field capacity, etc. can be simulated when placing the waste into the containers. The characteristic suction-moisture relationship with variation in depth (overburden pressure) and density may also be studied.

5.6.2. Modified method for in-situ suction determination in waste

The only modification in the standard filter paper test was an increment in the sample size. The recommended volume of specimen used is 115-230g that was increased to 0.2m^3 in order to acquire representative in situ waste sample. The rest of the procedure followed contact filter paper method as described in section 5.5.5.

Large sampling containers were acquired having a capacity of approximately 0.2 m^3 (610mm in diameter, 870mm in height). The containers used were standard metal barrels with a lid that incorporated a sealing device. The inside walls were lacquered for protection against possible corrosion. A typical municipal landfill waste was placed in three layers inside the barrel. At the base of the container a buffer layer of waste up to

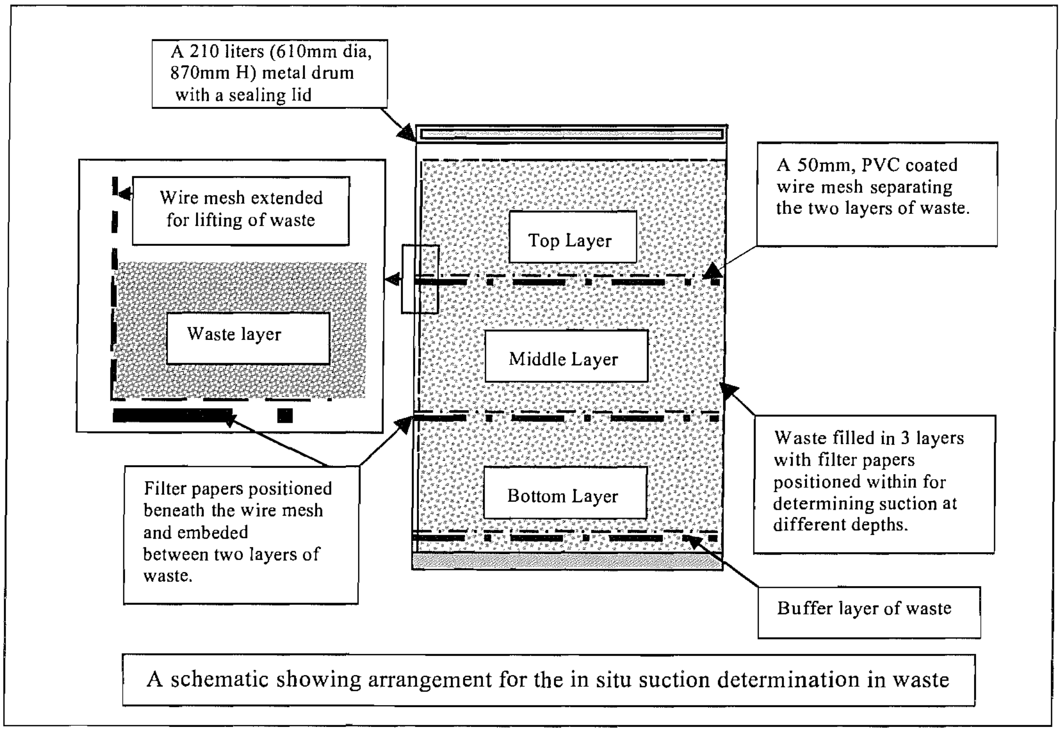


Figure 5.12. In-situ suction determination in waste – An application of filter paper, contact method

2-3 cm in thickness was evenly placed and levelled by gentle tapping with a wooden mallet. The first set of filter papers was positioned on top of the buffer layer. Each filter paper (placed for recording moisture) was placed between two other similar papers for protection against contamination with dirt and waste particles which can significantly affect the gravimetric analysis. After positioning the lower filters in the waste layer, PVC coated wire mesh (50mm aperture size) was placed on top of the buffer layer and extended up the container wall to facilitate the lifting of the waste layer and quick removal of the filter papers to determine moisture transfer. Three layers of waste; bottom, middle and top were placed in the container with a separating mesh between the waste layers as shown in Figure 5.13. The head space was 5-10cm. No filter paper was placed on the top layer as condensation formed during the equilibration period would affect its moisture content. The lid of the container was sealed and the waste was allowed to equilibrate for 7 days. The container was placed in isolation at a constant temperature of 20°C. At the end of the equilibration period, access to the filter paper was facilitated by removing the mesh and overlying waste. The filter papers were analysed for retained moisture.

5.7. Application of the modified method

The method described above for the in situ suction determination of waste was applied for determining suction profiles. The experiment was conducted using two identical containers designated as Cell A and Cell B respectively.

5.7.1. Waste density

The in-situ waste density obtained through manual compaction of the waste in the cells A and B was 375 and 425 kg/m^3 respectively. This was the bulk wet (in-situ) density achieved by placing the waste in test cells in three layers.

5.7.2. Moisture content in waste

The moisture content in each layer of waste placed was recorded at the end of the experiment. Considerable effort was expended to obtain a representative sample for the moisture measurement. However due to variations in the moisture content within the same layer due to the presence of highly absorbent material e.g. textiles, paper, cardboard, etc. it was difficult to assign a single representative value of moisture content for the waste layer.

5.7.3. Moisture profile

The moisture profiles of Dano waste that were observed in experimental cells A and B are given in the Figure 5.13. The moisture content at various depths was estimated, however, it was difficult to determine representative moisture content for a particular layer at certain depth due to heterogeneity of the material and presence of material with micro-pores such as paper, tissue, wood, etc.

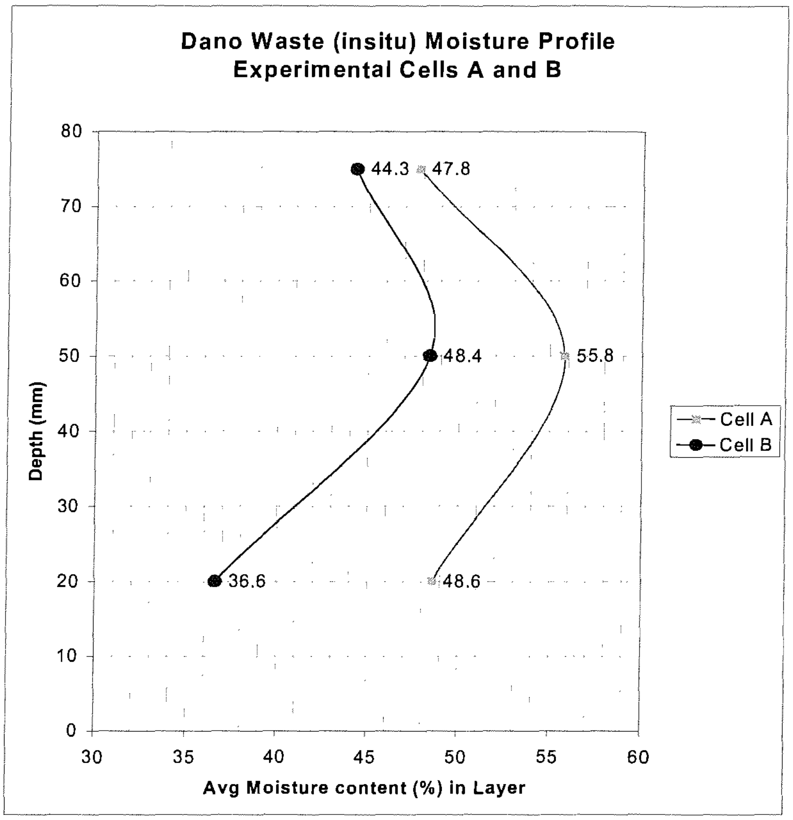


Figure 5.13. Moisture profiles of Dano waste as observed in cell A and B

5.7.4. Filter paper moisture and the suction in waste:

Three filter papers were placed in between each layer of waste. Due to the nature of the experiment the degree of contact remained uncertain, although at the end of experiment, the emplaced filter papers were found to be in good contact with the waste and appeared to collect the moisture well. The average suction value from the three emplaced filter papers was determined for each layer. The observed values of moisture content in each layer of waste were reported against the averaged suction values.

5.7.5. Suction profile

The suction profiles obtained are shown in Figure 5.14 for the two cells A and B

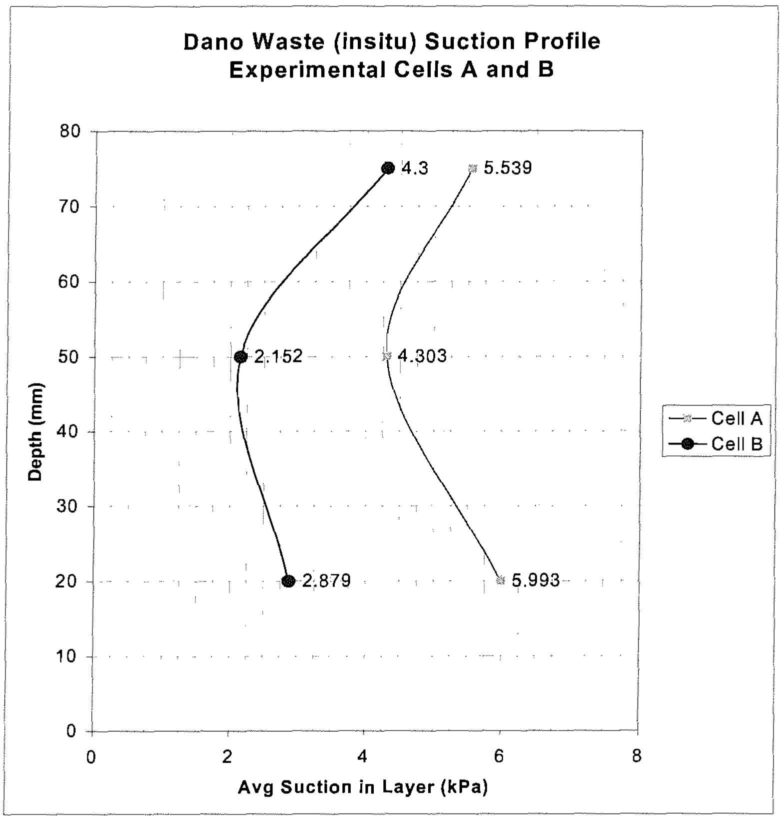


Figure 5.14. Suction profiles obtained for Dano waste in cell A and B

5.7.6. Discussion

Although the suction profile was in general agreement with the moisture profile obtained in the two experimental cells A and B, the suction values did not correspond as such to the moisture values determined in each layer. For example, the suction recorded in cell A for the moisture content of 36.6% is 2.88kPa which is very low when compared to the suction of 4.3kPa recorded for the moisture content of 44.3%. There may be several explanations for this unexpected behaviour. One major reason may be that the moisture measurements of the waste sample in each layer were not carried out in the vicinity of the emplaced filter papers. As mentioned earlier, the moisture content variation was fairly high in the waste sample therefore it was necessary to take the moisture measurements in proximity to the emplaced filter paper. The values of moisture contents were then averaged for the particular waste layer or may simply be reported independently against suction recorded individually by each filter paper.

The anticipated behaviour of suction in relation to the moisture or water content in waste show a tendency to decrease with the increasing depth due to increase in the moisture content, i.e. having a maximum value in the upper layer and then decreasing gradually to a minimum reported value in the bottom layer of waste. This however was not observed in both the cells. A possible explanation may be that the waste was placed in layers with each layer separated by the wire mesh: therefore, the entire waste mass may not be able to act as a continuous column. Another possible reason may be the heterogeneity of waste in itself, containing certain moisture retaining components such as textile, paper and cardboard, resulting in localised concentration of moisture that yielded randomly high values. The behaviour of suction to moisture can only be explained when the average moisture content of each layer is more extensively determined. It is suggested that moisture characteristic of waste is a highly variable entity and involves an element of uncertainty in its determination. No single value can therefore be assigned to represent the moisture content of waste in a layer as it varies from point to point within the waste mass. The experiment was repeated by taking readings of moisture in the vicinity of the filter paper. Again it was difficult to assign the moisture value to the waste layer and was not in correlation with the moisture contents values recorded by the filter paper.

As far as the non-contact technique is concerned, the particle diameter used in the experiments was restricted to a size compatible with the dimensions of the sample container. However, the determination of matric suction where the filter paper and waste particles are in physical contact, a situation may arise if the filter paper is smaller than individual waste particle. Or the waste particle is impervious such as a plastic bag, comes in contact with the filter paper then how filter paper will be able to record moisture? The size of Whatman No. 42 filter paper used in the experiments is 50mm in diameter which is relatively very small in comparison to the waste particle size usually occurring in waste. However, it is advocated that the filter paper records the suction regardless of the sizes of the surrounding particles.

5.8. Effects of dissolved salts on the sensitivity of filter paper

Recent investigations into the use of filter papers for suction determination in soils indicate that the presence of dissolved salts will cause a shift in the matric suction values when determined using the contact method (Ridley, 1999). It has been reported that as the salt concentration of soil / water increases, the matric suction values deduced from filter paper tests yield higher values in comparison to identical soils with lower or no salt content at the same water content. Ridley (1999) observed that the sensitivity of the filter paper in measuring matric suction is affected by the pore water solute concentrations. The effect on the sensitivity of filter paper was estimated by quantifying the shift experienced and comparing it to the change in the osmotic component of suction. The osmotic suction bears a direct relationship to the salt concentration in a solvent according to the van't Hoff's equation (Eq. 2.33).

5.8.1. Effects of dissolved salts on total and matric suction measurements

Investigations to identify qualitatively the effects of dissolved salts on the sensitivity of the filter paper in recording total and matric suctions, was also undertaken. Dissolved salts are present in the leachate produced in waste and therefore, if the filter paper method is to be employed on real waste, the effect on suction measurements need to be quantified. Ridley (1999) has attempted to quantify this effect for soils and found that:

- filter paper may not be able to accurately measure matric suction using the contact method in some soils containing dissolved salts, and
- filter paper measures total suction correctly but is affected by the presence of salt when making matric suction measurements.

5.8.2. Preliminary experiments

The investigations were carried out in two phases. The preliminary experiments were carried out using solute concentration reported similar to those by Ridely (1999) with soils. The later experiments were undertaken using representative landfill waste leachate salt concentrations.

5.8.3. Preparation of samples

The experiments were carried out using model waste (particle diameter less than 25mm) to determine the influence of solute concentration on total and matric suction values when using filter paper method. Two types of samples were prepared using two different solutions. One series containing pure distilled water and the other containing

0.5 Molar solution of NaCl were prepared with 3 different waste moisture contents (oven dry - no added moisture, 10% and 20%, dry weight basis).

5.8.4. Results

The results of the experiments are shown in Figure 5.15.

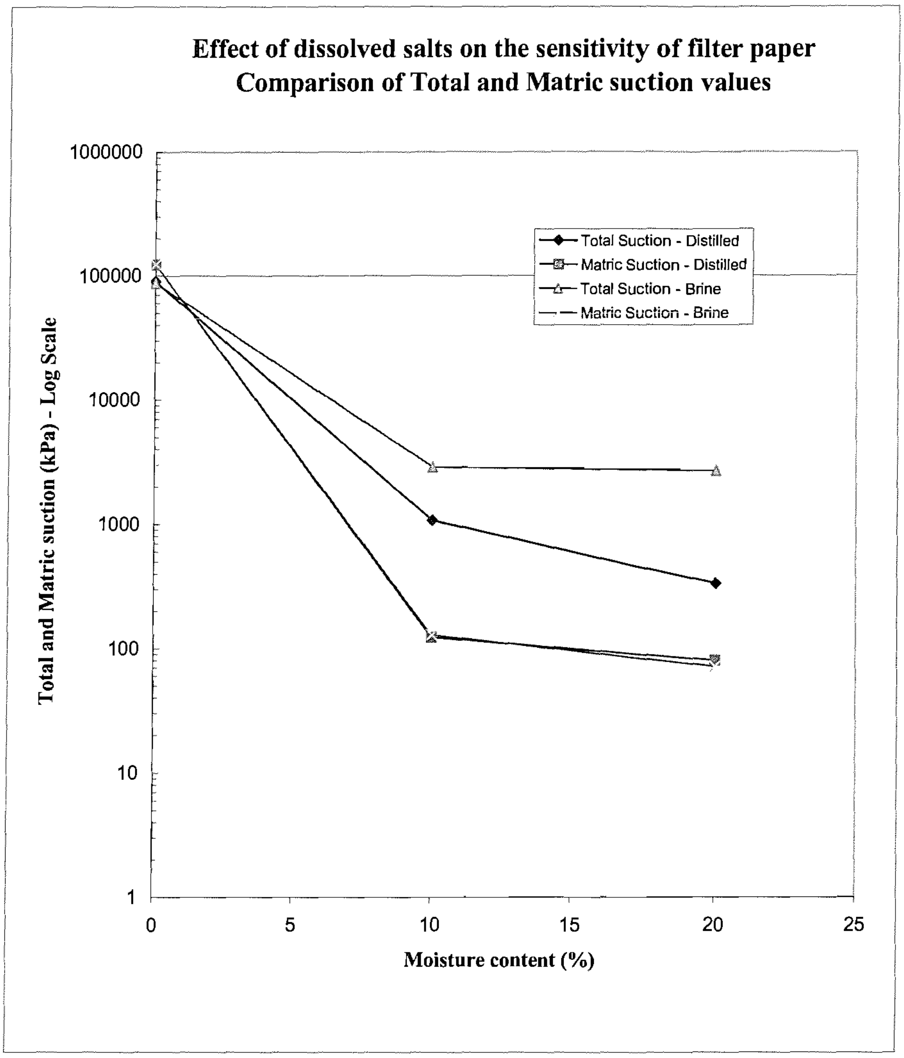


Figure 5.15. Effect of dissolve salts on the sensitivity of the filter method in recording total and matric suction values

The results show that the total suction measurements are substantially affected by the presence of dissolved salts in the pore fluid. However, the matric suction appear to be unaffected by the solute concentrations. The above findings were unable to confirm the Ridley (1999) investigations therefore, further investigation was undertaken.

5.8.5. Further investigations into the affect of dissolved salts on determination of suction values by filter paper method.

Sample preparation

The experiments were undertaken to investigate the typical effects in waste. A salt composition and concentration typical of landfill leachate was selected to formulate a solution that is representative of chief constituents* of landfill leachate (Table 2.13). The model waste with a particle diameter less than 10mm was used in order to enhance suctions in the waste. The solution comprising the dissolved salts is termed the 'Solute'. The solution used as a 'reference' solution using pure distilled water is referred to as the 'Blank'. Waste samples of constant dry density ($\rho_{dry} = 400kg/m^3$) were prepared with 'solute' and 'blank' solution of varying moisture content (5%, 10% and 15%). The total and matric suction were measured in two separate sets of experiments.

Results

The results of the experiments carried out to investigate into the sensitivity of the filter paper in measuring total and matric suction due to the presence of dissolve salts in pore fluid are shown in Figure 5.16 (a & b) and 5.17 (a & b).

5.8.6. Discussion

The experiments indicate that the solute and matric suction are both affected by the leachate concentration. Unfortunately, it is difficult to quantify this effect adequately due to time constraints. However, it is has been identified that the total suction is much affected by the leachate concentration and that the effect tends to increase with the increasing solute concentration in the pore fluid. Even taking into consideration the contribution of osmotic suction to the total suction values, the difference in the values of total suction for the blank and solute containing samples is far too high. The probable explanation for this is that due to the presence of solute the vapour pressure of the pore fluid decreases and therefore restricts the escape of water vapours to the neighbouring filter paper. In the case of no or little solute concentration in pore fluid the movement of the vapours is less restricted therefore the suction values are lower.

The same comment can be made for the increase in the matric suction due to the presence of solute concentrations in pore fluids. The dissolved salts appear to restrict the movement of the solvent particles (water) therefore resulting in the increase of reported matric suction values. However, this effect is minimised as the solution becomes dilute or the moisture content increases.

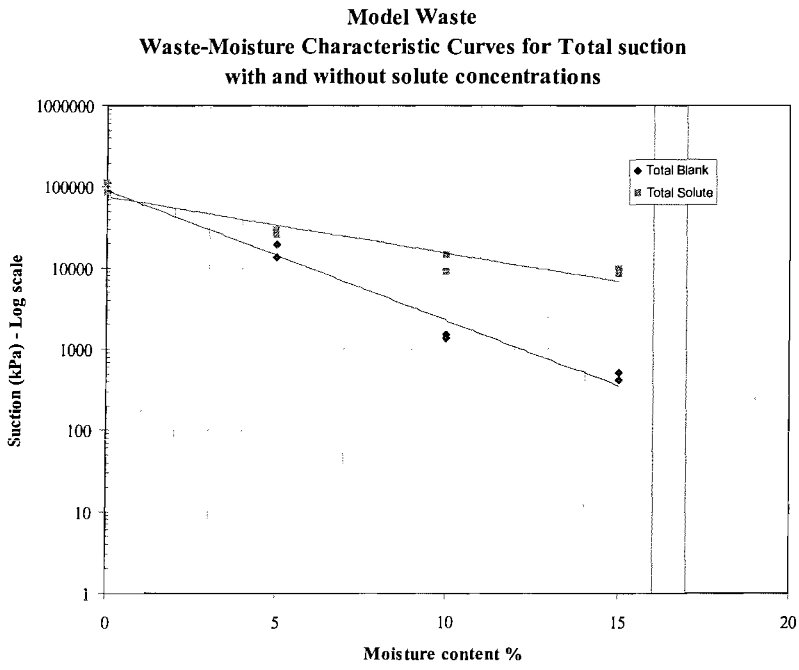


Figure 5.16a. Difference in total suction measured using 'Solute' and 'Blank' solutions – Test 1

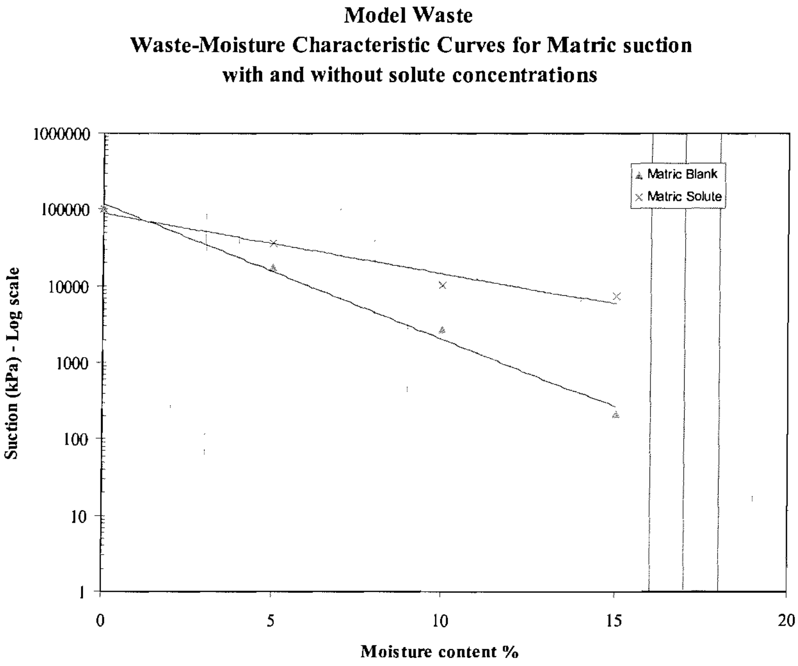


Figure 5.16b. Difference in matric suction measured using 'Solute' and 'Blank' solutions – Test 1

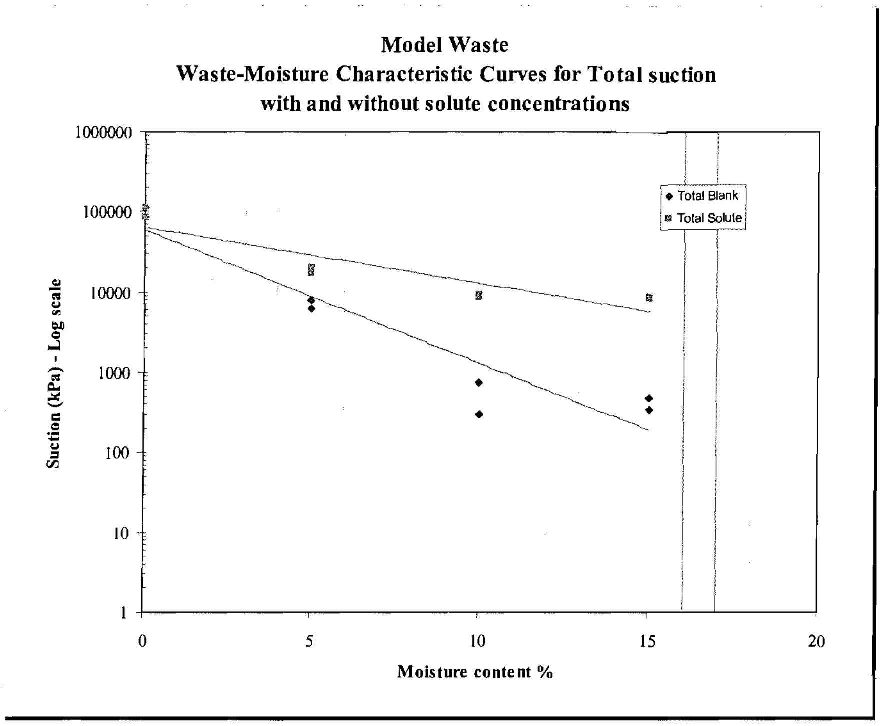


Figure 5.17a. Difference in total suction measured using 'Solute' and 'Blank' solutions – Test 2

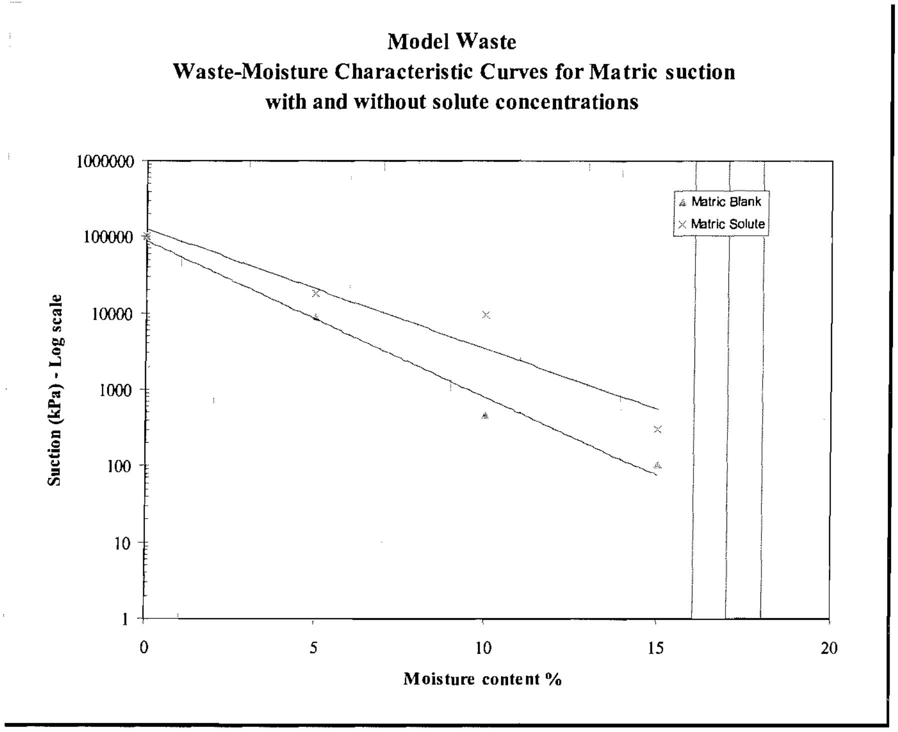


Figure 5.17b. Difference in matric suction measured using 'Solute' and 'Blank' solutions – Test 2

Chapter 6

Summary

6.1. Introduction

The results of the experiments undertaken to examine the applicability of standard soil mechanics testing methods to determine the engineering characteristics of waste are discussed. Similarly, the appropriateness and implications of using scaled waste are highlighted. Recommendations are made for the further study of waste in the context of standard soil mechanics applications and testing procedures.

6.2. Use of model waste

The method adopted to study the hydrogeological characteristics of waste was dependent upon establishing a model waste that could provide a consistent material with properties generally representative of real waste. Such a 'model' waste was therefore critical in providing a characterised landfill waste that could be used to study the application of soil mechanics principles at laboratory scale. The development of the model waste required that its composition was representative of real landfill waste. However, the degradable component was limited to ligno-cellulosic materials only (33%) to avoid changes due to degradation processes. The model waste was regarded as stable considering the time-scale of experiments in that no degradation was observed during the experimental study therefore excluding the potentially damaging effects of biodegradation on the hydrogeological characteristics of waste during the study. To summarise, the methodology adopted for the study of the hydrogeological characteristics of landfill waste at laboratory scale and the application of soil mechanics principles was based on simplification of the waste as an entity to obtain fairly representative waste samples for the experiments. The reduction of the particle size was required to make the samples compatible (in terms of dimensional similitude) with the 'test cells' used to facilitate the study at laboratory scale.

6.3. Waste characterisation

Although attempts have been made to classify and characterise waste, a systematic process or protocol for the waste *classification* and *characterisation* has not yet been standardised. However, the objective of undertaking the practice remains the same, i.e. to make the waste identifiable in terms of its composition and properties that are likely to govern its behaviour particularly in the context of its safe disposal in the environment. The terms waste *classification* and *characterisation* have been used interchangeably. However, the waste *characterisation* may be regarded as a specific term describing the behavioural characteristics of waste under certain hydrogeological conditions prevailing in landfill. The waste *classification* is however, a descriptive term defining the waste's physical make up and characteristics. Therefore for a better understanding of waste behaviour, the term *characterisation* may be used. Hence, unit weight, dry and bulk density, moisture content, hydraulic conductivity, effective stress and suction are the parameters that characterise the waste and describe its hydrogeological behaviour.

Landfill waste needs to be characterised in order to predict its geotechnical and hydrological properties and the general behaviour of refuse for the purpose of modelling. The physical make up of the waste is of much importance in understanding the long term behaviour of waste in the landfill. The compressibility of waste determines the useful volume of landfill and the biodegradability of waste identifies the conversion of mass into leachate and gas production potential. Moisture content is important for the biodegradation processes together with hydraulic conductivity, field capacity, absorptive capacity and effective porosity data, which is important in regulating the percolation of leachate and design of the landfill drainage system, etc. Unit weight and bulk density allow calculation of the overburden pressures and together with pore water pressures, the effective stresses in landfill may be estimated. Suction characteristics of waste are important in defining the in-situ stress state of waste in its partial or unsaturated state and may have a dominant role in the hydrogeological behaviour of landfill waste.

6.4. Methodology and experimental setup

The methodology was based on determining the feasibility of producing model waste that could be used to satisfy some of the known and tested principles of soil mechanics testing in comparison to real waste. In order to test real waste at laboratory scale it is required to have a representative sample in substantially low volume. The particle size range occurring in the waste and its heterogeneous nature makes it difficult to acquire fairly representative samples in succession. Hence, a model waste was introduced that could be representative of real waste in composition and would give representative samples as required. Once the compatibility of the two wastes (model and real) was established, the model waste could be successfully used for evaluating other key hydrogeological parameters. Since the research study was based on laboratory experiments, it required a 'test cell' into which the model waste samples could be placed in order to determine some of the characteristic hydrogeological relationships such as dry density-hydraulic conductivity, effective stress-hydraulic conductivity and suction-moisture characteristics with varying dry density. Three types of cells: large, medium and small scale test cells were used for establishing a relationship between hydraulic conductivity and dry density of the model waste. The use of three different sizes of test cells enabled the study of particle size effects on the hydraulic conductivity characteristics of waste. The effective stress and hydraulic conductivity relationship was studied in the large-scale test cell. For suction characteristics of model waste an independent testing scheme was developed based on the standard test method (ASTM D5298-92). On the basis of findings from the application of the standard test method for the determination of suction in soils, an in-situ method for the determination of suction in waste was developed.

6.5. Hydraulic conductivity characteristics of model waste

The hydraulic conductivity characteristics of the model waste were studied in relation to changes in dry density and effective stress. The relationship between the hydraulic conductivity and the dry density was determined together with the variation in particle size in relation to the test cell dimensions (aspect ratio). It was observed that it was the particle size rather than the aspect ratio (0.083 – 0.22) that affects the hydraulic conductivity characteristic of the model waste. The relationship between the hydraulic conductivity and the dry density of the model waste was linear for all three sizes of the permeameters on a semi-log scale. The maximum dry density value attained during the study was 750kg/m^3 in the large test cells and substantially lower density ranges were achieved in the small-scale cell (250kg/m^3). The overall range of hydraulic conductivity for the model waste observed in 3 scales of test was 3.65×10^{-6} to 6.75×10^{-3} m/s. These values are the average of hydraulic conductivity calculations obtained after successive runs on the permeameter by changing hydraulic gradient and flow rates.

Irrespective of the size of the permeameter used, the hydraulic conductivity values did not remain uniform over the entire depth of the waste column. This was due to non-uniform distribution of waste mass (differential compaction) within the permeameters occurring due to the side wall friction as the waste was compacted from one end (the top) of the permeameter (test cell). The result was that the waste was more compacted near the loading end and less compacted at the other end. Therefore, in general, lower hydraulic conductivity values were observed in sections adjacent to the compressive loading zone (upper half) compared to the values measured in the other sections (lower half) of the permeameters. The element of differential compaction was studied in the large-scale permeameter which showed that the differential compaction is relatively higher in high density waste. It suggested that although there is differential compaction the effect on the overall hydraulic conductivity is not significant. This was also verified by the hydraulic conductivity data (Appendix C). In order to overcome the effect of differential compaction, the average hydraulic conductivity values were obtained simply by measuring the hydraulic gradient across the entire depth of the waste column. It was also interesting to note that the hydraulic conductivity for a given dry density was sensitive to flow rate. The hydraulic conductivity increased with the decrease in the flow rate.

The hydraulic conductivity-dry density relationship of the model waste observed in the large-scale test was compared to earlier research (Beaven, 2000) carried out with landfill waste in a large compression cell (2m diameter). The comparison showed good correlation between the model and landfill waste hydraulic conductivity characteristics. On the basis of the correlation it was suggested that the model waste behaviour is similar to landfill waste and therefore, model waste may be used further in the determination of other hydrogeological properties together with the application of soil mechanics principles to landfill waste.

The model waste after several months of retention in a saturated state showed signs of degradation. The hydraulic conductivity of the 'degrading' waste was studied by decompressing (fluidising) the compressed waste to its original volume. The term 'degrading' was used merely to differentiate between the fresh model waste and the waste which was retained for nearly 18 months in the test cell. It was, however, suggested that no significant degradation or loss of mass occurred over the retention period and the characteristics of model waste remained unchanged. The term 'fluidising' of waste referred to the restoration of the original sample volume after being compressed to its minimum volume. The change in the hydraulic conductivity characteristic that was observed, i.e. a relative increase, was more likely due to the fluidising action which may have altered the physical structure, or reduced the tortuosity or created preferential flow paths. The test was repeated by re-fluidising the waste which gave consistent results. It is difficult to conclude whether there was any contribution due to on-set of aging of waste towards the hydraulic conductivity behaviour.

In the large-scale apparatus, the use of a slotted load platen enabled the applied load to be simulated as the effective stress. Since the pore pressure difference above and below the platen was low, it could therefore be assumed that the applied pressure would be equivalent to the effective stress provided that all the pressure is taken up within the waste matrix. However, it was difficult to estimate the effective stress due to the compressibility of the waste particles and the stress variation over the depth of the waste column in the test cell due to the effect of side wall friction. To simplify the loading condition, the applied load was regarded as an overburden pressure and the relationship between the overburden pressure and hydraulic conductivity was studied. It was observed that as the overburden pressure increased the hydraulic conductivity of the model waste decreased. It was inferred that since overburden pressure bears good correlation with dry density, its relationship to the hydraulic conductivity of waste would be similar. The effective stress, being equal to overburden pressure at the platen-waste interface, could be estimated for various depths in waste by using the equation given by Beaven (2000). The effective stress / overburden pressure relationship to the hydraulic conductivity was plotted and the decrease in the effective stress due to side wall friction with the depth of waste was also estimated. The effective stress decreased with the waste depth. It was also observed that an increase in the overburden pressure / effective stress affected the linearity of the flow rate and hydraulic gradient relationship. This may be associated with the increase in compactness of the waste and increased resistance to flow. However, the observed deviation was not significant and in general, Darcy's law was valid.

The investigation into the hydraulic conductivity behaviour of model waste indicates that model waste is a Darcian material, i.e. the direct relationship between the flow rate and the hydraulic gradient in all the three scales of tests is established.

6.6. Suction characteristics of model waste

The suction characteristic of waste, as stated earlier is an important aspect of landfill waste behaviour since most waste in a landfill exists mostly in a partially saturated state with negative stresses present which may be much higher than the positive stresses that would be present in saturated waste. Terzaghi's equation (Eq. 2.17) for saturated soil becomes invalid for materials in a partially saturated state and to a greater extent depends upon the suction characteristics which in turn relates with the degree of saturation (Eq. 2.20). The determination of suction in waste required a method which could take into consideration the waste particle size and distribution together with the heterogeneity of the material. The conventional laboratory methods, e.g. pressure plate technique and tensiometeric measurements may, therefore have encountered considerable practical limitations. The filter paper method (ASTM D5298-92) is a recognised standard method used for the determination of suction potentials of soils. It is an indirect method of suction determination that is not commonly used and is generally considered to be of limited application in geotechnical research. However, this method was successfully used to investigate the suction characteristics of waste. The method is applicable to smaller sample sizes approximately 200g, therefore it was necessary to restrict the particle size in the waste sample, hence particle size of the model waste in the initial specimens was kept less than 20mm. Either total or matric suction could be measured by the filter paper method.

Preliminary tests were carried out using the non-contact technique for the determination of total suction in model waste. Suction-moisture characteristics for the model waste were studied by developing waste-moisture characteristic curves. The van Gunechten model for determining the soil moisture characteristics was used to establish the suction-moisture relationship in the model waste. The soil-physical properties (which are the parameters of the van Gunechten equation) for the model waste were compared to the parameters obtained for a range of soil types. It was observed that the model waste parameters fall within the range observed for soils and are typical for coarser soil hence suggesting that model waste behaviour is similar to coarse soils. The saturation volumetric water content θ_s increased with the decrease in the dry density of the model waste mix while in the case of model waste samples soil parameter α decreased with the increase in dry density. These curves were found to have a relationship that varied with the dry density (500, 750 and 1000kg/m^3). Further investigations on model waste samples having low densities (300, 350 and 400kg/m^3) confirmed that the suction-moisture characteristics are influenced by the variation in the dry density. It may therefore be concluded that in general, model waste behaves like a soil in the context of the suction-moisture characteristics and proved to be a consistent material for studying waste suction behaviour.

The effect of the particle size on the suction characteristics was qualitatively assessed and identified the need for the modification in the sampling regime of the standard method. It was considered desirable to use the waste in its in-situ condition, i.e. without altering its particle size. For larger in-situ samples, the non-contact technique was not applicable because the head space above the waste sample would be large and the equilibration time required by the filter papers would be several weeks. Therefore, the contact technique which measures matric suction was used. The type of suction (matric or total) recorded by the contact technique remains dependent upon the degree of contact between the filter paper and the waste particles. The sample size was increased from 200g to 210 litres in volume holding the waste components in their original shape, form and size.

The suction and moisture profile in the waste was determined. It was possible to some extent to determine the suction-moisture characteristics while simulating the bulk densities of waste typically found in landfill. However, it was difficult to establish representative waste moisture content for a particular layer of waste under consideration. Waste material being extremely heterogeneous and possessing moisture absorbing components such as paper, cardboard, textiles, etc. that are randomly distributed in the waste mass, made the moisture estimation difficult because the samples drawn for the moisture determination process did not tend to be representative of the waste mass. To overcome this difficulty to some extent, the moisture content was measured in proximity to the emplaced filter paper. However, this practice again did not provide good approximation of the moisture content which was indicated by the moisture content absorbed by the filter papers and hence was not representative of the surrounding waste moisture.

There were certain practical issues regarding the use of filter paper for determining suction characteristics of waste. The sensitivity of the filter paper to moisture variation was found to be extremely high and therefore, slight variations in the moisture content changed the interpreted suction value substantially, particularly in the case of the non-contact technique where the transfer of moisture to filter paper depends upon the relative humidity and subsequent equilibration occurring in the limited head space above the specimen.

It was noted for the non-contact tests that samples having the same moisture content and dry density showed a significant difference in the measured suction values. This may be attributed to the sample preparation practice which in general, resulted in the accumulation of finer particles on the top of the waste sample where the filter paper was placed. The other possibility may be the non-uniform distribution of moisture in the samples particularly in the proximity to the filter paper. In either of the cases, the suction recorded was not consistent though the moisture content was the same. Due to ravelling and mixing action while preparing moist waste samples, the particle size of some of the waste components such as paper, wood and granules, etc. was reduced and since the waste was reused each time the particle size and distribution were changing successively. Also an increase in the finer fragments was observed due to repeated drying and re-use of the samples. It was therefore concluded that the method is sensitive to sample preparation.

The sensitivity of the filter paper method in the presence of dissolved salts in the moisture was also assessed. As identified by Ridley (1999), for soils the effect of a solute in the pore water may substantially affect the performance of the filter paper. Salt concentrations typically observed in leachate were used to assess the filter paper method by employing both the contact and non-contact methods for determination of suction. The total and matric suction were both affected by the presence of dissolved salts in pore fluids of waste. The total suction values were affected to a much greater extent, i.e. recorded suction measurements were higher. The possible explanation may be the decrease in the vapour pressure due to the presence of salts in the pore fluid which restricts the escape of vapours from the fluid to the filter paper during the equilibration process. Even considering the contribution of the osmotic suction due to solute concentration to the total suction value measured, the values were too far off from the expected values, indicating that the presence of dissolved salts in pore fluid, result in a substantial increase in the measured value of total suction. Matric suction was also affected but was less pronounced and tends to decrease with the lowering of salt concentrations.

Chapter 7

Conclusions and Recommendations

7.1. Conclusions

Prior to any investigation into landfill waste, its characterisation is essential. In general, the term characterisation is not specifically defined and is used interchangeably with the term classification, however it should be understood that characterisation is the term that not only encompasses the physical characteristics of the waste but also gives substantial information about the behavioural characteristics of waste which are necessary for the modelling of landfill.

The proposed methodology of using the model waste for studying the characteristic hydrogeological properties of landfill waste was a success, particularly in correlating its hydraulic conductivity characteristics to real landfill wastes. However, the preliminary determination of waste suction characteristics of model waste was limited due to particle size restriction required for the filter paper method.

The hydraulic conductivity characteristics of waste was studied using 3 different sizes of permeameters and was informative in highlighting the effect of particle size to cell permeameter ratio (aspect ratio) on the hydraulic conductivity characteristics of model waste. It demonstrated that it is not the aspect ratio but rather it is the particle size that influences the hydraulic conductivity characteristics. Hence, a reduction in the particle size decreases the hydraulic conductivity at a given dry density of waste. Overall, model waste behaved as a Darcian material, i.e. in general, the hydraulic gradient remained proportional to flow rate. However, it was observed in extreme cases of dry density and effective stress that flow rate and hydraulic gradient relationship became non-linear.

The hydraulic conductivity values (3.65×10^{-6} to 6.75×10^{-3}m/s) measured for model waste are comparable to landfill waste values reported by earlier researchers ($10^{-7} - 10^{-3}$ m/s) for a typical range of waste density existing in landfill. In general, the hydraulic conductivity decreases with an increase in the dry density and over burden pressure (effective stress).

The filter paper (non-contact) method was successful in determining suction characteristics of waste with a reduced particle size (< 20mm). For the in-situ waste suction characteristics the filter paper (contact) method was experimented and was found applicable. Due to the heterogeneous nature of waste, the determination of moisture content was particularly difficult therefore, moisture content measurement in a layer of waste where filter papers were placed could not be determined correctly. This difficulty in determining volumetric moisture content meant that the waste moisture characteristics of waste could not be determined.

In general, waste-moisture characteristic curves showed that model waste behaves similarly to coarse soil and the effect of variations in dry density affects the waste suction-moisture characteristics. The application of the van Genuchten model suggests that waste's suction-moisture characteristics can be parameterised and as such will help understand the behaviour of landfill waste that is required for predictive modelling.

The filter paper (non-contact) method is influenced by the sample preparation practice and technique. The particle size variation and their relative distribution in the specimen may cause significant variation in the measured suction values. Therefore, the alternative filter paper (contact) method is more practical and is capable of yielding more consistent results. The filter paper (contact) method is found suitable for determining in-situ waste suction characteristics however the measurement of moisture in the waste by gravimetric method is difficult, particularly in assigning a representative value to a waste layer. Therefore some alternate methods such as using a water activity probe may be more suitable. It was due to the waste heterogeneity that yielded inconsistent moisture content values that could not be correlated with the moisture values recorded by the emplaced filter papers.

The presence of salts in the pore fluid affected the measurements of suction by the filter paper method. Total suction was particularly affected by pore fluid salts leading to an overestimation of values. Matric suction was also affected in a similar manner but to a lesser extent. This effect is reduced as the pore fluid solution decreases.

7.2. Recommendations for future investigations

- Study of some of the hydrogeological characteristics of waste is further required in the proposed manner which may provide a better understanding of waste behaviour and their effect on moisture characteristics. Biodegradation and settlement characteristic of waste are aspects that need to be studied for an improved modelling of landfill waste.

- The effects of biodegradability of waste on the hydrogeological characteristics of waste need to be assessed as these are thought to considerably influence the long term behaviour of waste in landfill. Similarly, the assimilation of daily cover material needs to be assessed fully.

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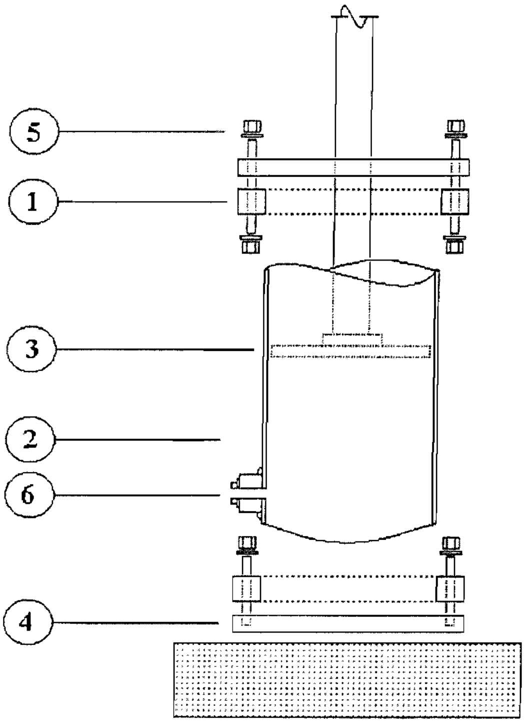
Appendix A

(Design calculations and Material properties of Test cell)

Design calculations for the laboratory scale testing cylinder (Test Cell)

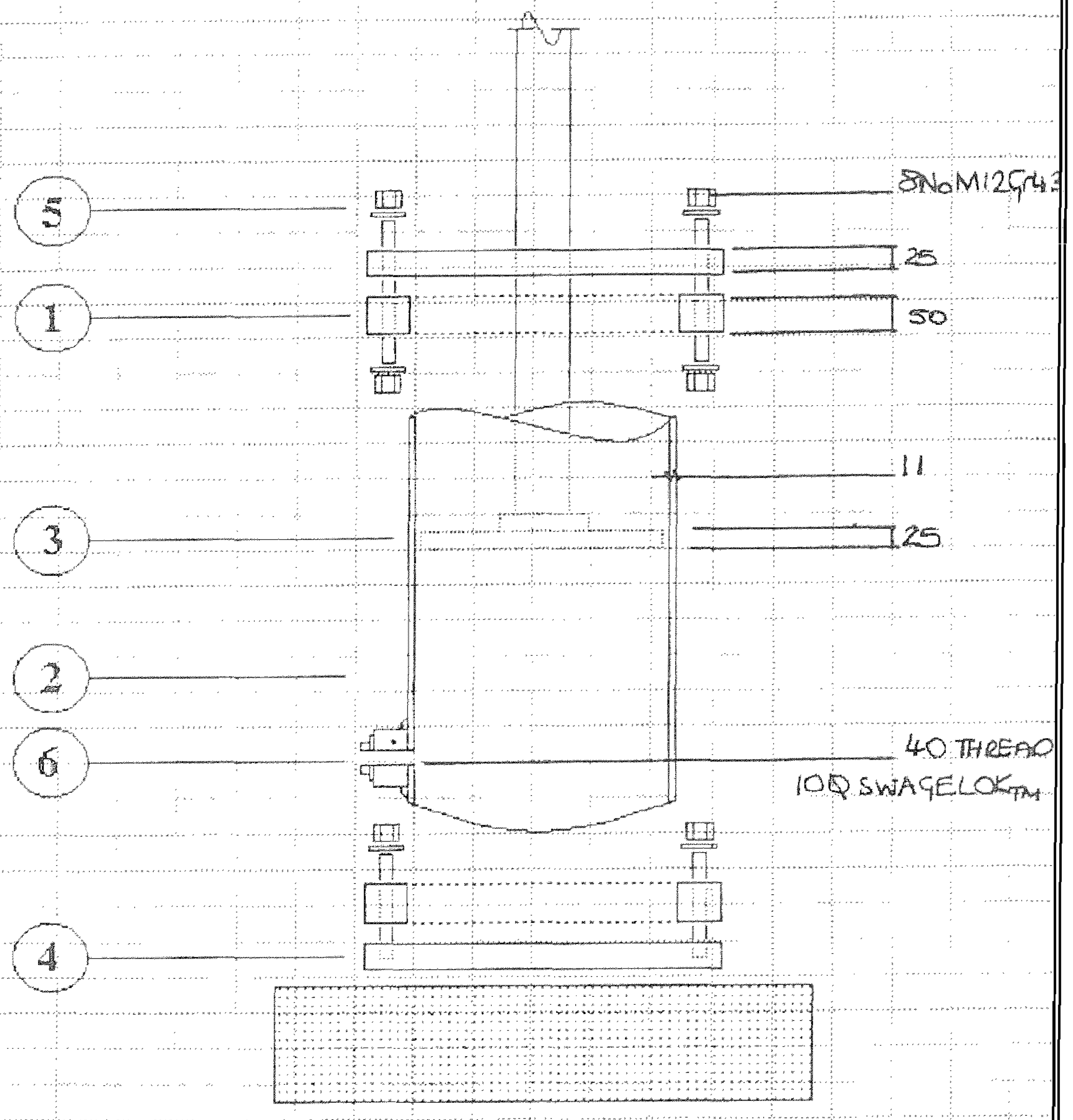
Including checks for the following components:

1. Flange
2. Cylinder
3. Platen
4. Lids
5. Connections
6. Ports and Hose Fittings



General Arrangement

SUMMARY of DESIGN CALCULATIONS

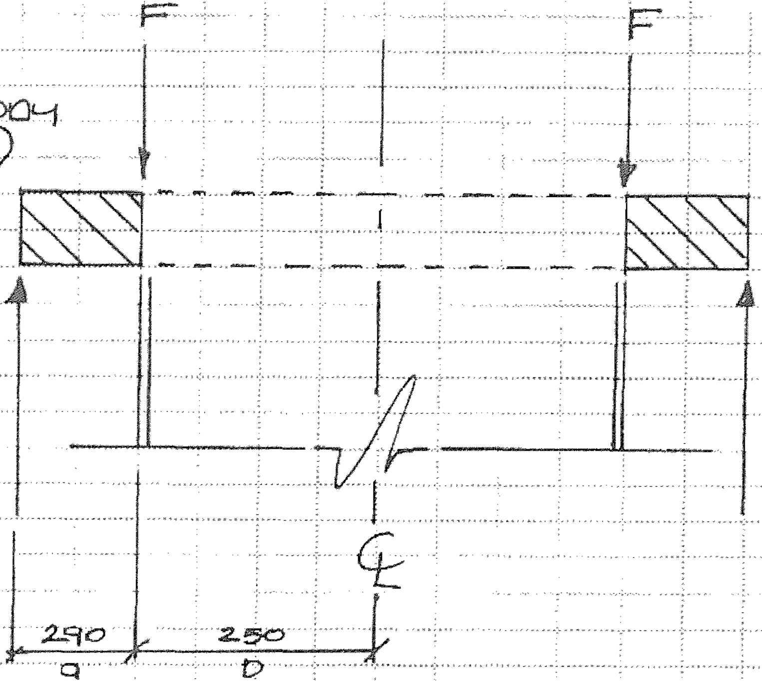


1. FLANGES

MAX DESIGN STRESS $(\sigma_{DESIGN}) = 7\times10^{6}\,Nm^{-2}$

LOADING CASE I (SEE NOTES).

F.B.D.
(FREE BODY
DIAG.)



ASSUME POISSONS RATIO $\nu = 0.30$ ACTUAL ν(PERSPEX) $= 0.36$ (SEE NOTES)

PRESSURE = 300kPa

$$P = \frac{F}{A} \qquad 300 = \frac{F}{\left(\frac{0.5}{2}\right)^{2}\pi} = \frac{F}{0.2}$$

$F = 300\times10^{3}\times 0.2$
$= 60kN$

F.o.S = 1·5

F = 90kN

1. FLANGES

A TOTAL OF EIGHT BOLTS, EACH BOLT TRANSMITS FORCE F_B

$F = 90 kN$

$F_B = \frac{90}{8} = 11.25 kN$

$\frac{a}{b} = 1.16$ SO FOR 'CASE I' $C' = 0.341$

$C'' = 1.10$

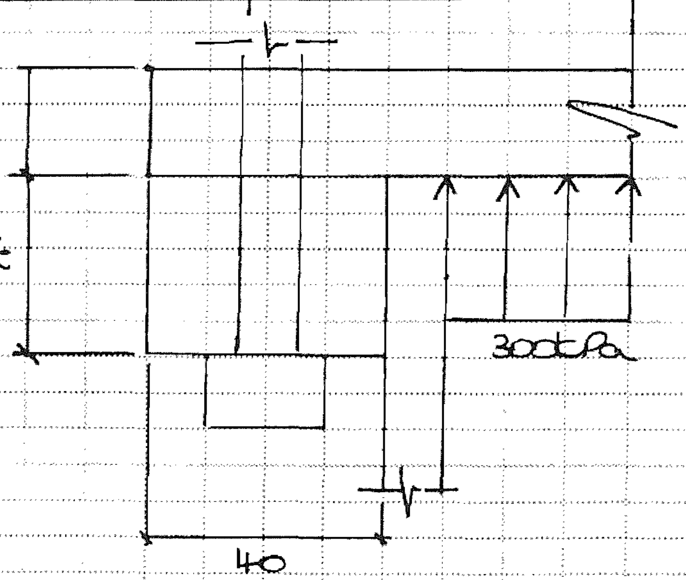
$\sigma_{MAX} = \frac{C'' F}{h^2}$

$h = \sqrt{\left(\frac{1.10 \times 11.25 \times 10^3}{7 \times 10^6}\right)}$

$= 0.042 m$

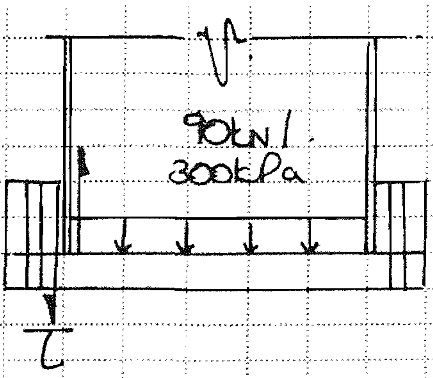
$= 42 mm$

SHEAR CAPACITY CHECK



DESIGN FOR BASE FLANGE = 300kPa.

1. FLANGE



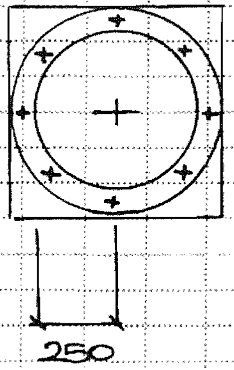
TOTAL AXIAL FORCE = 90kN

FORCE / METRE RUN OF PERIPHERY $= \frac{F}{D}$.

$D = \pi d$.

$= 3.142 \times 0.5$

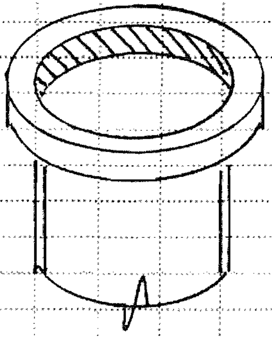
$= 1.571$



$F_m = \frac{F}{D} = \frac{90\times10^3}{1.571}$

$= 57.29\,\text{kNm}^{-1}$.

SHEAR DESIGN STRENGTH (APPROX) $= 5\times10^6\,\text{Nm}^{-2}$. G/A



$P = \frac{F}{A}$

$5\times10^6 = \frac{F}{A} = \frac{F}{tD} = \frac{57.29\times10^3}{t}$

$t = \frac{57.29\times10^3}{5\times10^6}$

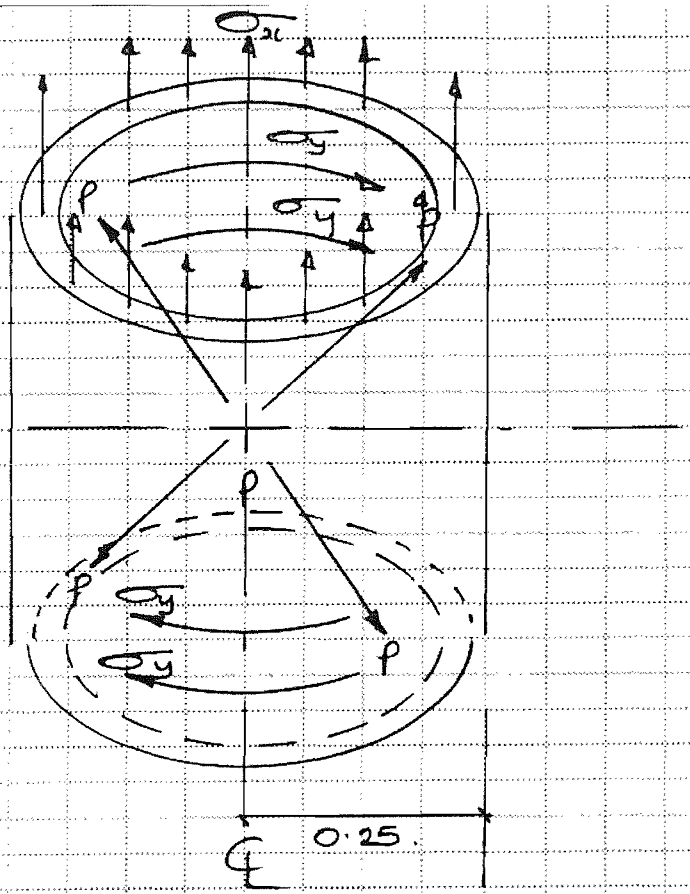
$= 0.0115\text{m}$

$= 11\text{mm}$

USE 2" PERSPEX SHEET FOR FLANGES (50mm) BECAUSE OF 42mm REQD FROM STRESS CHECK.

2. CYLINDER

F.B.D.



INTERNAL PRESSURE (P) = 300kPa

AXIAL STRESS $= \frac{pr}{2t} = \sigma_x$

HOOP STRESS $= \frac{pr}{t} = \sigma_y$

SINCE HOOP STRESS $\sigma_y = 2\sigma_x$ DESIGN TO σ_y ONLY

MAX PERMISSIBLE HOOP STRESS $\sigma_y = \sigma_{DESIGN}$

$= 7\times10^6\ \mathrm{Nm^{-2}}$

$\sigma_y = \frac{pr}{t}$

(SEE NOTES)

$t = \frac{pr}{\sigma_y} = \frac{75000}{7\times10^6}$

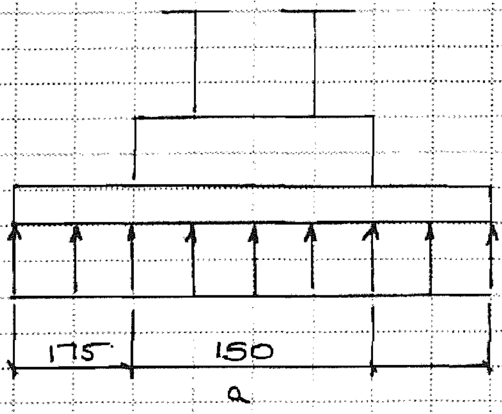
$\underline{t = 11\mathrm{mm}}$ thickness reqd for P= 300kPa

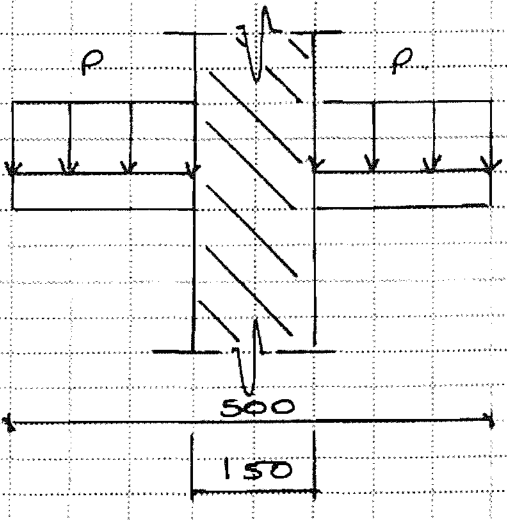
3. PLATEN

$\sigma_{DESIGN} = 275\ Nmm^{-2}$
$= 275 \times 10^6\ Nm^{-2}$ for Gr 43 Steel

LOADING G|A

CASE 7 (SEE NOTES)





$\frac{a}{b} = \frac{250}{75} = 3\frac{1}{3}.$

FROM DESIGN CHART (SEE NOTES)

$C' = 0 \cdot 37$
$C'' = 2 \cdot 40$

$p = 90\ kN / \frac{1}{2} m\ run$
$= 180\ kNm^{-1}$

$\sigma_{MAX} = \frac{C'' p a^2}{h^2}$

$h = \sqrt{\left(\frac{2 \cdot 4 \times 180 \times 10^3 \times 0 \cdot 25^2}{275 \times 10^6}\right)}$

$h = 0 \cdot 01m$
$= 10mm$

Use 1" (25mm) STEEL PLATE.

3. PLATEN

DEFLECTION

$$\delta_{max} = \frac{C'pa^4}{Eh^3}$$

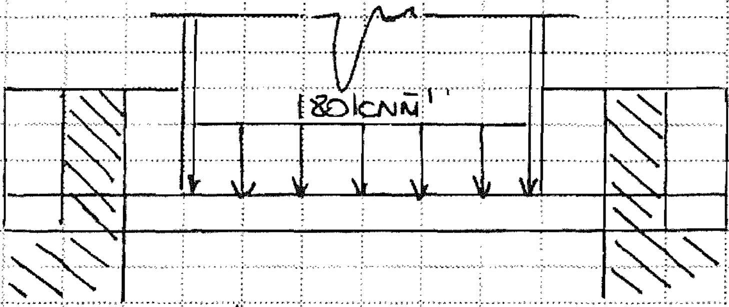
$$= \frac{0{\cdot}37 \times 180 \times 10^3 \times 0{\cdot}25^4}{205 \times 10^9 \times 0{\cdot}025^3}$$

$$= 8 \times 10^{-5} m$$

$$= 0{\cdot}08 mm.$$

4 LIDS.

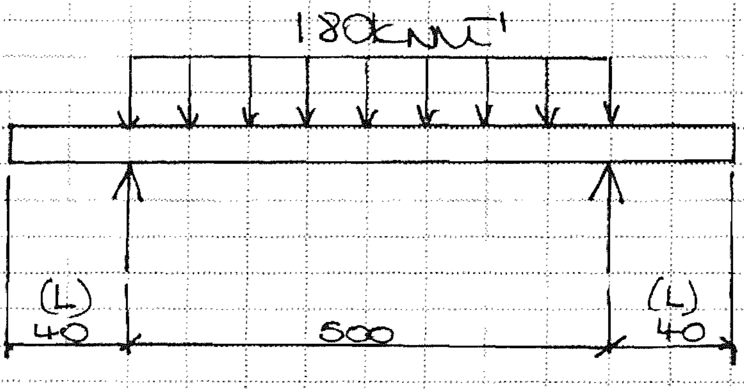
STEEL LIDS $\sigma_{max} = 275 \times 10^6 Nm^{-2}$ Gr43 STEEL



PRESSURE = 300kPa
= 180kNm.

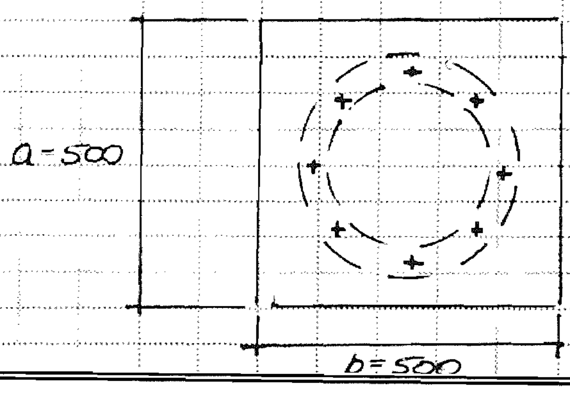
ADOPT A WORST CASE SCENARIO of SIMPLY SUPPORTED BEAM WITH UDL. S.S. AT VERTICALLY OPPOSITE CYLINER BOUNDARY.

F.B.D.



LENGTH (L) BEYOND SUPPORTS NOT AFFECTED.

G/A.



4 LIDS

USING DATA SHEET & DESIGN CHART (SEE NOTES)

$\sigma_{MAX} = \sigma_{DESIGN} = 275 \times 10^{6} \, Nm^{-2}$

$\sigma_{MAX} = \frac{\beta w b^{2}}{t^{2}}$ @ CENTRE.

$\frac{a}{b} = 1. \quad \beta = 0 \cdot 2874$

$\sigma_{MAX} = 275 \times 10^{6} = \frac{0 \cdot 2874 \times 180 \times 10^{3} \times 0 \cdot 5^{2}}{t^{2}}$

$t = \sqrt{\left(\frac{0 \cdot 2874 \times 180 \times 10^{3} \times 0 \cdot 5^{2}}{275 \times 10^{6}} \right)}$.

$t = 7 \times 10^{-3}$.

$t = 7mm$.

USE 1" (25mm) STEEL PLATE.

DEFLECTION CHECK.

$\delta_{MAX} = \frac{\alpha w b^{2}}{E t^{2}}$ @ CENTRE $\quad \frac{a}{b} = 1 \quad \alpha = 0 \cdot 0444$

$\delta_{MAX} = \frac{0 \cdot 0444 \times 180 \times 10^{3} \times 0 \cdot 5^{2}}{205 \times 10^{9} \times 0 \cdot 025^{2}}$

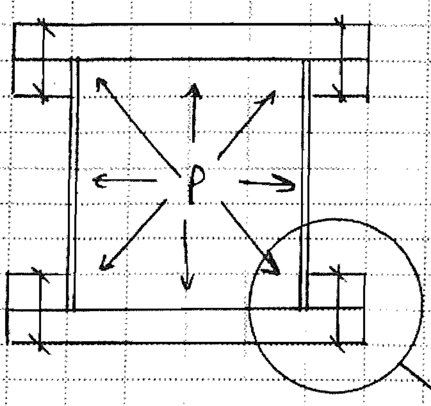
$= 1 \cdot 56 \times 10^{-5} m$

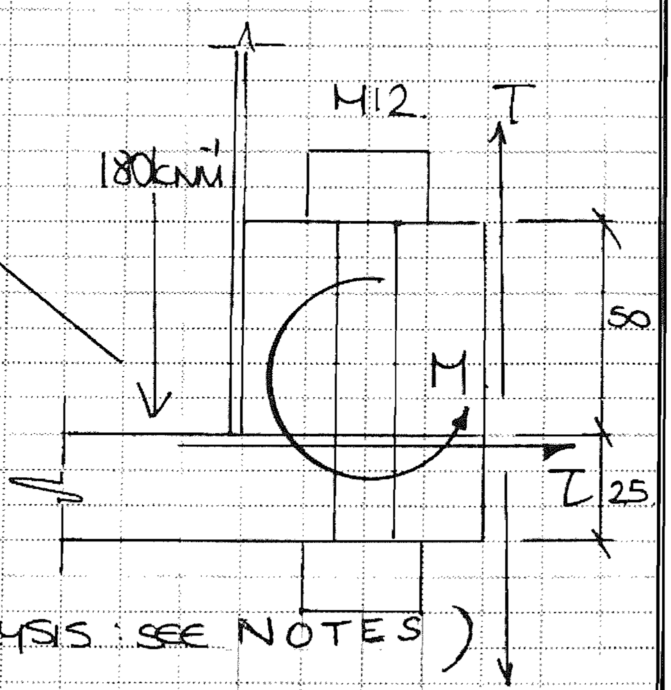
$= 0 \cdot 02mm$.

5. CONNECTIONS

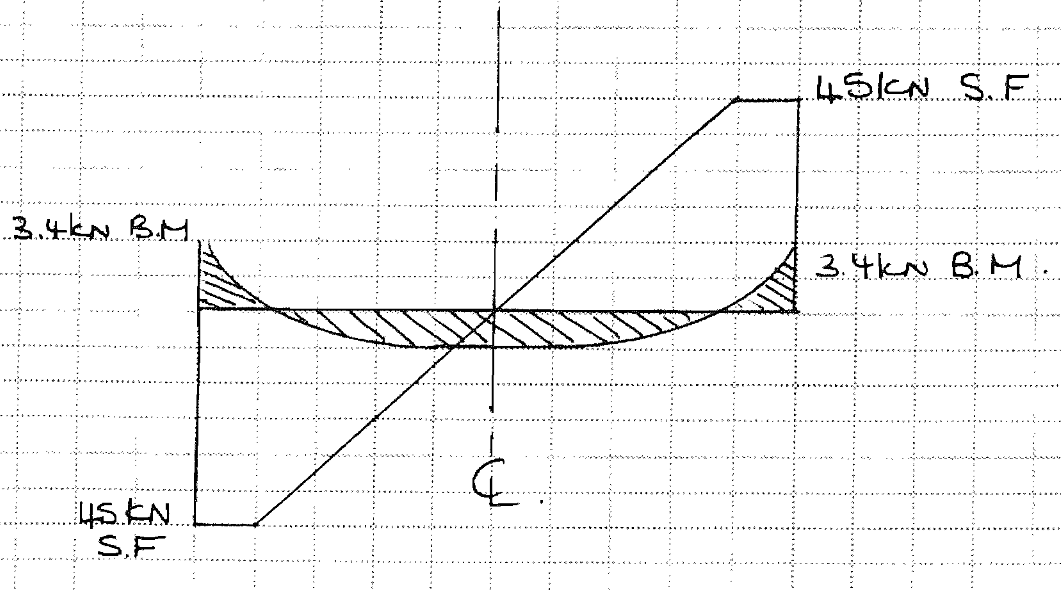
P=300kPa

PROPOSE 8No M12 Gr4.4. bolts





LOADING (USE ANALYSIS: SEE NOTES)



5 CONNECTIONS.

M12 BOLT CAPACITIES.

SHEAR $P_s = p_s A_s$ $A_s = 84.3\text{mm}^2$

$= 160 \times 10^6 \times 84.3 \times 10^{-6}$ (BS 4190 / BS 3692)

$= 13.488$ kN | bolt

BEARING $P_b = p_{bb} dt$

$P_b = 460 \times 10^6 \times 10 \times 10^{-3} \times 75 \times 10^{-3}$.

$P_b = 144$kN | bolt

TENSION $P_t = p_t A_s$

$= 195 \times 10^6 \times 84.3 \times 10^{-6}$

$= 16.43$ kN | bolt

TENSION

$F = 90$kN

$F_b = \frac{90\text{kN}}{8} = 11.25$ kN | bolt < 16.43 ∴ OK.

SHEAR.

$P_{CRIT} = \frac{45}{8} = 5.625$kN/bolt < 13.488 kN/bolt ∴ OK

BEARING

NOT CRITICAL SINCE P_b SO LARGE (DUE TO THICKNESS (t) OF LID & FLANGE.

5. CONNECTIONS.

a.

COMBINED TENSION & SHEAR CHECK 23.5.5

$$\frac{F_s}{P_s} + \frac{F_t}{P_t} \le 1.4$$

$$\frac{(45/8)}{13.49} + \frac{(90/8)}{16.43} \le 1.4$$

$$0.42 + 0.68 \le 1.4$$

$$1.01 \le 1.4 \quad \therefore \ \underline{\text{OK}}$$

6. PORTS & BOSSES.

CHECK FOR BLOW OUT OF 'SWAGELOK'TM PORTS.

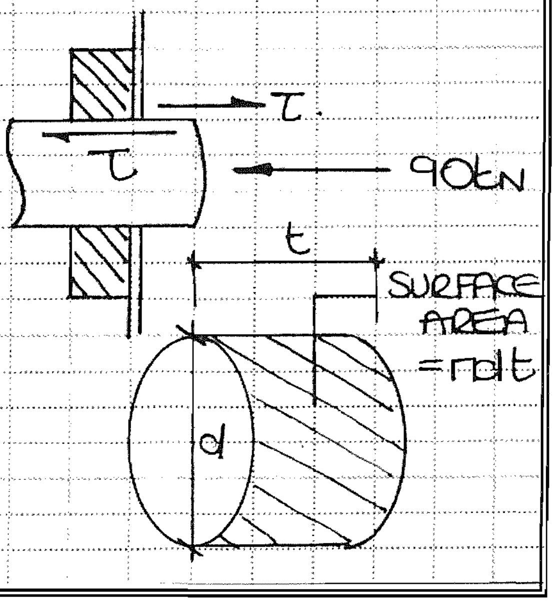
BRASS CONSTRUCTION $\sigma_{DESIGN} = 76 \times 10^6 \, Nm^{-2}$

$$\sigma = \frac{F}{A}$$

$$\sigma_{DESIGN} = \frac{F}{\pi d t}$$

$$76 \times 10^6 = \frac{90 \times 10^3}{\pi 10 \times 10^{-3} \times t}$$

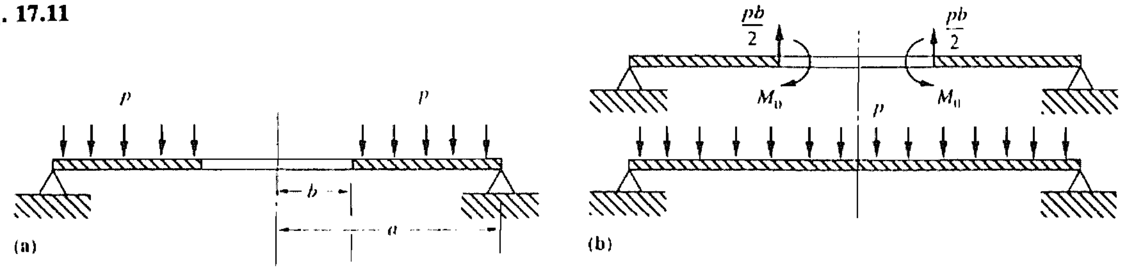
$\underline{t = 38mm \text{ MIN REQD}}$



DISTRIBUTED LOADING ON PLATE WITH CENTRAL HOLE

The situation illustrated in Fig. 17.11(*a*) can be simulated by taking the deflection of the solid plate subjected to uniform loading and superposing that due to the appropriate moment and shear force at radius b, as in Fig. 17.11(*b*).

Fig. 17.11

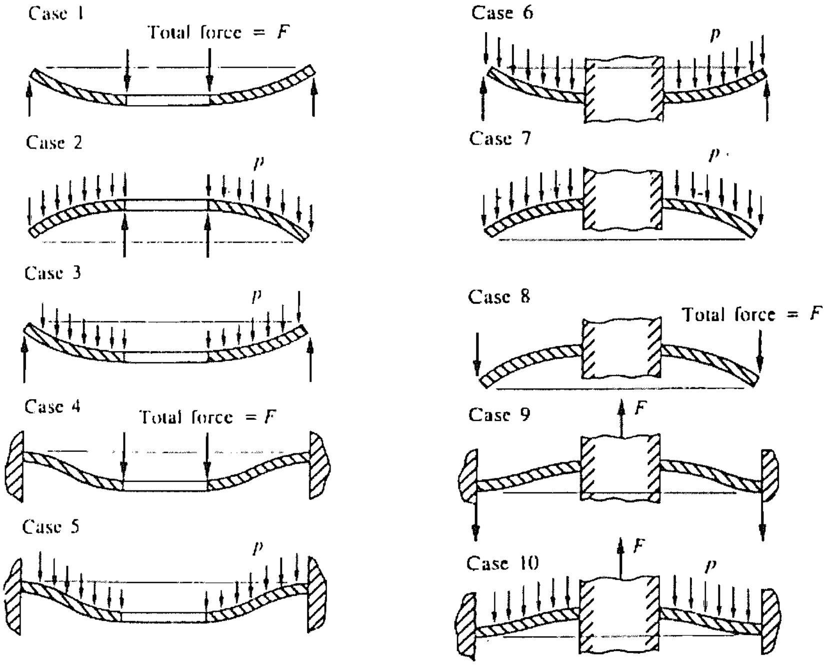


FIXED INNER BOUNDARY

This edge condition can be associated with several types of loading and merely entails applying the appropriate moment to give zero slope and shear force as a function of the applied loading.

A variety of configurations and loadings are illustrated in Fig. 17.12, all

Fig. 17.12



of which can be dealt with easily by superposition of the required components which give the appropriate boundary conditions. However, in all these cases the maximum deflection can be represented by the following relations:

$$w_{max} = c'\frac{pa^4}{Eh^3} \quad \text{or} \quad w_{max} = c'\frac{Fa^2}{Eh^3}$$

where c' is a factor involving the ratio a/b and Poisson's ratio.

The maximum stresses can also be expressed by formulae as follows:

$$\sigma_{max} = c''\frac{pa^2}{h^2} \quad \text{or} \quad \sigma_{max} = \frac{c''F}{h^2}$$

where c'' is also a factor as defined above. Values of c' and c'' for $\nu = 0.3$ and a/b in the range $1\frac{1}{4}$ to 5 for the cases in Fig. 17.12 are given in Table 17.1.

Table 17.1
Coefficients c' and c" for the plate cases shown in Fig. 17.12

a/b =	1.25		1.5		2		3		4		5	
Case	c''	c'	c''	c'	c''	c'	c''	c'	c''	c'	c''	c'
1	1.10	0.341	1.26	0.519	1.48	0.672	1.88	0.734	2.17	0.724	2.34	0.704
2	0.66	0.202	1.19	0.491	2.04	0.902	3.34	1.220	4.30	1.300	5.10	1.310
3	0.592	0.184	0.976	0.414	1.440	0.664	1.880	0.824	2.08	0.830	2.19	0.813
4	0.194	0.00504	0.320	0.0242	0.454	0.0810	0.673	0.172	1.021	0.217	1.305	0.238
5	0.105	0.00199	0.259	0.0139	0.480	0.0575	0.657	0.130	0.710	0.162	0.730	0.175
6	0.122	0.00343	0.336	0.0313	0.74	0.1250	1.21	0.291	1.45	0.417	1.59	0.492
7	0.135	0.00231	0.410	0.0183	1.04	0.0938	2.15	0.293	2.99	0.448	3.69	0.564
8	0.227	0.00510	0.428	0.0249	0.753	0.0877	1.205	0.209	1.514	0.293	1.745	0.350
9	0.115	0.00129	0.220	0.0064	0.405	0.0237	0.703	0.062	0.933	0.092	1.13	0.114
10	0.090	0.00077	0.273	0.0062	0.71	0.0329	1.54	0.110	2.23	0.179	2.80	0.234

Coefficients For The Determination of Maximum Stresses and Bending in a Circular Plate

Thursday 24th July 1997

LOAD CASE 7 : Centrally Supported with UDL

Ratio a/b	c'	c"
1.25	0.135	0.00231
1.5	0.41	0.0183
2	1.04	0.0938
3	2.15	0.293
4	2.99	0.448
5	3.69	0.564

PLATE GEOMETRY
Radius (a) = 0.25 m
Support Boundary = 0.075 m
Thickness = 0.2 m

LOAD = 1.20E+05 Nm

a/b ratio = 250 / 75 = 3.3333

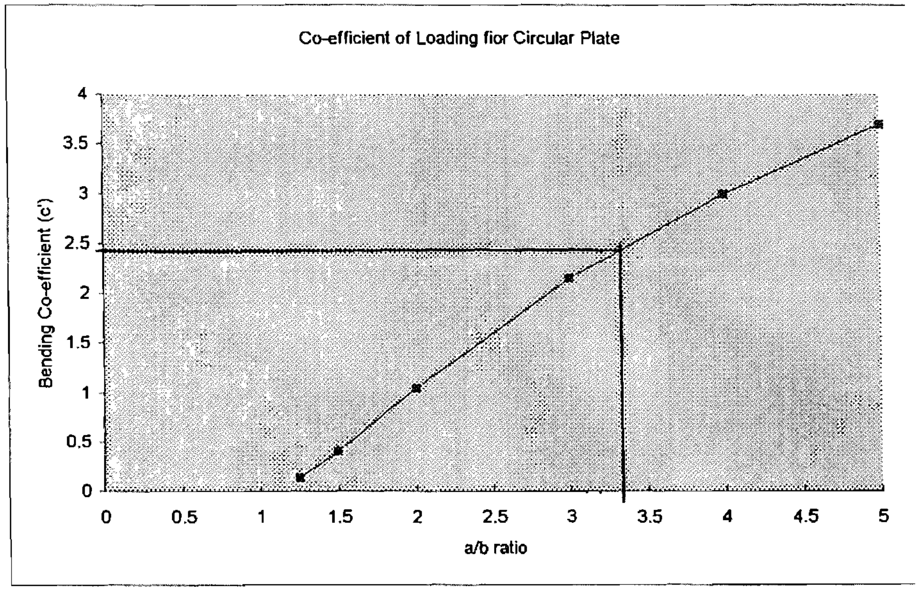
At a/b ratio value 3.33333 coefficient values are :

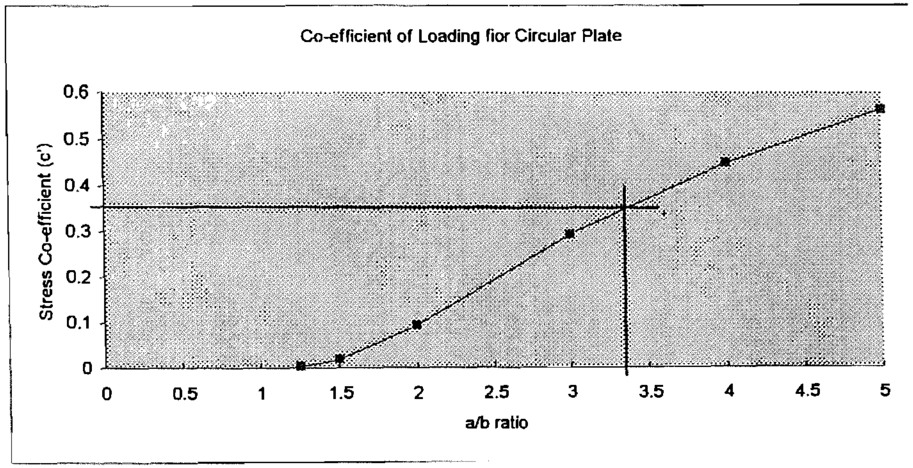
Bending (c') = **0.37**

Stress (c") = **2.4**

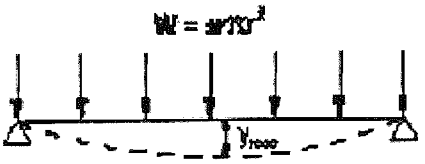
Max Def nt = **0.0001058** m

Max Stress = 45 MPa





Circular Disk, Edge Supported, Uniform Load



$w =$ load/unit area

$$m = \frac{1}{v}$$

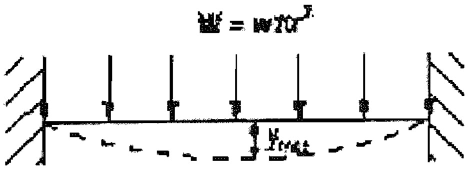
$$y_{max} = \frac{-3W(m-1)(5m+1)r^2}{16\pi E m^2 t^3} \text{ @ center}$$

$$\sigma_{max} = \frac{-3W(3m+1)}{8\pi m t^2} \text{ @ center}$$

Figure III-30.

Circular Disk, Fully Fixed, Uniform Load

$w =$ load/unit area



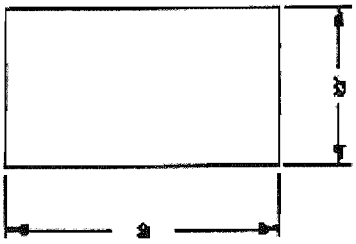
$$y_{max} = \frac{-3W(m^2-1)r^2}{16\pi E m^2 t^3} \text{ @ center}$$

$$\sigma_{max} = \frac{3W}{4\pi t^2} \text{ @ edge}$$

$$m = \frac{1}{v}$$

Figure III-31.

Rectangular Plate, Uniform Load, Simply Supported



$$y_{max} = \frac{\alpha w b^4}{E t^3} \text{ @ center}$$

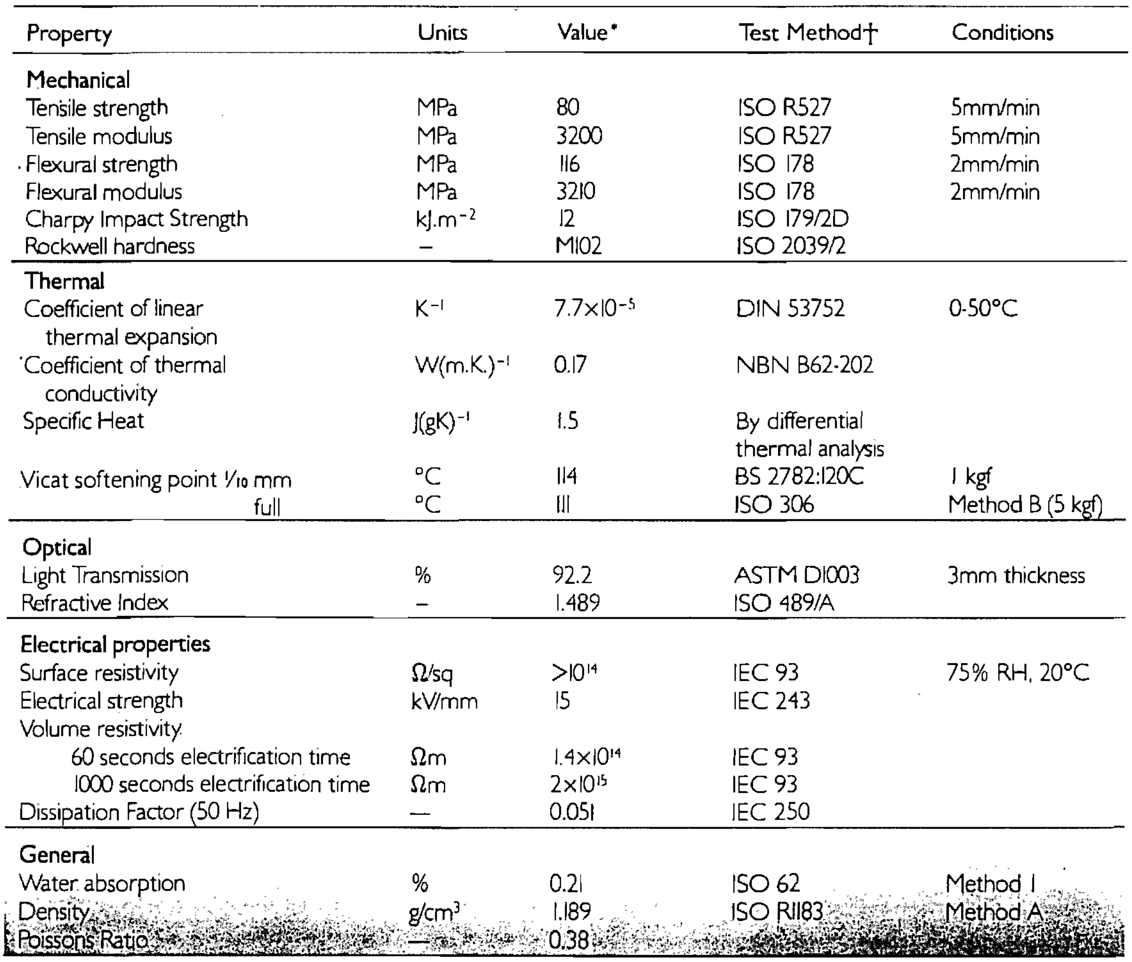
$$\sigma_{max} = \frac{\beta w b^2}{t^2} \text{ @ center}$$

a/b	1	1.2	1.4	1.6	1.8
β	0.2874	0.3762	0.4530	0.5172	0.5688
α	0.0444	0.0616	0.0770	0.0906	0.1017

a/b	2	3	4	5	∞
β	0.6102	0.7134	0.7410	0.7476	0.750
α	0.1110	0.1335	0.1400	0.1417	0.1421

Figure III-32.

Table 1. Typical Physical properties of 'Perspex' cast acrylic sheet

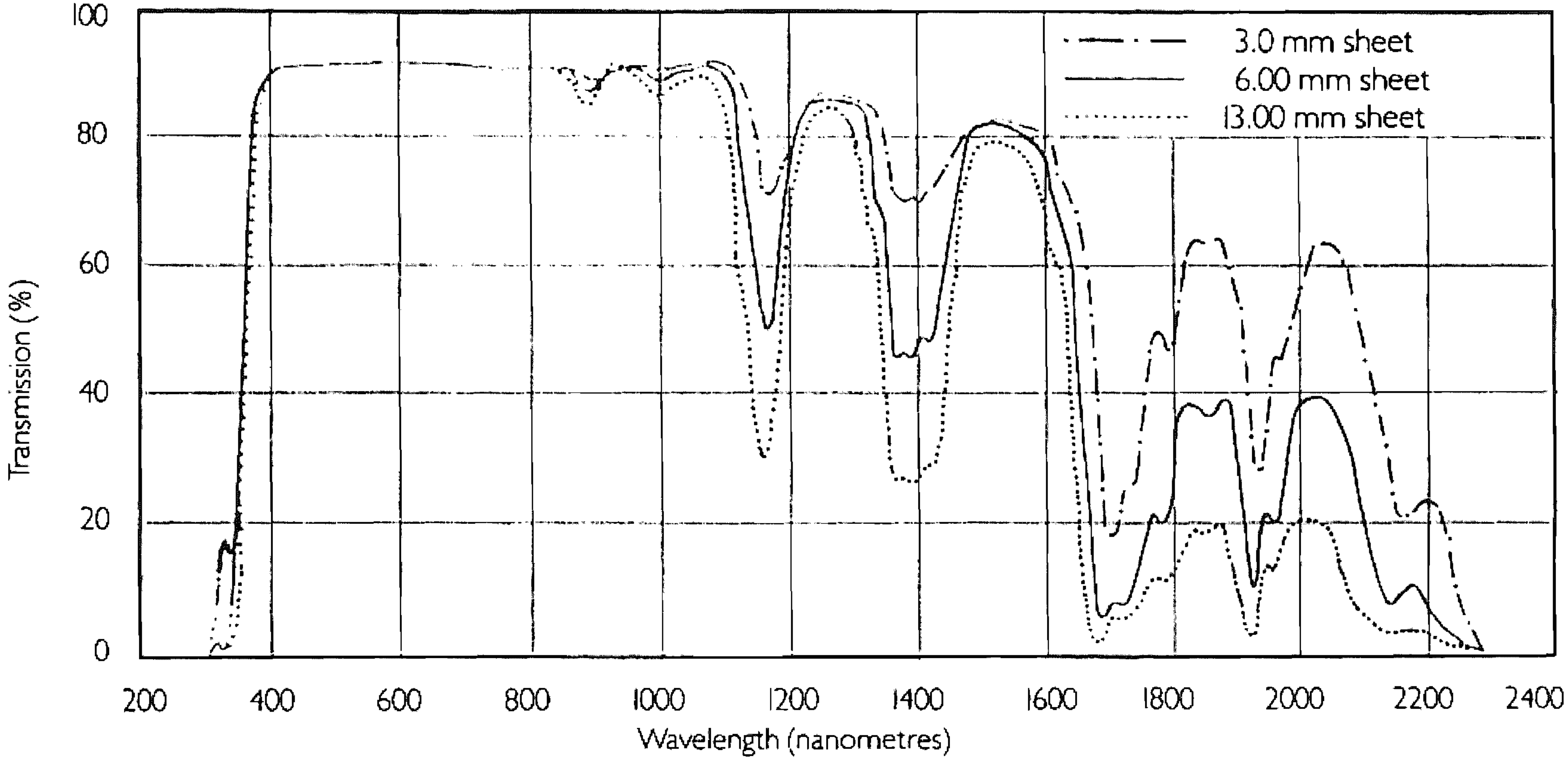


Property	Units	Value*	Test Method†	Conditions
Mechanical				
Tensile strength	MPa	80	ISO R527	5mm/min
Tensile modulus	MPa	3200	ISO R527	5mm/min
Flexural strength	MPa	116	ISO 178	2mm/min
Flexural modulus	MPa	3210	ISO 178	2mm/min
Charpy Impact Strength	$kJ.m^{-2}$	12	ISO 179/2D	
Rockwell hardness	–	M102	ISO 2039/2	
Thermal				
Coefficient of linear thermal expansion	K^{-1}	7.7×10^{-5}	DIN 53752	0-50°C
Coefficient of thermal conductivity	$W(m.K.)^{-1}$	0.17	NBN B62-202	
Specific Heat	$J(gK)^{-1}$	1.5	By differential thermal analysis	
Vicat softening point $^{1}/_{10}$ mm	°C	114	BS 2782:120C	1 kgf
full	°C	111	ISO 306	Method B (5 kgf)
Optical				
Light Transmission	%	92.2	ASTM D1003	3mm thickness
Refractive Index	–	1.489	ISO 489/A	
Electrical properties				
Surface resistivity	Ω/sq	$>10^{14}$	IEC 93	75% RH, 20°C
Electrical strength	kV/mm	15	IEC 243	
Volume resistivity				
60 seconds electrification time	Ωm	1.4×10^{14}	IEC 93	
1000 seconds electrification time	Ωm	2×10^{15}	IEC 93	
Dissipation Factor (50 Hz)	—	0.051	IEC 250	
General				
Water absorption	%	0.21	ISO 62	Method 1
Density	g/cm^3	1.189	ISO R1183	Method A
Poissons Ratio	—	0.38		

† Except where otherwise stated, tests were conducted in an atmosphere to ISO 291 (23 ± 2°C, 50 ± 5% RH)

*These are typical results obtained from representative samples of 'Perspex' 000 and do not constitute a specification.

Figure 1. Typical spectral transmission of 'Perspex' Clear 000



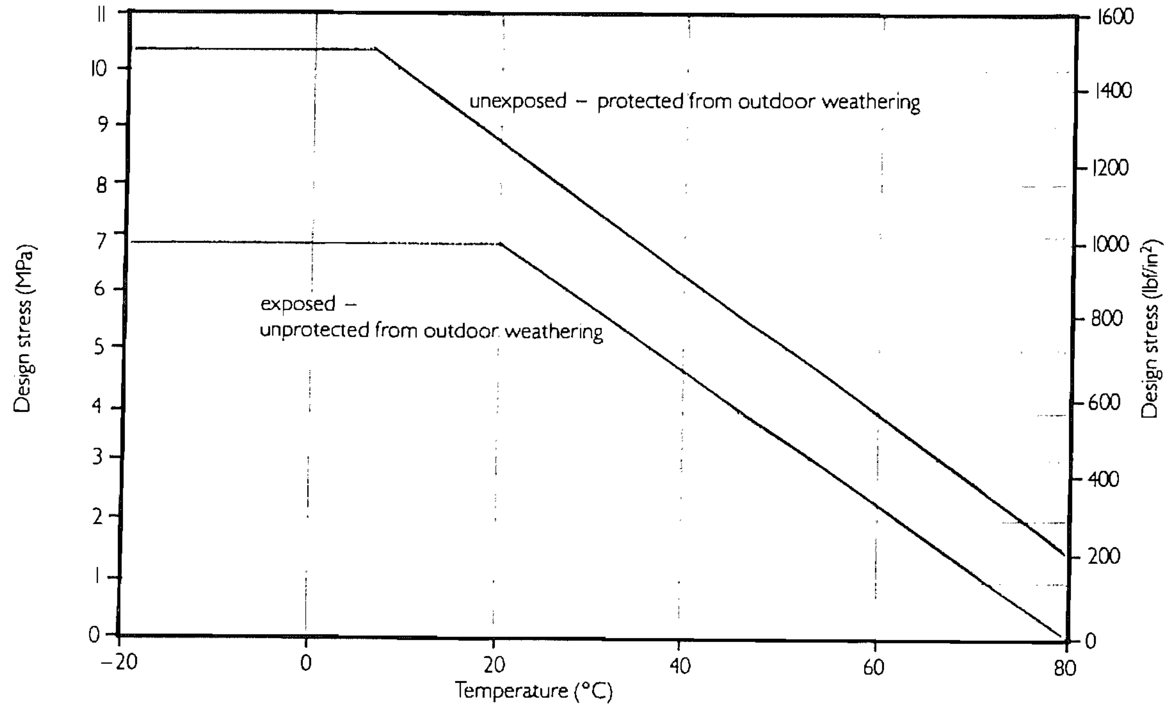
Mechanical Properties and Engineering Design Data

The mechanical properties of *Perspex* necessary for engineering design depend on the temperature at which they are measured and rate at which the *Perspex* is stressed or strained. The relevant properties are given in **Table 1** and **2** and **Figure 2**.

Table 2. *Perspex* design data at 20°C

Property	Units	Short-term design (6 hours)	Long-term design (10 years)
Tensile strength (unexposed)	kgf/cm^2	170	88
	MPa	17	8.6
	Lbf/in^2	2500	1250
Tensile strength (exposed)	kgf/cm^2	140	70
	MPa	14	7
	Lbf/in^2	2000	1000
Modulus	Kgf/cm^2	2.5x10^4	1.25x10^4
	GPa	2.5	1.25
	Lbf/in^2	3.6x10^5	1.8x10^5
Poisson's ratio		0.38	0.40

Figure 2. Design stress for 'Perspex' as a function of temperature



Appendix B

(Standard Test Methods)

Designation: D 5298 – 92

Standard Test Method for Measurement of Soil Potential (Suction) Using Filter Paper[1]

This standard is issued under the fixed designation D 5298; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the use of laboratory filter papers as passive sensors to evaluate the soil matric (matrix) and total potential (suction), a measure of the free energy of the pore-water or tension stress exerted on the pore-water by the soil matrix (1, 2).[2] The term potential or suction is descriptive of the energy status of soil water.

1.2 This test method controls the variables for measurement of the water content of filter paper that is in direct contact with soil or in equilibrium with the partial pressure of water vapor in the air of an airtight container enclosing a soil specimen. The partial pressure of water vapor in the air is assumed to be in equilibrium with the vapor pressure of pore-water in the soil specimen.

1.3 This test method provides a procedure for calibrating different types of filter paper for use in evaluating soil matric and total potential.

1.4 The values stated in SI units are to be regarded as the standard. The inch-pound units given in parentheses are approximate and for information only.

1.5 *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 114 Test Methods for Chemical Analysis of Hydraulic Cement[3]

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[4]

D 1125 Test Method for Electrical Conductivity and Resistivity of Water[5]

D 2216 Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock[4]

D 2325 Test Method for Capillary-Moisture Relationships for Coarse and Medium-Textured Soils by Porous-Plate Apparatus[4]

D 3152 Test Method for Capillary-Moisture Relationships for Fine-Textured Soils by Pressure-Membrane Apparatus[4]

D 4542 Test Method for Pore-Water Extraction and Determination of the Solute Salt Content of Soils by Refractometer[4]

D 4753 Specification for Evaluating, Selecting, and Specifying Balances and Scales for Use in Soil and Rock Testing[4]

E 337 Test Method for Measuring Humidity With a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)[6]

E 832 Specification for Laboratory Filter Papers[6]

3. Terminology

3.1 *Definitions:*

3.1.1 Refer to Terminology D 653 for definitions of terms applicable to this test method.

3.2 *Descriptions of Terms Specific to This Standard:*

3.2.1 *atmosphere*—a unit of pressure equal to 76 cm mercury or 101 kPa at 0°C.

3.2.2 *matric (matrix) suction, hm (kPa)*—the negative pressure (expressed as a positive value), relative to ambient atmospheric pressure on the soil water, to which a solution identical in composition with the soil water must be subjected in order to be in equilibrium through a porous permeable wall with the soil water; pressure equivalent to that measured by Test Methods D 2325 and D 3152. Matric suction is also the decrease in relative humidity due to the difference in air and water pressure across the water surface; the relative humidity or water vapor pressure decreases as the radius of curvature of the water surface decreases. The term "matric" is grammatically correct, while matrix is commonly used in the civil engineering literature.

3.2.3 *molality, moles/1000 g*—number of moles of solute per 1000 g of solvent.

3.2.4 *mole, n*—molecular weight of a substance in grams.

3.2.5 *osmotic (solute) suction, hs (kPa)*—the negative pressure to which a pool of pure water must be subjected in order to be in equilibrium through a semipermeable membrane with a pool containing a solution identical in composition with the soil water; decrease in relative humidity due to the presence of dissolved salts in pore-water.

3.2.6 *pF*—a unit of negative pressure expressed as the logarithm to the base 10 of the height in centimeters that a column of water will rise by capillary action or negative gage pressure (Mg/m^2) divided by the unit weight of water (Mg/m^3) times 1000. pF $\approx$ 3 + logarithm to the base 10 of the negative pressure in atmospheres. Refer to capillary head or capillary rise in Terminology D 653.

3.2.7 *soil relative humidity, R_h*—the ratio of the vapor

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[1] This test method is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.04 on Hydrologic Properties of Soil and Rocks.

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[2] The boldface numbers given in parentheses refer to a list of references at the end of the text.

[3] *Annual Book of ASTM Standards*, Vol 04.01.

[4] *Annual Book of ASTM Standards*, Vol 04.08

[5] *Annual Book of ASTM Standards*, Vol 11.01.

[6] *Annual Book of ASTM Standards*, Vol 15.09.

pressure of pore water in the soil to the vapor pressure of free pure water. Relative humidity in the soil is defined as relative humidity measured by Test Method E 337.

3.2.8 *total potential (kPa)*—the sum of gravitational, pressure, osmotic, and external gas potentials. Potential may be identified with suction when gravitational and external gas potentials are neglected.

3.2.9 *total soil suction, h (kPa)*—the negative pressure, relative to the external gas pressure on the soil water, to which a pool of pure water must be subjected to be in equilibrium with the soil water through a semipermeable membrane that is permeable to water molecules only. Total soil suction (expressed as a positive value) is the sum of osmotic (solute) and matric (matrix) suctions.

3.2.10 *vapor pressure of free pure water (kPa)*—the saturation vapor pressure of free pure water at a given dry-bulb temperature.

3.2.11 *vapor pressure of pore water in soil (kPa)*—the partial pressure of water vapor that is in equilibrium with pore-water in soil at a given dry-bulb temperature.

4. Summary of Test Method

4.1 Filter papers are placed in an airtight container with a specimen for seven days to allow sufficient time for the vapor pressure of pore-water in the specimen, vapor pressure of pore water in the filter paper, and partial vapor pressure of water in the air inside the container to reach equilibrium. The mass of the filter papers is subsequently determined and the suction of the specimen is determined from a calibration relationship of the filter paper water content with suction applicable to the type of filter paper and the test procedure of this test method.

5. Significance and Use

5.1 Soil suction is a measure of the free energy of the pore-water in a soil. Soil suction in practical terms is a measure of the affinity of soil to retain water and can provide information on soil parameters that are influenced by the soil water; for example, volume change, deformation, and strength characteristics of the soil.

5.2 Soil suction is related with soil water content through water retention characteristic curves (see Test Method D 2325). Soil water content may be found from Test Method D 2216.

5.3 Measurements of soil suction may be used with other soil and environmental parameters to evaluate hydrologic processes (**1**) and to evaluate the potential for heave or shrinkage, shear strength, modulus, in situ stress, and hydraulic conductivity of unsaturated soils.

5.4 The filter paper method of evaluating suction is simple and economical with a range from 10 to 100 000 kPa (0.1 to 1000 bars).

6. Apparatus

6.1 *Filter Paper*—The paper used must be ash-free quantitative Type II filter paper, in accordance with Specification E 832; for example, Whatman No. 42, Fisherbrand 9-790A, or Schleicher and Schuell No. 589 White Ribbon. A suitable diameter is 5.5 cm (2.2 in.).

6.2 *Specimen Container*, 115 to 230 g (4 to 8 oz) capacity metal or glass (rust free) container and lid (for example, coated with zinc chromate to retard rusting) to contain the specimen and filter papers. The inside of these containers may also be coated with wax to retard rusting.

6.3 *Filter Paper Container*—This container holds filter paper following the equilibration of suction and removal from the specimen container.

6.3.1 *Metal Container Alternate*, two nominal 60 g (2 oz) capacity metal moisture containers (aluminum or stainless) with lids to dry the filter paper. The containers should be numbered by imprinting with a metal stamp. The containers should not be written on with any type of marker or labelled in any manner. Throw-away vinyl surgical non-powdered or similar gloves should be used anytime the small containers designated for filter paper measurements are handled to prevent body oils from influencing any mass measurements made prior to handling.

6.3.2 *Plastic Bag Alternate*—Plastic bag large enough to accommodate the filter paper disks (approximately 50 mm in dimension) capable of an airtight seal.

6.4 *Insulated Chest*—A box of approximately 0.03 m^3 (1 ft^3) capacity insulated with foamed polystyrene or other material capable of maintaining temperature within ±1°C when external temperatures vary ±3°C.

6.5 *Balance*—A balance or scale having a minimum capacity of 20 g and meeting the requirements of 4.2.1.1 of Specification C 114, for a balance of 0.0001 g readability. In addition, balances for performance of Test Method D 2216, meeting requirements of Specification D 4753.

6.6 *Drying Oven*, thermostatically-controlled, preferably of the forced-draft type, and capable of maintaining a uniform temperature of 110 ± 5°C throughout the drying chamber and meeting requirements of Test Method D 2216.

6.7 *Metal Block*—A metal block > 500 g mass with a flat surface to hasten cooling of the metal tare cans.

6.8 *Thermometer*—An instrument to determine the temperature of the tested soil to an accuracy of ±1°C.

6.9 *Miscellaneous Equipment*, tweezers, trimming knife, flexible plastic electrical tape, O-rings, screen wire, brass discs, etc. Tweezers should be at least 110 mm (4.5 in.) in length.

7. Calibration

7.1 Obtain a calibration curve applicable to a specific filter paper by following the procedure in Section 8, except for replacing the soil specimen with salt solutions such as reagent grade potassium chloride or sodium chloride of known molality in distilled water.

7.1.1 Suspend the filter paper above at least 50 cc of a salt solution in the specimen container, see 6.2, by placing it on an improvised platform made of inert material such as plastic tubing or stainless steel screen.

7.1.2 Calculate the suction of the filter paper from the relative humidity of the air above the solution by the following:

$$h = \frac{RT}{v} \cdot \ln R_h \qquad (1)$$

where:

h = suction, kPa,
R = ideal gas constant, 8.31432 Joules/mole·K,
T = absolute temperature, degrees kelvin (K),
v = volume of a mole of liquid water, 0.018 kilomoles/m^3, and
R_h = relative humidity, fraction.

7.1.3 Use standard critical tables to evaluate the relative humidity of water in equilibrium with the salt solution as illustrated in Table 1. Refer to Test Method E 337 for further information on relative humidity.

7.2 Typical calibration curves for filter papers (for example, Whatman No. 42, Schleicher and Schuell No. 589), see Fig. 1, consists of two parts. The upper segment represents moisture retained as films adsorbed to particle surfaces, while the lower segment represents moisture retained by capillary or surface tension forces between particles. The filter paper water content break point is w_f = 45.3 % for Whatman No. 42 (**3**, **4**) and w_f = 54 % for Schleicher and Schuell No. 589 (**2**, **4**).

7.3 The calibration curves in Fig. 1 are applicable to total suction (**2**, **5**). Variability in results is less than 2 % of the suction above 100 kPa. Soil disturbance has minimal influence on suction above 20 kPa. At moisture contents with suctions less than 20 kPa, sample disturbance increases variability of measurement (**2**, **4**). The right vertical axis of Fig. 1 provides the suction in units pF and atmospheres pressure; for example, h = 2 log atmospheres is a suction of 100 atmospheres, while pF = 5 or 100 000 cm water.

NOTE 1—Filter paper may be calibrated by using the pressure membrane, Test Method D 3152 for the range 100 to 1500 kPa (1 to 15 atm), and the ceramic plate, Test Method D 2325 for the range 10 to 100 kPa (0.1 to 1 atm).

8. Procedure

8.1 *Filter Paper Preparation*—Dry filter papers selected for testing at least 16 h or overnight in the drying oven. Place filter papers in a desiccant jar over desiccant after drying for storage until use.

8.2 *Measurement of Suction*—Total suction will be measured if filter papers are not in contact with the soil specimen. Moisture transfer will be limited to vapor transfer through the air inside the specimen container. Matric suction will be measured if the filter paper is in physical contact with the soil. Physical contact between the soil and filter paper allows fluid transfer including transfer of salts that may be dissolved in the pore water.

TABLE 1 Salt Solution Concentrations for Evaluating Soil Suction

kPa	log kPa	pF	atm	R_h	20°C g NaCl / 1000 mL water	20°C g KCl / 1000 mL water
−98	1.99	3.0	−0.97	0.99927	1.3	1.7
−310	2.49	3.5	−3.02	0.99774	3.8	5.3
−980	2.99	4.0	−9.68	0.99278	13.1	17.0
−3099	3.49	4.5	−30.19	0.97764	39.0	52.7
−9800	3.99	5.0	−96.77	0.93008	122.5	165.0

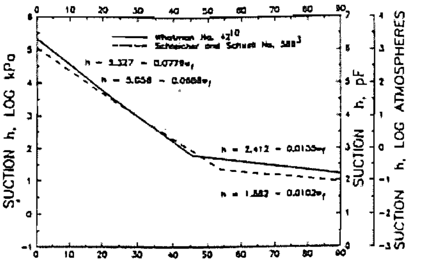


FIG. 1 Calibration Suction-Water Content Curves for Wetting of Filter Paper (3) (Coefficient of Determination r > 0.99)

NOTE 2—When the soil is not sufficiently moist, adequate physical contact between the filter paper and soil may not always be possible. This can cause an inaccurate measure of matric suction. Matric suction may be inferred by subtracting the osmotic suction from the total suction. The osmotic suction may be determined by measuring the electrical conductivity (see Test Method D 1125) of pore-water extracted from the soil using a pore fluid squeezer (**6**) or using Test Method D 4542; a calibration curve (**7**) may be used to relate the electrical conductivity to the osmotic suction.

8.3 *Filter Paper Placement*—Place an intact soil specimen or fragments of a soil sample, 115 to 230 g mass, in the specimen container. The soil specimen should nearly fill the specimen container to reduce equilibration time and to minimize suction changes in the specimen.

8.3.1 *Measurement of Total Suction*—Remove two filter papers from the desiccator and immediately place over the specimen, but isolate from the specimen by inserting screen wire, O-rings, or other inert item with minimal surface area between the filter papers and the soil, see Fig. 2(*a*). A filter paper edge should be bent up or offset slightly to hasten later removal of the filter paper from these large containers with tweezers, see 8.6.

8.3.2 *Measurement of Matric Suction*—Place three stacked filter papers in contact with the soil specimen, see Fig. 2(*b*). The outer filter papers prevent soil contamination of the center filter paper used for analysis of the matric suction. The outer filter papers should be slightly larger in diameter than the center filter paper. This can be accomplished by cutting the center paper so that the diameter is at least 3 to 4 mm smaller than the outer filter papers. This will help prevent direct soil contact with the center filter paper.

8.4 *Equilibrating Suction*—Put the lid of the specimen container in place and seal with at least one wrapping of plastic electrical tape. Then place the sealed container in an insulted chest and place in a location with temperature variations less than 3°C. A typical nominal temperature is 20°C. The suction of the filter paper and the specimen in the container should be allowed to come to equilibration for a minimum of seven days.

NOTE 3—If filter papers are placed with soil specimens while in the field, the filter papers should be oven dried overnight then stored in an airtight container over desiccant to minimize moisture in the filter paper. Moisture in the filter paper prior to testing expands the fibers and alters the filter paper void space that may lead to a change in the calibration curve of the filter paper. The insulated chest while in the field should be kept in the shade during hot summer days and in a heated area during cold winter days. The chest with the sealed containers should be placed in a temperature controlled room at about 20°C following return from the field.

NOTE 4—Equilibration of suction between the soil, filter paper, and air in the closed container is the desired result of the equilibration period. It must be recognized that the equilibration process is dependent upon the initial suction of the soil, initial relative humidity of the air, soil mass, and space in the container. The seven day period is sufficient for conditions normally involved in soil mechanics; however, under many conditions equilibration will be completed more quickly. This suction measurement must avoid condensation so thermostatic control may be necessary. Sample temperature control during equilibration will ensure that condensation effects are minimized. Storing the specimen containers containing the soil specimen and filter paper in a thermostatic box (for example, ice chest) made of polystyrene insulation and packing expanded vermiculite or similar material around the box will help minimize thermal fluctuations. It is possible to limit thermal fluctuations to ±0.01°C with such an insulation scheme.

8.5 *Predetermining Mass of Filter Paper Containers*—At the end of the equilibration period, place each of the two filter papers, if total suction is to be measured, or the center filter paper of a three-layer stack, if matrix suction is to be measured, in a separate filter paper container of predetermined mass. Determine the mass to the nearest 0.0001 g, designated T_c (tare-cold), before the specimen container is removed from the insulated chest. It is suggested that the mass of the filter paper container be determined immediately prior to determining the total mass of the filter paper and filter paper container.

8.6 *Transferring the Filter Papers*—Utilizing a pair of tweezers, transfer each filter paper from the specimen container into a metal container alternate or plastic bag alternate of predetermined mass (T_c). This entire process must be completed in 3 to 5 s. The key to successful measurements of filter paper water content is to minimize water loss during transfer of filter paper from the specimen container and during mass determination prior to oven drying. Observations have been made of 5 % or more mass loss due to evaporation during a 5 to 10 s exposure of the filter paper to room humidity of 30 to 50 R_h.

8.6.1 *Metal Container Alternate*—Place lids loosely on metal container alternates (not ajar). Care must be taken to seal the metal container alternate after each transfer; that is, take the filter paper from the specimen container and place the filter paper into a metal container, then seal the container. Repeat this procedure for the second filter paper using the second container of predetermined mass if total suction is to be determined. The containers should be sealed as quickly as possible to ensure that ambient air does not alter the moisture condition of the soil specimen or filter papers.

8.6.2 *Plastic Bag Alternate*—Quickly transfer a filter paper to a plastic bag of predetermined initial mass and seal the bag. Repeat this procedure for additional filter papers.

8.7 *Determining Mass of Filter Paper and Filter Paper Containers*—Immediately determine the mass of each of the filter paper containers with the filter papers to the nearest 0.0001 g. This mass, M_1, is

$$M_1 = M_f + M_w + T_c \tag{2}$$

where:

M_1 = total mass of filter paper container and filter paper prior to oven drying, g,
M_f = mass of dry filter paper, g,
M_w = mass of water in the filter paper, g, and
T_c = mass of the cold filter paper container, g.

8.8 *Equilibrating Temperature:*

8.8.1 *Metal Container Alternate*—Place the metal filter paper containers in an oven at 110 ± 5°C with the lids slightly adjar or unsealed to permit moisture to escape. The containers should remain in the oven for a minimum of 2 h. After the minimum time, seal the containers and leave in the oven for at least 15 min to allow temperature equilibration. Remove the tares from the oven and then determine in mass to 0.0001 g to calculate the dry total mass:

$$M_2 = M_f + T_h \tag{3}$$

where:

M_2 = dry total mass, g, and
T_h = hot container mass, g.

NOTE 5—If the filter paper containers are metal, they should be placed on a metal block for approximately 30 s to cool. The metal block acts as a heat sink and will reduce the temperature variation during determination of mass. Immediately remove and discard the filter paper and redetermine the mass of the filter paper container to 0.0001 g, that is the mass of the hot container, T_h. This procedure is repeated for additional containers.

8.8.2 *Plastic Bag Alternate*—Place the filter paper in the drying oven for a minimum of 2 h, then place in a desiccant jar over silica jel or standard desiccant to cool for a minimum of 2 to 3 min. Place in the plastic bag and determine the mass (M_2) from Eq 3. Remove the filter paper and determine the final mass of the plastic bag (T_h).

8.8.3 Once the masses of the dried filter papers have been determined, discard the filter papers. Under no circumstances shall oven-dried filter papers be re-used in conducting this test method.

9. Calculation

9.1 Calculate the following for each filter paper:

$$M_f = M_2 - T_h \tag{4}$$

$$M_w = M_1 - M_2 + T_h - T_c \tag{5}$$

from the measured quantities:

$$M_1, M_2, T_c, \text{ and } T_h$$

NOTE 6—The hot container mass, T_h, may be consistently less than the cold tare mass, T_c, if metal filter paper containers are used because of the loss of surface adsorbed moisture when heated. Air currents from rising of air heated by the hot metal tare may also contribute to a smaller hot tare mass. The average difference between hot and cold tare mass for 69 measurements is 4.6 ± 0.9 % of the filter paper mass and must be considered if measurements of the filter paper mass are to have an error less than 5 %. No test results are available for plastic bags.

9.2 The water content of the filter paper, w_f, by mass is as follows:

$$w_f = \frac{M_w}{M_f} \cdot 100 \tag{6}$$

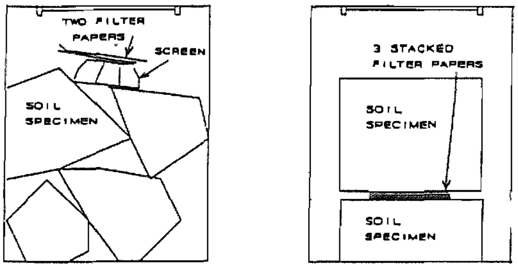
where:

w_f = filter paper water content, percent.

9.3 Convert the filter paper water content, w_f, to a suction value by reference to a calibration curve or calculate the suction from the following:

$$h = m \cdot w_f + b \tag{7}$$

where:



A. Total Suction

B. Matrix Suction

FIG. 2 Setup for Equilibrating Suction in Large Container

m = slope of filter paper calibration curve, $\log_{10}$ kPa/% water content, and

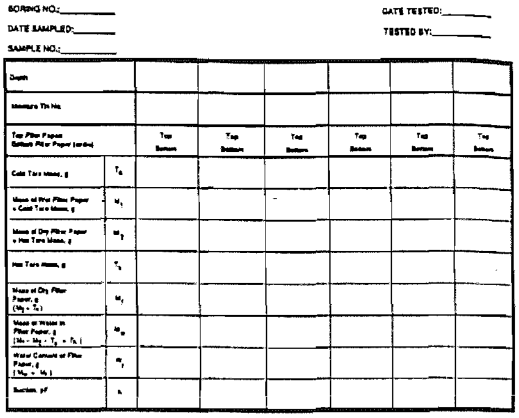
b = intercept of the filter paper calibration, $\log_{10}$ kPa.

9.4 A calibration curve defined by Eq 7 is unique for each type of filter paper and consists of a line with a relatively steep slope and a relatively flat slope, see Fig. 2. Take the suction determined from the calibration curve as the average of the suctions evaluated from the water contents if two filter papers were used to determine the soil suction. Discard the test results if the difference in suction between the two filter papers exceeds 0.5 log kPa.

10. Report

10.1 Figure 3 is an example data sheet for evaluating soil suction using filter paper.

10.2 Report the soil water content corresponding to the total soil suction, temperature of measurement and equilibration time, method of calibrating filter paper, and bulk density of soil.



BORING NO.:__________
DATE SAMPLED:__________
SAMPLE NO.:__________
DATE TESTED:__________
TESTED BY:__________

Depth							
Moisture Tin No.							
Top Filter Paper Bottom Filter Paper (circle)		Top Bottom	Top Bottom	Top Bottom	Top Bottom	Top Bottom	Top Bottom
Cold Tare Mass, g	T_c						
Mass of Wet Filter Paper + Cold Tare Mass, g	M_1						
Mass of Dry Filter Paper + Hot Tare Mass, g	M_2						
Hot Tare Mass, g	T_h						
Mass of Dry Filter Paper, g ($M_2 - T_h$)	M_f						
Mass of Water in Filter Paper, g ($M_1 - M_2 - T_c + T_h$)	M_w						
Water Content of Filter Paper, % (M_w / M_f)	w_f						
Suction, pF	h						

FIG. 3 Evaluation of Soil Suction Using Filter Paper

10.3 Report the salinity of the pore water if determined to permit evaluation of osmotic suction and calculation of matric suction $hm = h - hs$.

11. Precision and Bias

11.1 *Precision*—Data are being evaluated to determine the precision of this test method. In addition, Subcommittee D18.04 is seeking pertinent data from users of this test method.

11.2 *Bias*—There is no accepted reference value for this test method, therefore, bias cannot be determined.

12. Keywords

12.1 filter paper; soil relative humidity; soil suction

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(2) McQueen, I. S., and Miller, R. F., "Calibration and Evaluation of a Wide Range Gravimetric Method for Measuring Moisture Stress," *Soil Science*, Vol 106, No. 3, 1968, pp. 225–231.

(3) Greacen, E. L., Walker, G. R., and Cook, P. G., "Evaluation of the Filter Paper Method for Measuring Soil Water Suction," *International Conference on Measurement of Soil and Plant Water Status*, Logan, UT, 1987, p. 138; "Procedure for the Filter Paper Method of Measuring Soil Water Suction," Division of Soils, Report 108, CSIRO, Glen Osmond, South Australia, Australia.

(4) Orig. Footnote 12 in text.

(5) Fawcett, R. G., and Collis-George, N., "A Filter Paper Method for Determining the Moisture Characteristic of Soil," *Australian Journal of Experimental Agriculture and Animal Husbandry*, Vol 7, 1967, pp. 162–167.

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Evaluation of Waste Suction Using Filter Paper Method

Sample Designation: ____________________
Sampling Date: ____________________
Testing Date: ____________________

Sample Density: ____________________
Other Information: ____________________

Moisture Tin No													
Top/Bottom Filter Paper		Top Bottom	Top Bottom	Top Bottom	Top Bottom	Top Bottom	Top Bottom	Top Bottom	Top Bottom	Top Bottom	Top Bottom	Top Bottom	Top Bottom
Cold Tare Mass, g	T_c												
Mass of Wet Filter paper + Cold Tare Mass, g	M_1												
Mass of Dry Filter paper + Hot Tare Mass, g	M_2												
Hot Tare Mass, g	T_h												
Mass of Dry Filter paper, g (M_2-T_h)	M_f												
Mass of Water in Filter paper, g (M_1-M_2-T_c+T_h)	M_w												
Water Content of Filter paper, g (M_w/M_f)	W_f												
Suction, kPa	ψ												
Sample Moisture Content W_s	W_s												
Volumetric Water Content of Sample (θ_w)	θ_w												
Sample Bulk Density ρ_w (kg/m^3)	ρ_w												

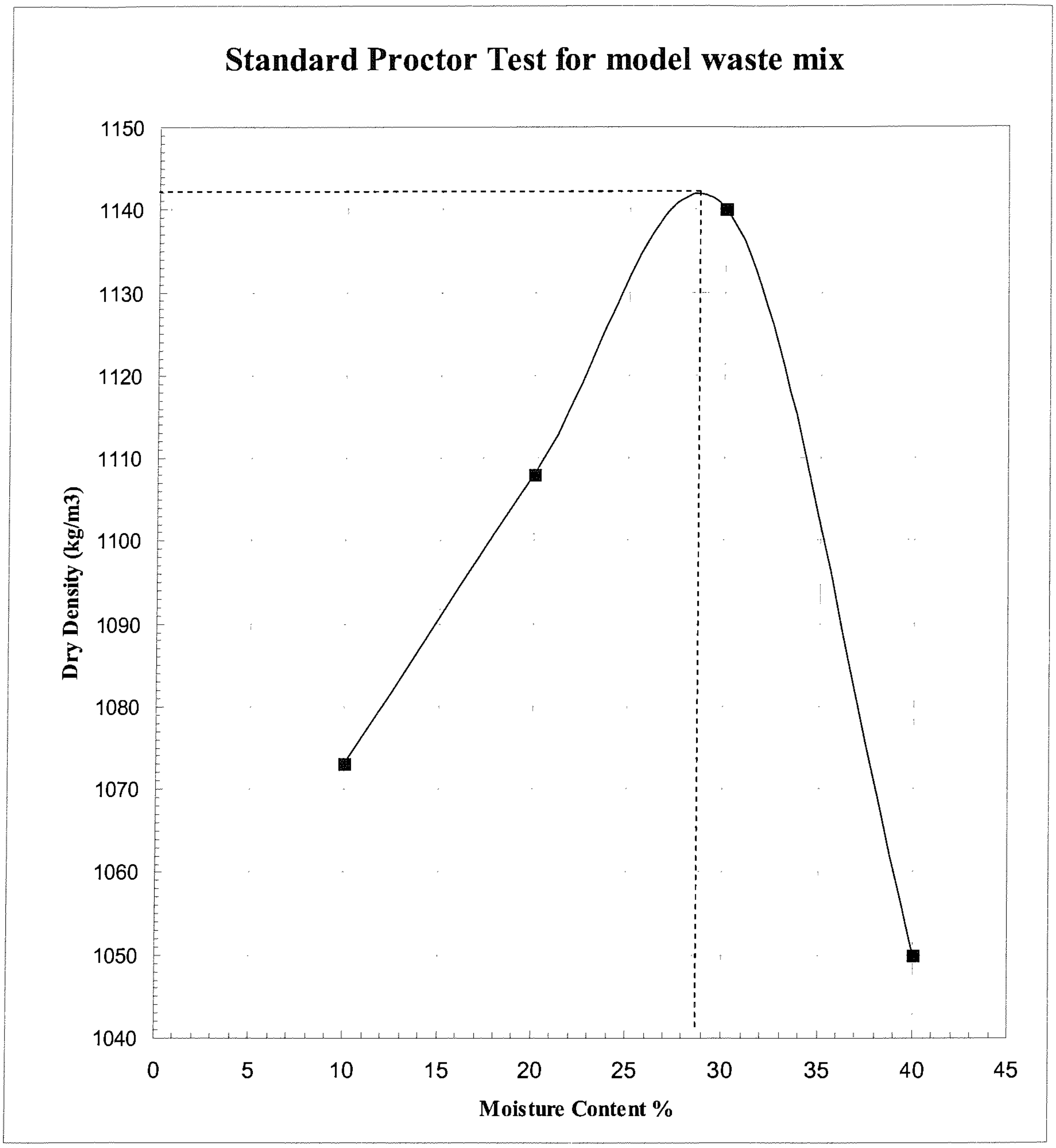
Gas Jar Method (BS 1377: 1975, Test 6(A))

The method is used for the determination of specific gravity of soils (having particle size up to 37.5mm). The method was used to determine the specific gravity (G_s) of the model waste mix having particle size less than 25mm.

The value of G_s determined by the above method was = 1.625

Standard Proctor Test (ASTM D 698)

The maximum dry density and optimum moisture content of the model waste mix was determined using the above method. The result is shown in the following graph.



Standard Proctor Test result for Model waste mix

Appendix C

(Hydraulic conductivity measurements – Tables and Graphs)

Determination of Hydraulic conductivity of Model waste using Large-scale permeameter - Constant Head Test

Dry density of waste = 400kg/m3

Observations & Calculations

Length of Sample = 0.62 m

X Area of Sample = 0.19635 m^2

Test run No	Hp1	Hp2	Hp3	Hp4	Hp5	Hp6	P(H2-H1)	P(H3-H2)	P(H4-H3)	P(H5-H4)	P(H6-H5)	P(H3-H1)	Grad(12)	Grad(23)	Grad(34)	Grad(45)	Hgrad(13)	1 lit in min	sec	Q = (m^3/s)	K (1-2)	K(2-3)	K (3-4)	K (4-5)	K (1-3)	Q	K	Hyd Grad
	m	m	m	m	m	m	m	m	m	m	m	m									(m/sec)	(m/sec)	(m/sec)	(m/sec)	(m/sec)	(m^3/s)	(m/sec)	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	1.480	1.483	1.488	1.498	1.508	1.511	0.003	0.005	0.010	0.010	0.010	0.028	0.025	0.038	0.083	0.077	0.056	0	38	2.63E-05	5.36E-03	3.48E-03	1.61E-03	1.74E-03	2.39E-03	2.63E-05	2.3933E-03	0.056
2	1.565	1.567	1.570	1.580	1.589	1.592	0.002	0.003	0.010	0.009	0.009	0.024	0.017	0.023	0.083	0.069	0.048	0	43	2.33E-05	7.11E-03	5.13E-03	1.42E-03	1.71E-03	2.47E-03	2.33E-05	2.4675E-03	0.048
3	1.700	1.702	1.705	1.713	1.719	1.720	0.002	0.003	0.008	0.006	0.006	0.019	0.017	0.023	0.067	0.046	0.038	0	55	1.82E-05	5.56E-03	4.01E-03	1.39E-03	2.01E-03	2.44E-03	1.82E-05	2.4368E-03	0.038
4	1.845	1.845	1.847	1.853	1.858	1.857	0.000	0.002	0.006	0.005	0.005	0.013	0.000	0.015	0.050	0.038	0.026	1	10	1.43E-05	#DIV/0!	4.73E-03	1.46E-03	1.89E-03	2.80E-03	1.429E-05	2.7983E-03	0.026

Avg K = 2.5240E-03 m/sec

Density of Waste

Waste sample volume = X-sec Area x Length of Sample
= 0.19635 x 0.62
= 0.12174 m^3

Dry waste weight = 50 kgs

Dry Density = Weight / Volume
= 410.721 kg/m^3

Table C-1.1. Hydraulic conductivity of model waste using large-scale permeameter – constant head test (ρ_{dry} = 400kg/m^3)

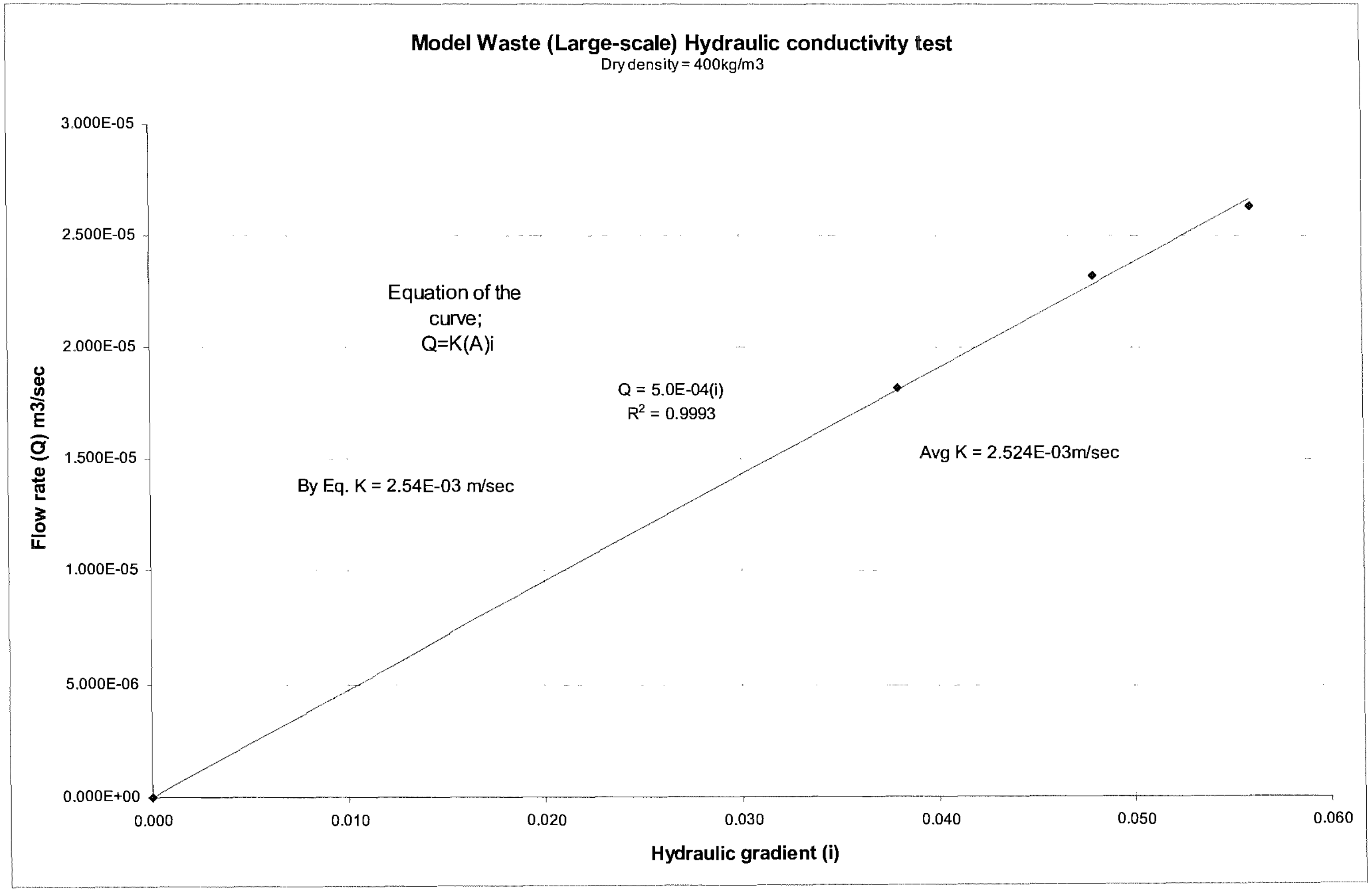


Figure C-1.1. Darcian relationship in model waste using large-scale permeameter – constant head test ($\rho_{dry} = 400kg/m^3$)

Determination of Hydraulic conductivity of Model waste using Large-scale permeameter - Constant Head Test

Dry density of waste = 450kg/m3

Observations & Calculations

Length of Sample = 0.57 m

X Area of Sample = 0.19635 m^2

Test run No	Hp1 m	Hp2 m	Hp3 m	Hp4 m	Hp5 m	Hp6 m	P(H2-H1) m	P(H3-H2) m	P(H4-H3) m	P(H5-H4) m	P(H6-H5) m	P(H3-H1) m	Grad(12)	Grad(23)	Grad(34)	Grad(45)	Hgrad(13)	1 lit in min	1 lit in sec	Q = (m^3/s)	K (1-2) (m/sec)	K(2-3) (m/sec)	K (3-4) (m/sec)	K (4-5) (m/sec)	K (1-3) (m/sec)	Q (m^3/s)	K (m/sec)	Hyd Grad
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	1.358	1.364	1.377	1.407	1.436	1.441	0.006	0.013	0.030	0.029	0.029	0.078	0.050	0.100	0.250	0.223	0.156	0	32	3.13E-05	3.18E-03	1.59E-03	6.37E-04	7.13E-04	1.02E-03	3.13E-05	1.0202E-03	0.156
2	1.615	1.620	1.629	1.649	1.668	1.672	0.005	0.009	0.020	0.019	0.019	0.053	0.042	0.069	0.167	0.146	0.106	0	45	2.22E-05	2.72E-03	1.63E-03	6.79E-04	7.74E-04	1.07E-03	2.22E-05	1.0677E-03	0.106
3	1.820	1.822	1.826	1.839	1.850	1.852	0.002	0.004	0.013	0.011	0.011	0.030	0.017	0.031	0.108	0.085	0.060	1	10	1.43E-05	4.37E-03	2.36E-03	6.72E-04	8.60E-04	1.21E-03	1.43E-05	1.2126E-03	0.060

Avg K = 1.1002E-03 m/sec

Density of Waste

Waste sample volume = X-sec Area x Length of Sample

= 0.19635 x 0.57

= 0.11192 m^3

Dry waste weight = 50 kgs

Dry Density = Weight / Volume

= 446.75 kg/m^3

Table C-1.2. Hydraulic conductivity of model waste using large-scale permeameter – constant head test (ρ_{dry} = 450kg/m^3)

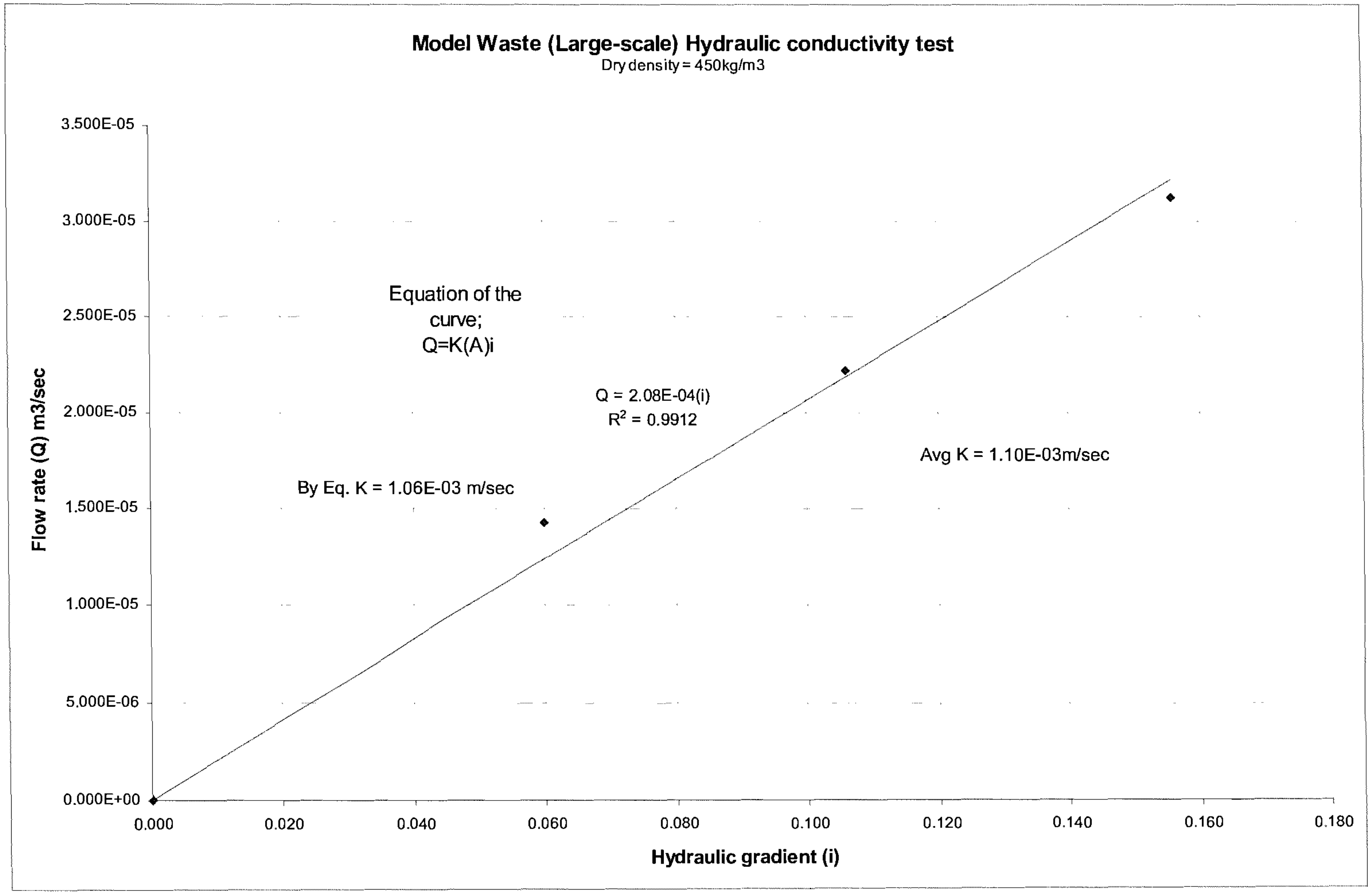


Figure C-1.2. Darcian relationship in model waste using large-scale permeameter – constant head test (ρ_{dry} = 450kg/m^3)

Determination of Hydraulic conductivity of Model waste using Large-scale permeameter - Constant Head Test

Dry density of waste = 500kg/m3

Observations & Calculations

Length of Sample = 0.51 m

X Area of Sample = 0.19635 m^2

Test run No	Hp1	Hp2	Hp3	Hp4	Hp5	Hp6	P(H2-H1)	P(H3-H2)	P(H4-H3)	P(H5-H4)	P(H6-H5)	P(H3-H1)	Grad(12)	Grad(23)	Grad(34)	Grad(45)	Hgrad(13)	1 lit in min	sec	Q = (m^3/s)	K (1-2)	K(2-3)	K (3-4)	K (4-5)	K (1-3)	Q	K	Hyd Grad
	m	m	m	m	m	m	m	m	m	m	m	m									(m/sec)	(m/sec)	(m/sec)	(m/sec)	(m/sec)	(m^3/s)	(m/sec)	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	1.496	1.522	1.563	1.604	1.650	1.643	0.026	0.041	0.041	0.046	0.046	0.108	0.217	0.315	0.342	0.354	0.292	0	42	2.38E-05	5.60E-04	3.84E-04	3.55E-04	3.43E-04	4.15E-04	2.38E-05	4.1543E-04	0.292
2	1.735	1.751	1.776	1.804	1.830	1.827	0.016	0.025	0.028	0.026	0.026	0.069	0.133	0.192	0.233	0.200	0.186	1	3	1.59E-05	6.06E-04	4.20E-04	3.46E-04	4.04E-04	4.33E-04	1.59E-05	4.3349E-04	0.186
3	1.818	1.830	1.850	1.871	1.892	1.889	0.012	0.020	0.021	0.021	0.021	0.053	0.100	0.154	0.175	0.162	0.143	1	21	1.23E-05	6.29E-04	4.09E-04	3.59E-04	3.89E-04	4.39E-04	1.23E-05	4.3894E-04	0.143
4	1.890	1.897	1.910	1.925	1.938	1.934	0.007	0.013	0.015	0.013	0.013	0.035	0.058	0.100	0.125	0.100	0.095	1	57	8.55E-06	7.46E-04	4.35E-04	3.48E-04	4.35E-04	4.60E-04	8.55E-06	4.6017E-04	0.095

Avg K = 4.3701E-04 m/sec

Density of Waste

Waste sample volume = X-sec Area x Length of Sample

= 0.19635 x 0.51

= 0.10014 m^3

Dry Density = Weight / Volume

= 499.308 kg/m^3

Dry waste weight = 50 kgs

Table C-1.3. Hydraulic conductivity of model waste using large-scale permeameter – constant head test (ρ_{dry} = 500kg/m^3)

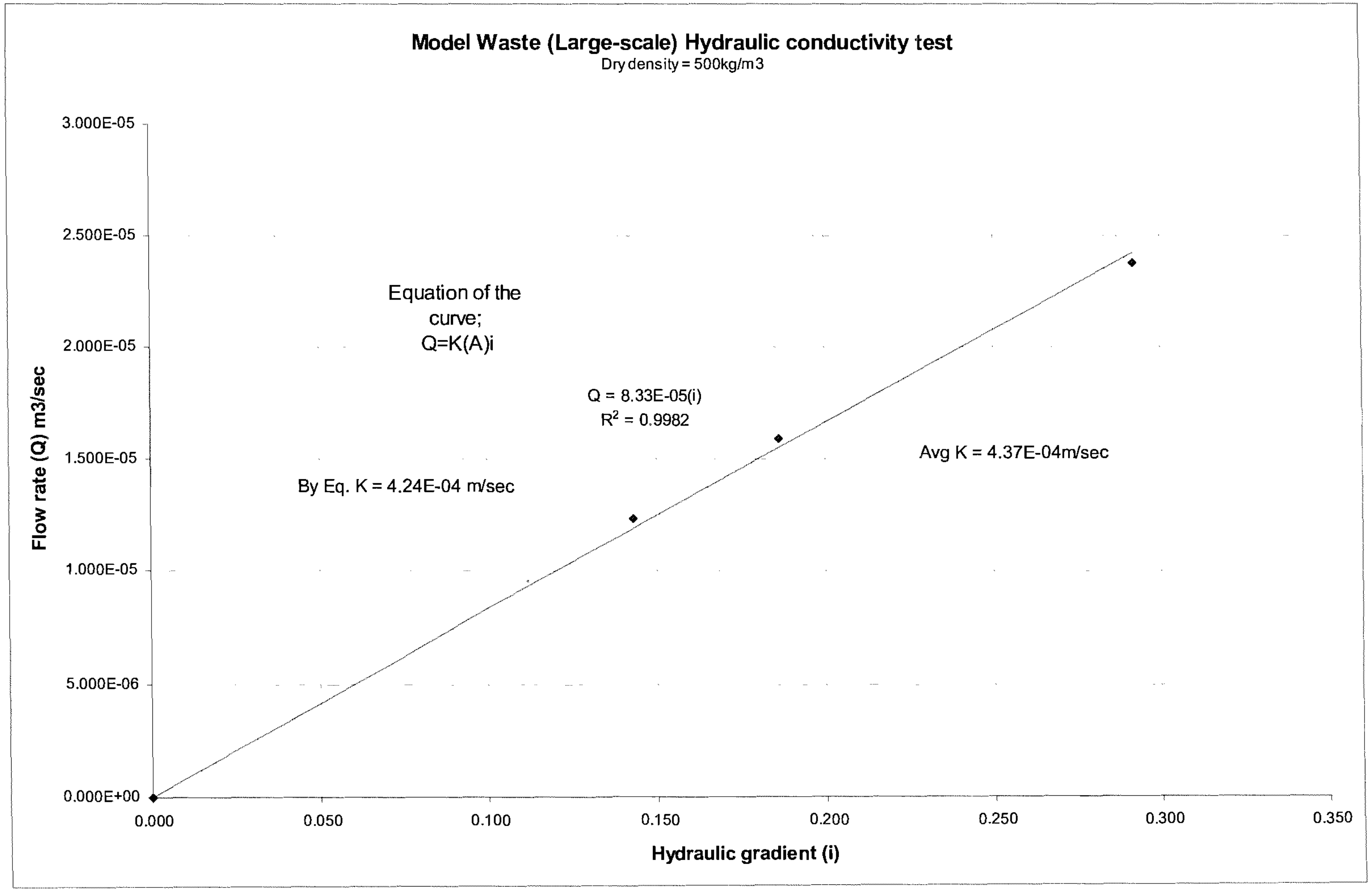


Figure C-1.3. Darcian relationship in model waste using large-scale permeameter – constant head test (ρ_{dry} = 500kg/m^3)

Determination of Hydraulic conductivity of Model waste using Large-scale permeameter - Constant Head Test

Dry density of waste = 550kg/m3

Observations & Calculations

Length of Sample = 0.46 m

X Area of Sample = 0.19635 m^2

Test run No	Hp1	Hp2	Hp3	Hp4	Hp5	Hp6	P(H2-H1)	P(H3-H2)	P(H4-H3)	P(H5-H4)	P(H6-H5)	P(H3-H1)	Grad(12)	Grad(23)	Grad(34)	Grad(45)	Hgrad(13)	1 lit in min	sec	Q = (m^3/s)	K (1-2)	K(2-3)	K (3-4)	K (4-5)	K (1-3)	Q	K	Hyd Grad
	m	m	m	m	m	m	m	m	m	m	m	m									(m/sec)	(m/sec)	(m/sec)	(m/sec)	(m/sec)	(m^3/s)	(m/sec)	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	1.707	1.734	1.785	1.820	1.840	1.838	0.027	0.051	0.035	0.020	0.020	0.113	0.225	0.392	0.292	0.154	0.305	1	56	8.62E-06	1.95E-04	1.12E-04	1.51E-04	2.85E-04	1.44E-04	8.62E-06	1.4376E-04	0.305
2	1.560	1.605	1.680	1.738	1.770	1.769	0.045	0.075	0.058	0.032	0.032	0.178	0.375	0.577	0.483	0.246	0.481	1	15	1.33E-05	1.81E-04	1.18E-04	1.40E-04	2.76E-04	1.41E-04	1.33E-05	1.4115E-04	0.481
3	1.360	1.422	1.533	1.620	1.676	1.670	0.062	0.111	0.087	0.056	0.056	0.260	0.517	0.854	0.725	0.431	0.703	0	53	1.89E-05	1.86E-04	1.13E-04	1.33E-04	2.23E-04	1.37E-04	1.89E-05	1.3675E-04	0.703

Density of Waste

Avg K = 1.4055E-04 m/sec

Waste sample volume = X-sec Area x Length of Sample
= 0.19635 x 0.46
= 0.09032 m^3

Dry Density = Weight / Volume
= 553.581 kg/m^3

Dry waste weight = 50 kgs

Table C-1.4. Hydraulic conductivity of model waste using large-scale permeameter – constant head test (ρ_{dry} = 550kg/m^3)

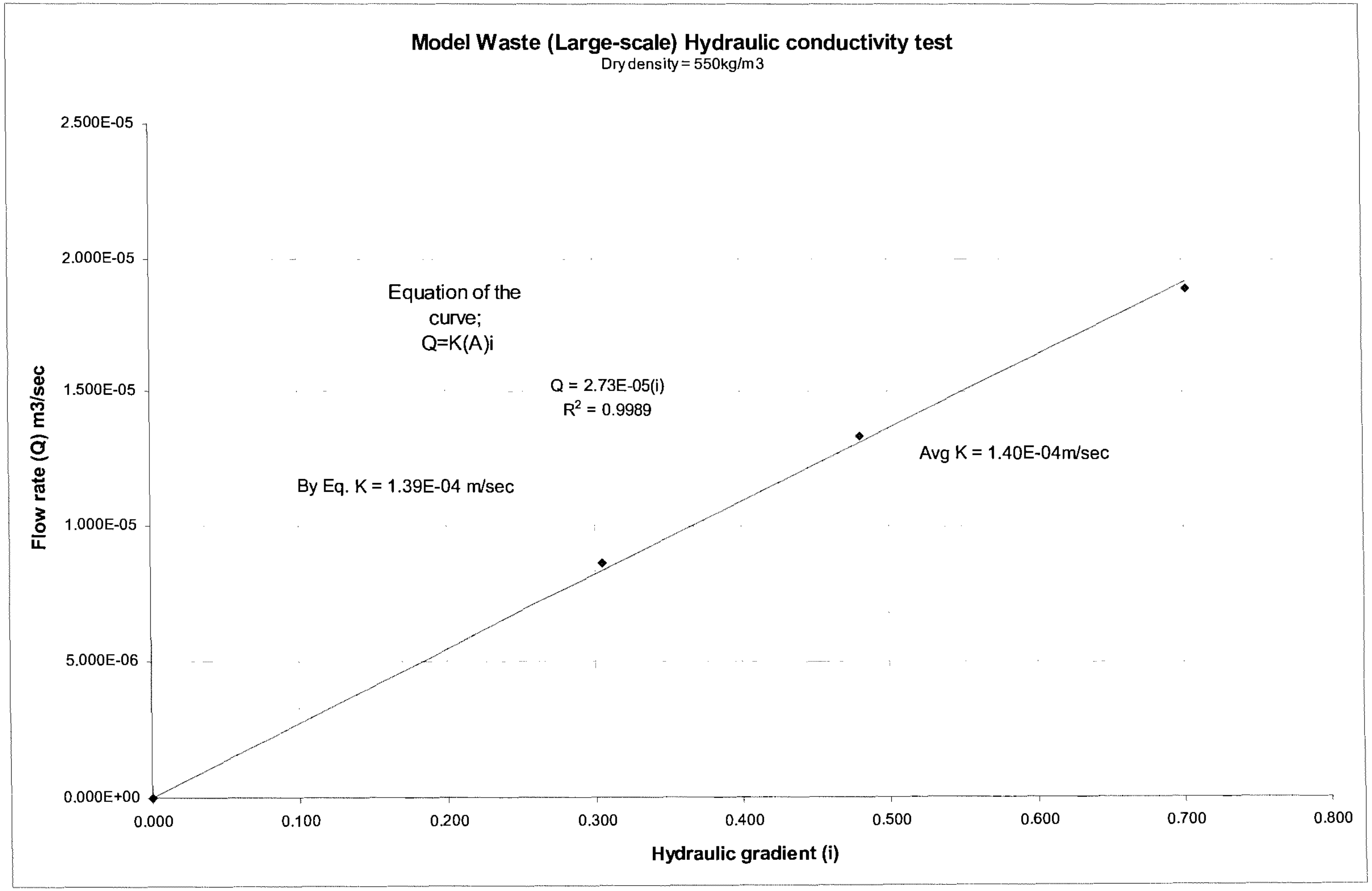


Figure C-1.4. Darcian relationship in model waste using large-scale permeameter – constant head test ($\rho_{dry} = 550kg/m^3$)

Determination of Hydraulic conductivity of Model waste using Large-scale permeameter - Constant Head Test

Dry density of waste = 600kg/m3

Observations & Calculations

Length of Sample = 0.42 m
X Area of Sample = 0.19635 m²

Test run No	Hp1	Hp2	Hp3	Hp4	Hp5	Hp6	P(H2-H1)	P(H3-H2)	P(H4-H3)	P(H5-H4)	P(H6-H5)	P(H3-H1)	Grad(12)	Grad(23)	Grad(34)	Grad(45)	Hgrad(13)	1 lit in min	sec	Q = (m³/s)	K (1-2)	K(2-3)	K (3-4)	K (4-5)	K (1-3)	Q	K	Hyd Grad
	m	m	m	m	m	m	m	m	m	m	m	m									(m/sec)	(m/sec)	(m/sec)	(m/sec)	(m/sec)	(m³/s)	(m/sec)	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	1.476	1.524	1.585	-	-	-	0.048	0.061	-	-	-	0.109	0.400	0.469	-	-	0.436	3	48	4.39E-06	5.58E-05	4.76E-05	-	-	5.12E-05	4.39E-06	5.1233E-05	0.436
2	1.625	1.727	1.849	-	-	-	0.102	0.122	-	-	-	0.224	0.850	0.938	-	-	0.896	2	2	8.20E-06	4.91E-05	4.45E-05	-	-	4.6591E-05	8.20E-06	4.6591E-05	0.896
3	1.452	1.587	1.755	-	-	-	0.135	0.168	-	-	-	0.303	1.125	1.292	-	-	1.212	1	27	1.15E-05	5.20E-05	4.53E-05	-	-	4.8300E-05	1.15E-05	4.8300E-05	1.212

Density of Waste

Avg K = 4.8708E-05 m/sec

Waste sample volume = X-sec Area x Length of Sample
= 0.19635 x 0.42
= 0.08247 m³

Dry waste weight = 50 kgs

Dry Density = Weight / Volume
= 606.303 kg/m³

Table C-1.5. Hydraulic conductivity of model waste using large-scale permeameter – constant head test (ρ_{dry} = 600kg/m³)

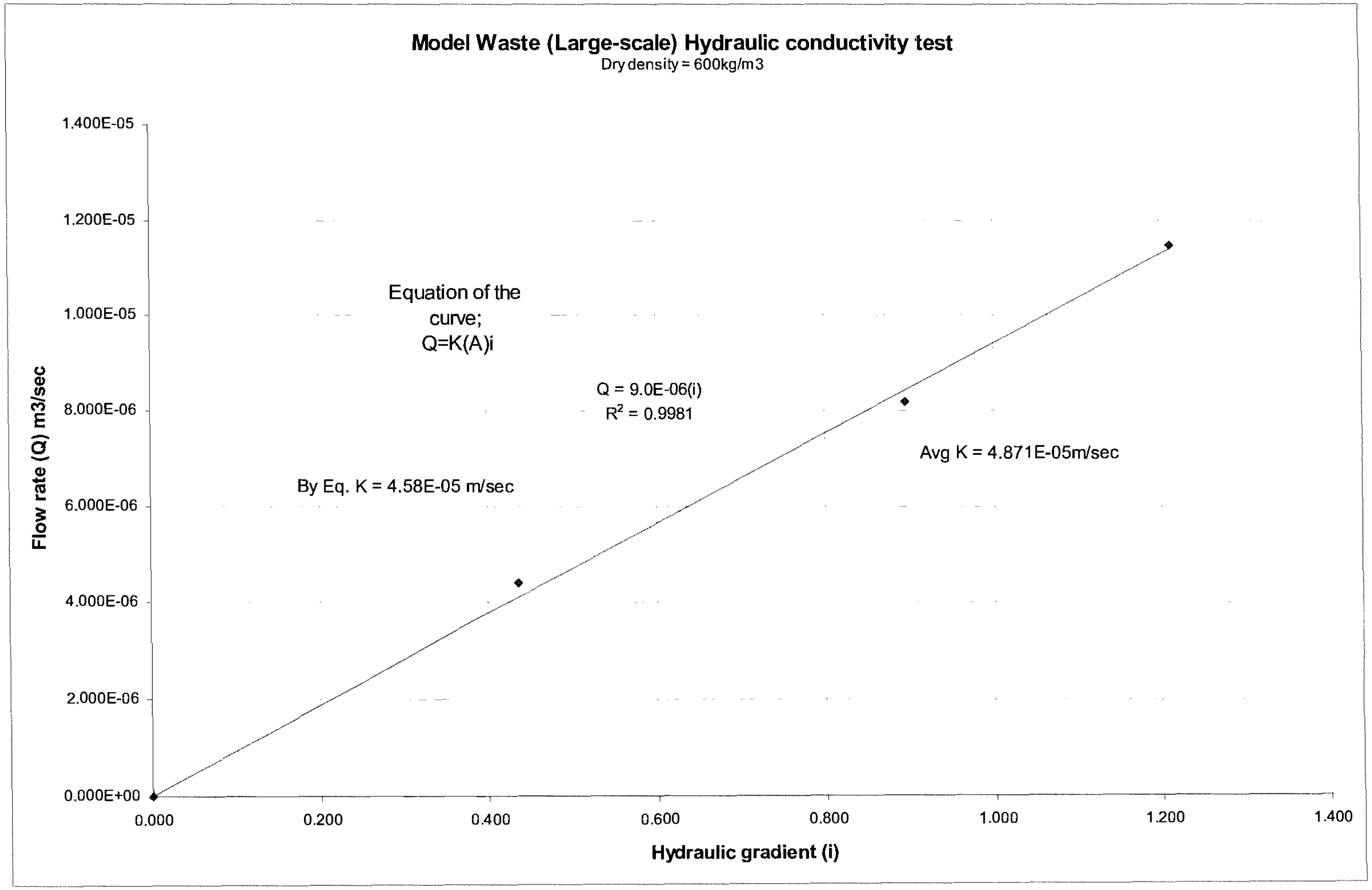


Figure C-1.5. Darcian relationship in model waste using large-scale permeameter – constant head test (ρ_{dry} = 600kg/m^3)

Determination of Hydraulic conductivity of Model waste using Large-scale permeameter - Constant Head Test

Dry density of waste = 650kg/m3

Observations & Calculations

Length of Sample = 0.39 m
X Area of Sample = 0.19635 m^2

																		1 lit	in									
Test run No	Hp1	Hp2	Hp3	Hp4	Hp5	Hp6	P(H2-H1)	P(H3-H2)	P(H4-H3)	P(H5-H4)	P(H6-H5)	P(H3-H1)	Grad(12)	Grad(23)	Grad(34)	Grad(45)	Hgrad(13)	min	sec	Q = (m^3/s)	K (1-2)	K(2-3)	K (3-4)	K (4-5)	K (1-3)	Q	K	Hyd Grad
	m	m	m	m	m	m	m	m	m	m	m	m									(m/sec)	(m/sec)	(m/sec)	(m/sec)	(m/sec)	(m^3/s)	(m/sec)	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	1.891	1.922	1.963				0.031	0.041				0.072	0.258	0.315			0.288	14	50	1.12E-06	2.22E-05	1.81E-05			1.99E-05	1.12E-06	1.9869E-05	0.288
2	1.430	1.585	1.820				0.155	0.235				0.390	1.292	1.808			1.560	3	14	5.15E-06	2.03E-05	1.45E-05			1.6828E-05	5.15E-06	1.6828E-05	1.560
3	1.320	1.518	1.778				0.198	0.260				0.458	1.650	2.000			1.832	2	41	6.21E-06	1.92E-05	1.58E-05			1.7267E-05	6.21E-06	1.7267E-05	1.832

Density of Waste

Avg K = 1.7988E-05 m/see

Waste sample volume = X-sec Area x Length of Sample
= 0.19635 x 0.39
= 0.07658 m^3

Dry waste weight = 50 kgs

Dry Density = Weight / Volume
= 652.942 kg/m^3

Table C-1.6. Hydraulic conductivity of model waste using large-scale permeameter – constant head test (ρ_{dry} = 650kg/m^3)

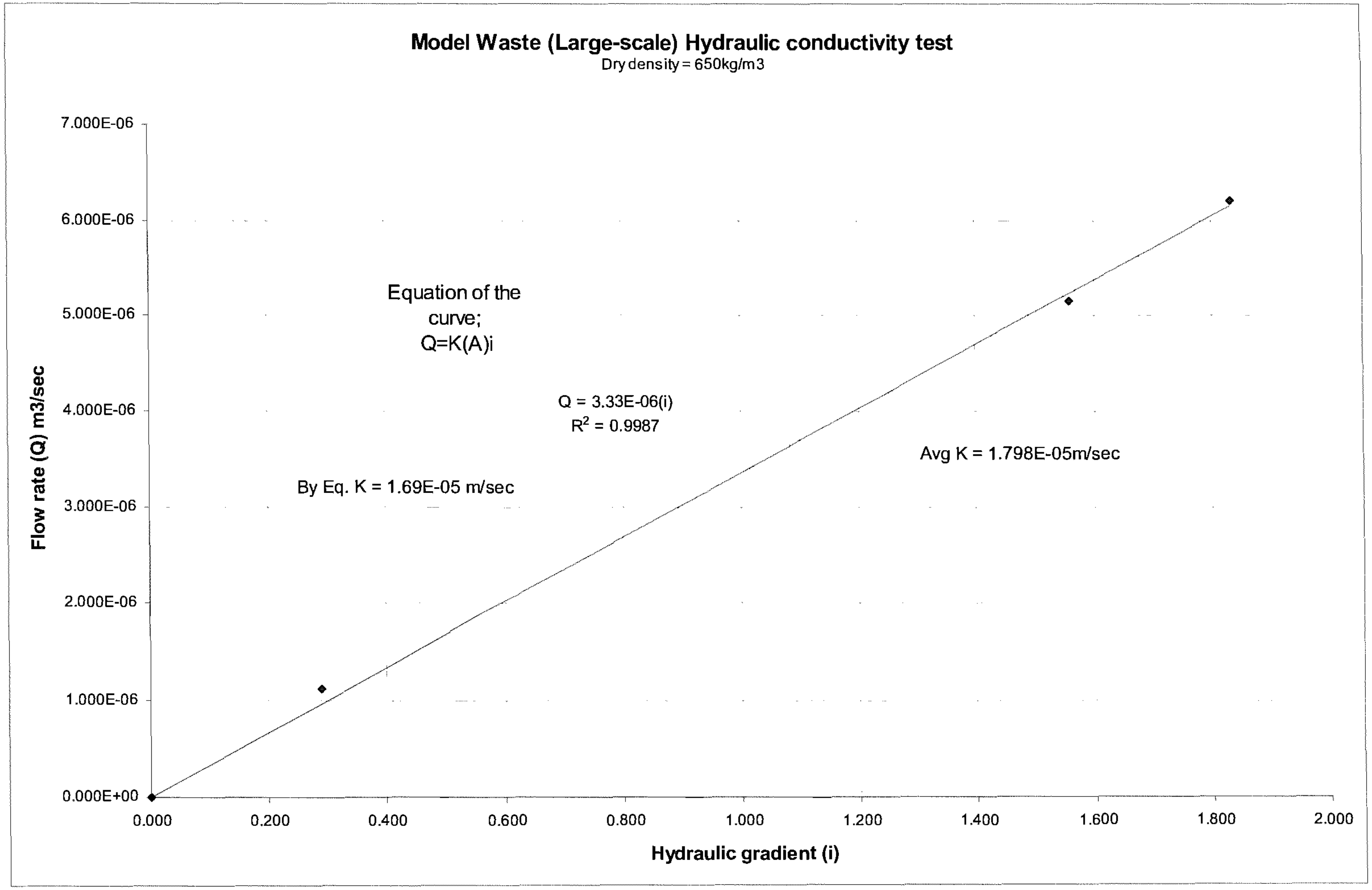


Figure C-1.6. Darcian relationship in model waste using large-scale permeameter – constant head test (ρ_{dry} = 650kg/m^3)

Determination of Hydraulic conductivity of Model waste using Large-scale permeameter - Constant Head Test

Dry density of waste = 700kg/m3

Observations & Calculations

Length of Sample = 0.36 m
X Area of Sample = 0.19635 m^2

																		1 lit in										
Test run No	Hp1	Hp2	Hp3	Hp4	Hp5	Hp6	P(H2-H1)	P(H3-H2)	P(H4-H3)	P(H5-H4)	P(H6-H5)	P(H3-H1)	Grad(12)	Grad(23)	Grad(34)	Grad(45)	Hgrad(13)	min	sec	Q = (m^3/s)	K (1-2)	K(2-3)	K (3-4)	K (4-5)	K (1-3)	Q	K	Hyd Grad
	m	m	m	m	m	m	m	m	m	m	m	m									(m/sec)	(m/sec)	(m/sec)	(m/sec)	(m/sec)	(m^3/s)	(m/sec)	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	1.415	1.560	1.795	-	-	-	0.145	0.235	-	-	-	0.380	1.208	1.808	-	-	1.520	5	32	3.01E-06	1.27E-05	8.49E-06	-	-	1.01E-05	3.01E-06	1.0092E-05	1.520
2	0.860	1.165	1.625	-	-	-	0.305	0.460	-	-	-	0.765	2.542	3.538	-	-	3.060	3	5	5.41E-06	5.91E-06	7.78E-06	-	-	8.9965E-06	5.41E-06	8.9965E-06	3.060
3	0.275	0.765	1.480	-	-	-	0.490	0.715	-	-	-	1.205	4.083	5.500	-	-	4.820	2	15	7.41E-06	9.24E-06	6.86E-06	-	-	7.8269E-06	7.41E-06	7.8269E-06	4.820
4	0.225	0.710	1.455	-	-	-	0.485	0.745	-	-	-	1.230	4.042	5.731	-	-	4.920	2	10	7.69E-06	9.69E-06	6.84E-06	-	-	7.96E-06	7.69E-06	7.9627E-06	4.920

Avg K = 8.7196E-06 m/sec

Density of Waste

Waste sample volume = X-sec Area x Length of Sample
= 0.19635 x 0.36
= 0.07069 m^3

Dry Density = Weight / Volume
= 707.354 kg/m^3

Dry waste weight = 50 kgs

Table C-1.7. Hydraulic conductivity of model waste using large-scale permeameter – constant head test ($\rho_{dry} = 700kg/m^3$)

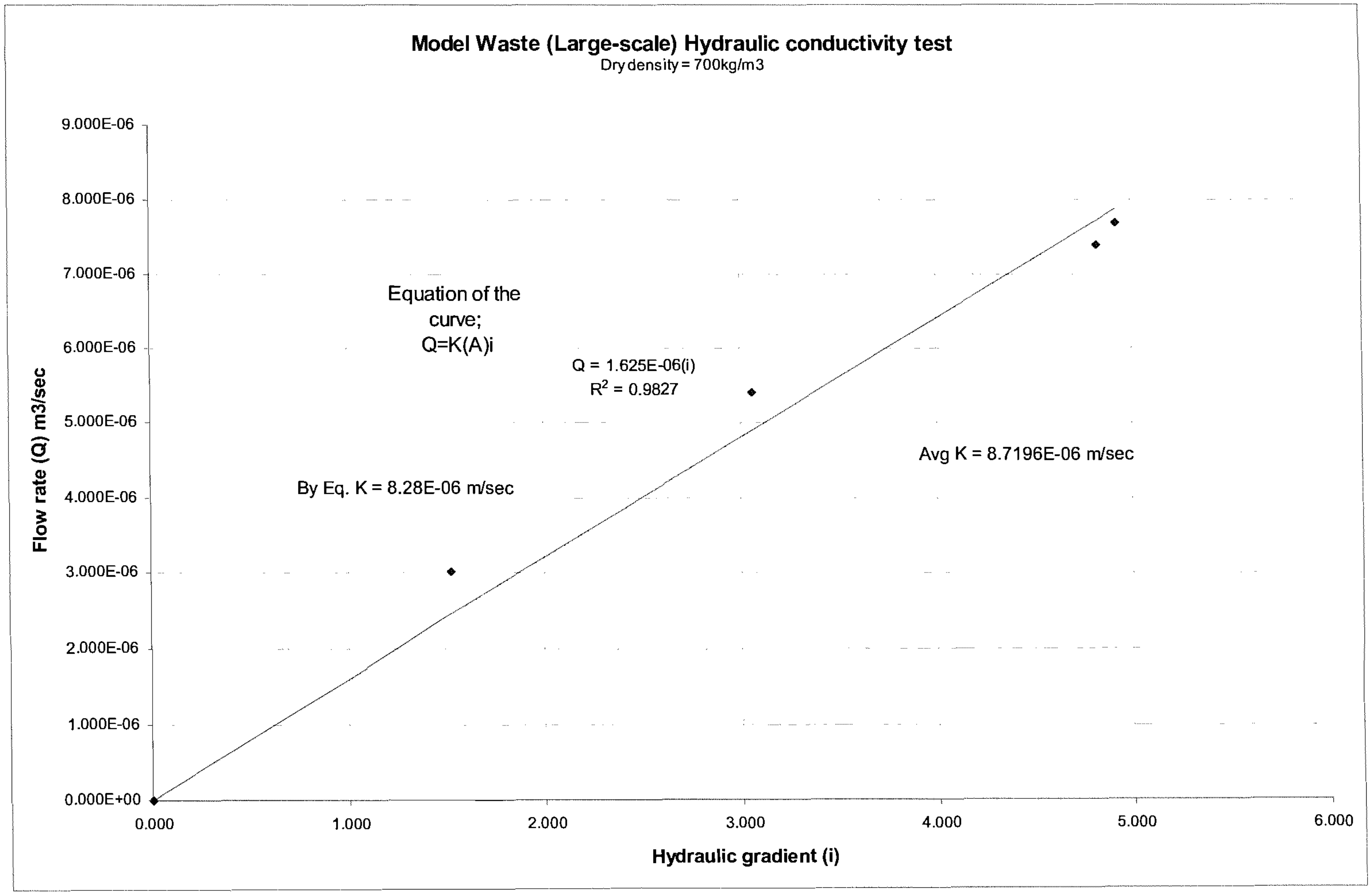


Figure C-1.7. Darcian relationship in model waste using large-scale permeameter – constant head test (ρ_{dry} = 700kg/m^3)

Determination of Hydraulic conductivity of Model waste using Large-scale permeameter - Constant Head Test

Dry density of waste = 750kg/m3

Observations & Calculations

Length of Sample = 0.34 m
X Area of Sample = 0.19635 m^2

																		1 lit	in									
Test run No	Hp1	Hp2	Hp3	Hp4	Hp5	Hp6	P(H2-H1)	P(H3-H2)	P(H4-H3)	P(H5-H4)	P(H6-H5)	P(H3-H1)	Grad(12)	Grad(23)	Grad(34)	Grad(45)	Hgrad(13)	min	sec	Q = (m^3/s)	K (1-2)	K(2-3)	K (3-4)	K (4-5)	K (1-3)	Q	K	Hyd Grad
	m	m	m	m	m	m	m	m	m	m	m	m									(m/sec)	(m/sec)	(m/sec)	(m/sec)	(m/sec)	(m^3/s)	(m/sec)	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	1.615	1.730	1.940	-	-	-	0.115	0.210	-	-	-	0.325	0.958	1.615	-	-	1.300	18	25	9.05E-07	2.78E-06	2.85E-06	-	-	3.55E-06	9.05E-07	3.5454E-06	1.300
2	1.445	1.615	1.925	-	-	-	0.170	0.310	-	-	-	0.480	1.417	2.385	-	-	1.920	11	45	1.42E-06	5.10E-06	3.03E-06	-	-	3.76E-06	1.42E-06	3.7625E-06	1.920

Density of Waste

Avg K = 3.6540E-06 m/sec

Waste sample volume = X-sec Area x Length of Sample
= 0.19635 x 0.34
= 0.06676 m^3

Dry Density = Weight / Volume
= 748.963 kg/m^3

Dry waste weight = 50 kgs

Table C-1.8. Hydraulic conductivity of model waste using large-scale permeameter – constant head test (ρ_{dry} = 750kg/m^3)

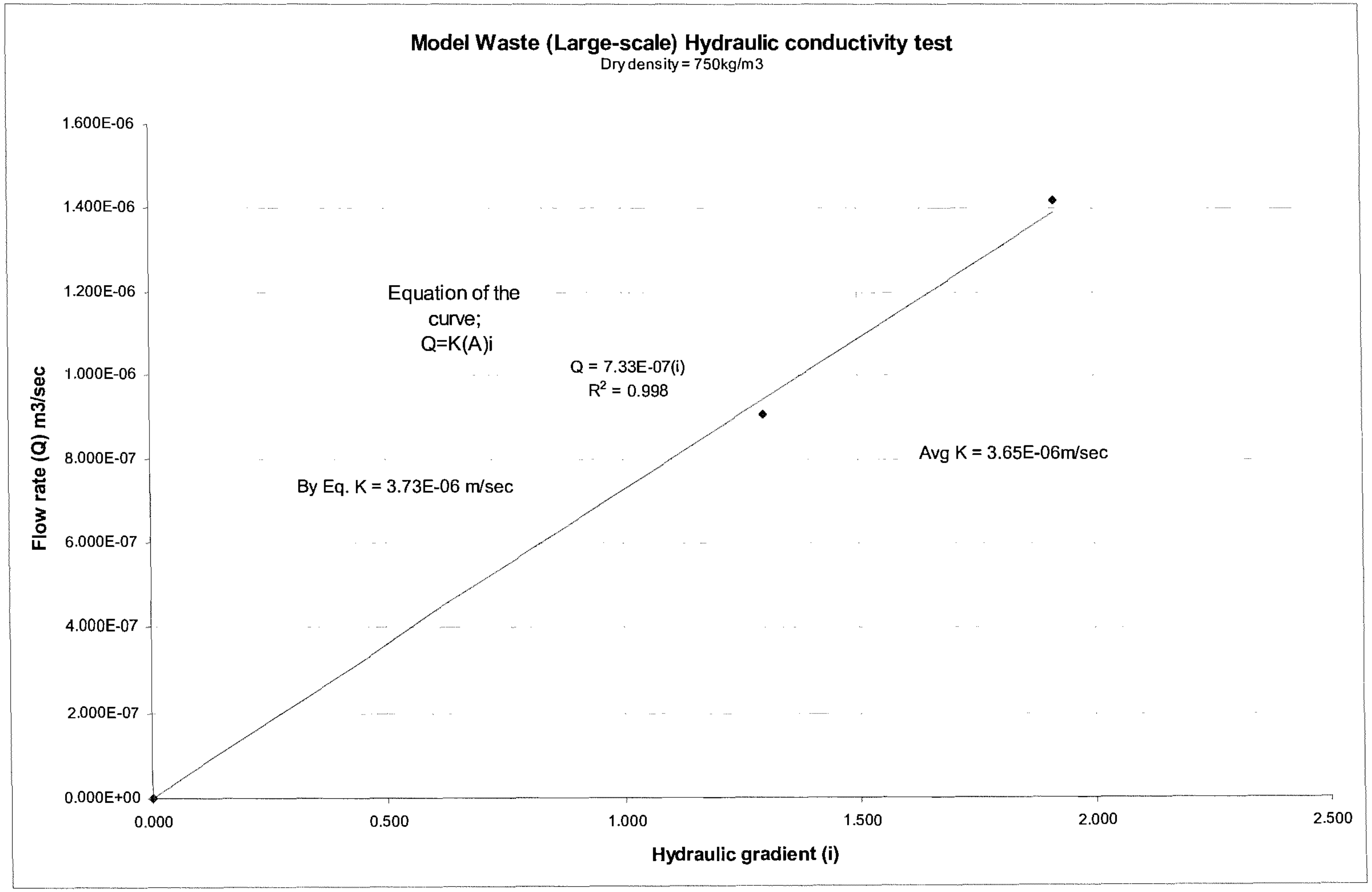


Figure C-1.8. Darcian relationship in model waste using large-scale permeameter – constant head test (ρ_{dry} = 750kg/m^3)

Determination of Hydraulic conductivity of Model waste using Medium-scale permeameter - Constant Head Test

Dry density of waste = 365kg/m3

Observations & Calculations

Length of Sample = 0.30 m
X Area of Sample = 0.04524 m^2

											1 lit	in							
Test run No	Hp1 m	Hp2 m	Hp3 m	Hp4 m	P(H1-H2) m	P(H2-H3) m	P(H1-H3) m	Grad(12)	Grad(23)	Hgrad(13)	min	sec	Q = (m^3/s)	K (1-2) (m/sec)	K (2-3) (m/sec)	K (1-3) (m/sec)	Q (m^3/s)	K (m/sec)	Hgrad(13)
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	1.439	1.443	1.453	1.455	0.004	0.010	0.014	0.035	0.080	0.058	6	13	2.68E-06	1.7038E-03	7.4079E-04	1.0159E-03	2.68E-06	1.0159E-03	0.058
2	1.275	1.295	1.325	1.330	0.020	0.030	0.050	0.174	0.240	0.208	2	1	8.26E-06	1.0505E-03	7.6120E-04	8.7690E-04	8.26E-06	8.7690E-04	0.208
3	1.200	1.230	1.265	1.275	0.030	0.035	0.065	0.261	0.280	0.271	1	32	1.09E-05	9.2105E-04	8.5813E-04	8.8717E-04	1.09E-05	8.8717E-04	0.271
																	Avg k =	9.2667E-04	m/sec

Density of Waste

Volume of Waste Sample = X-sec Area x Length of Sample
= 0.04524 x 0.30
= 0.01357 m^3

Dry Density = Weight / Volume

Weight of Waste (Dry) = 5000 gms

= 368.406 kg/m^3

Table C-2.1. Hydraulic conductivity of model waste using medium-scale permeameter – constant head test (ρ_{dry} = 365kg/m^3)

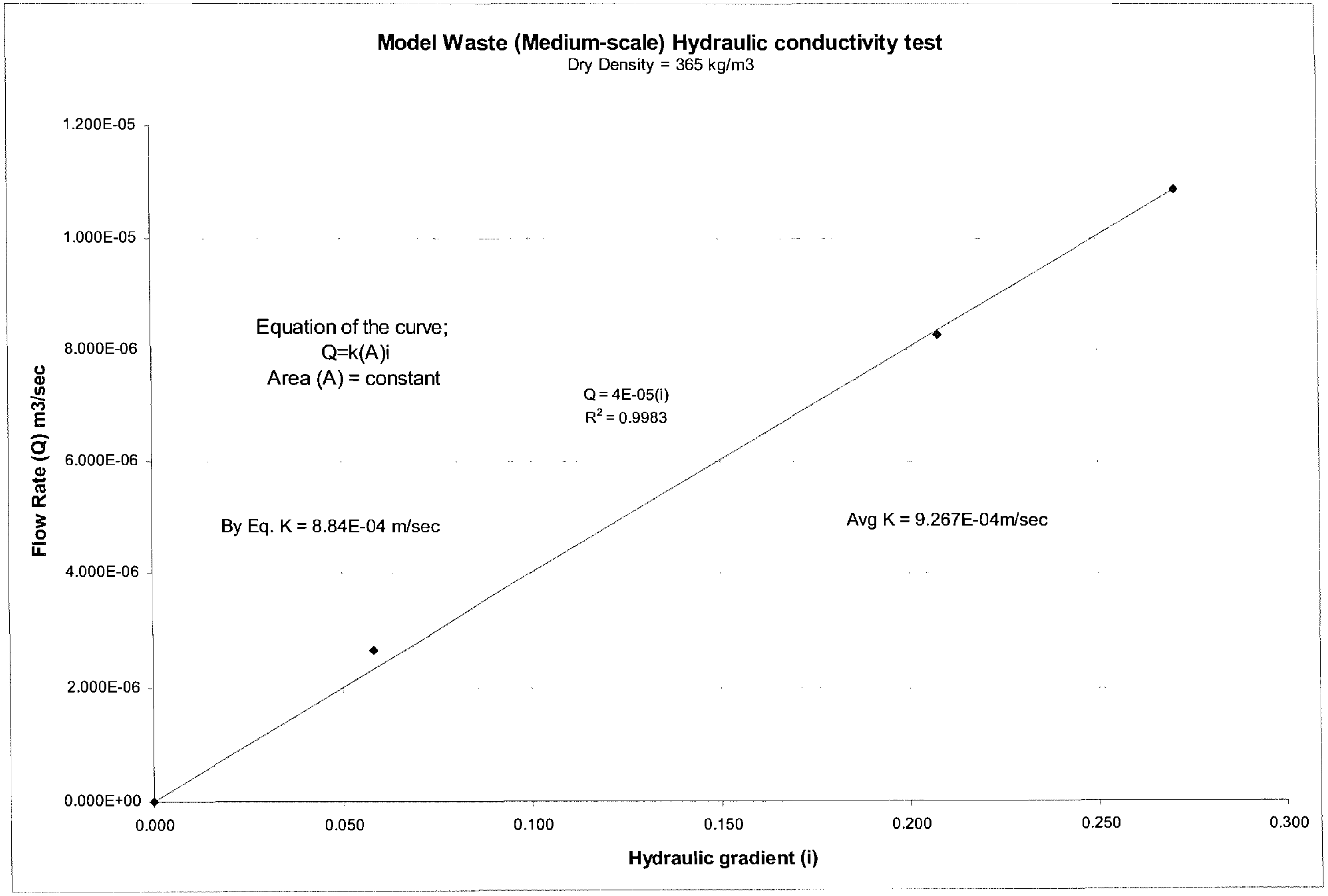


Figure C-2.1. Darcian relationship in model waste using medium-scale permeameter – constant head test (ρ_{dry} = 365kg/m^3)

Determination of Hydraulic conductivity of Model waste using Medium-scale permeameter - Constant Head Test

Dry density of waste = 400kg/m3

Observations & Calculations

Length of Sample = 0.30 m
X Area of Sample = 0.04524 m^2

											1 lit	in							
Test run No	Hp1	Hp2	Hp3	Hp4	P(H1-H2)	P(H2-H3)	P(H1-H3)	Grad(12)	Grad(23)	Hgrad(13)	min	sec	Q = (m^3/s)	K (1-2)	K (2-3)	K (1-3)	Q	K	Hgrad(13)
	m	m	m	m	m	m	m							(m/sec)	(m/sec)	(m/sec)	(m^3/s)	(m/sec)	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	1.405	1.430	1.450	1.455	0.025	0.020	0.045	0.217	0.160	0.188	4	25	3.77E-06	3.8371E-04	5.2135E-04	4.4489E-04	3.77E-06	4.4489E-04	0.188
2	1.190	1.280	1.355	1.365	0.090	0.075	0.165	0.783	0.600	0.688	1	20	1.25E-05	3.5307E-04	4.6053E-04	4.0191E-04	1.25E-05	4.0191E-04	0.688
3	0.725	0.870	1.000	1.020	0.145	0.130	0.275	1.261	1.040	1.146	0	52	1.92E-05	3.3715E-04	4.0875E-04	3.7100E-04	1.92E-05	3.7100E-04	1.146
																	Avg k =	4.0593E-04	m/sec

Density of Waste

Volume of Waste Sample = X-sec Area x Length of Sample
= 0.04524 x 0.30
= 0.01357 m^3

Dry Density = Weight / Volume

Weight of Waste (Dry) = 5425 gms

= 399.72 kg/m^3

Table C-2.2. Hydraulic conductivity of model waste using medium-scale permeameter – constant head test (ρ_{dry} = 400kg/m^3)

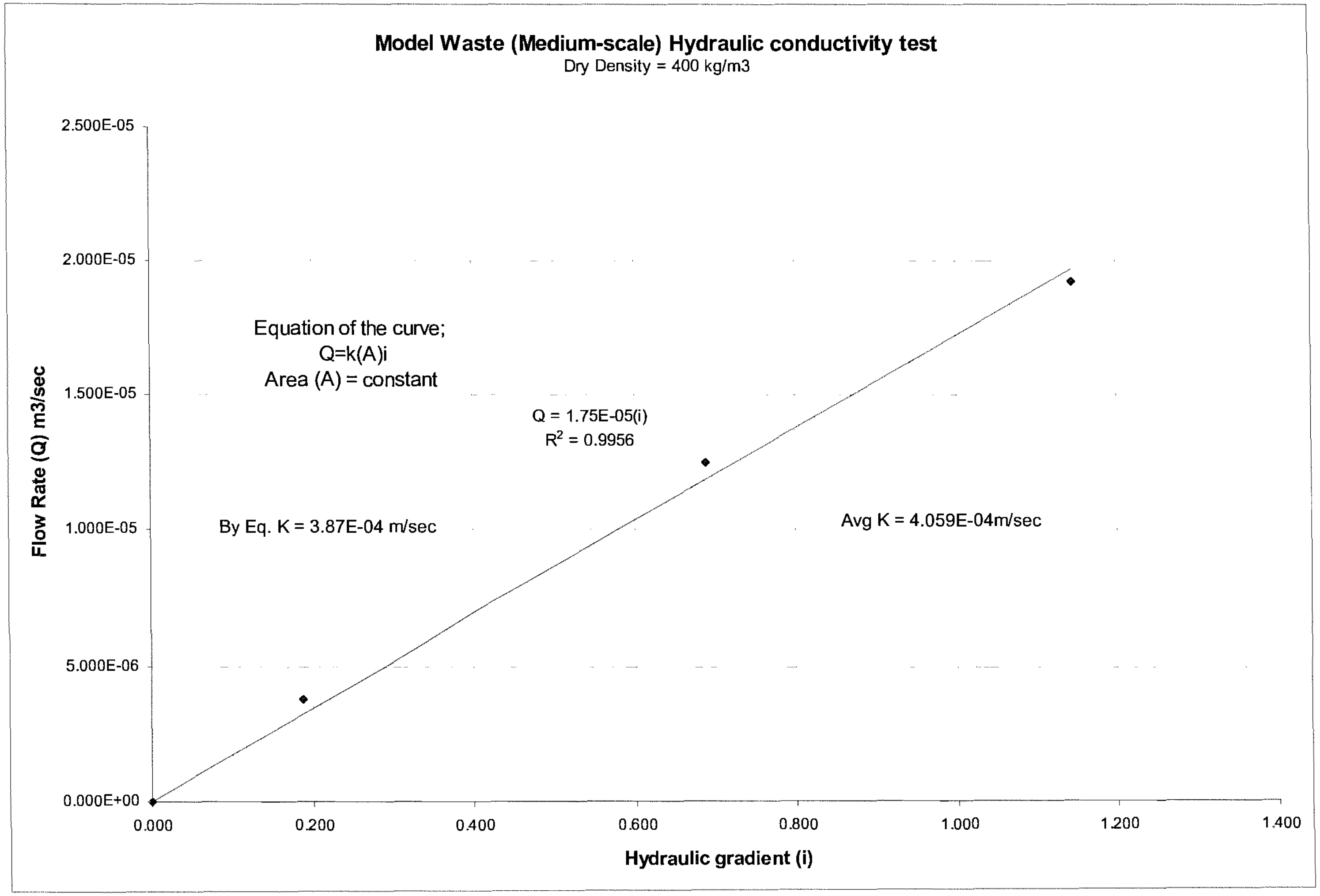


Figure C-2.2. Darcian relationship in model waste using medium-scale permeameter – constant head test ($\rho_{dry} = 400 kg/m^3$)

Determination of Hydraulic conductivity of Model waste using Medium-scale permeameter - Constant Head Test

Dry density of waste = 440kg/m3

Observations & Calculations

Length of Sample = 0.30 m
X Area of Sample = 0.04524 m^2

											1 lit in								
Test run No	Hp1 m	Hp2 m	Hp3 m	Hp4 m	P(H1-H2) m	P(H2-H3) m	P(H1-H3) m	Grad(12)	Grad(23)	Hgrad(13)	min	sec	Q = (m^3/s)	K (1-2) (m/sec)	K (2-3) (m/sec)	K (1-3) (m/sec)	Q (m^3/s)	K (m/sec)	Hgrad(13)
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	1.358	1.375	1.435	1.440	0.017	0.060	0.077	0.148	0.480	0.321	5	39	2.95E-06	4.4111E-04	1.3585E-04	2.0324E-04	2.95E-06	2.0324E-04	0.321
2	1.275	1.305	1.415	1.423	0.030	0.110	0.140	0.261	0.880	0.583	3	9	5.29E-06	4.4834E-04	1.3291E-04	2.0050E-04	5.29E-06	2.0050E-04	0.583
3	1.070	1.125	1.335	1.345	0.055	0.210	0.265	0.478	1.680	1.104	1	47	9.35E-06	4.3196E-04	1.2297E-04	1.8710E-04	9.35E-06	1.8710E-04	1.104
																	Avg k =	1.9695E-04	m/sec

Density of Waste

Volume of Waste Sample = X-sec Area x Length of Sample
= 0.04524 x 0.30
= 0.01357 m^3

Weight of Waste (Dry) = 6000 gms

Dry Density = Weight / Volume
= 442.087 kg/m^3

Table C-2.3. Hydraulic conductivity of model waste using medium-scale permeameter – constant head test (ρ_{dry} = 440kg/m^3)

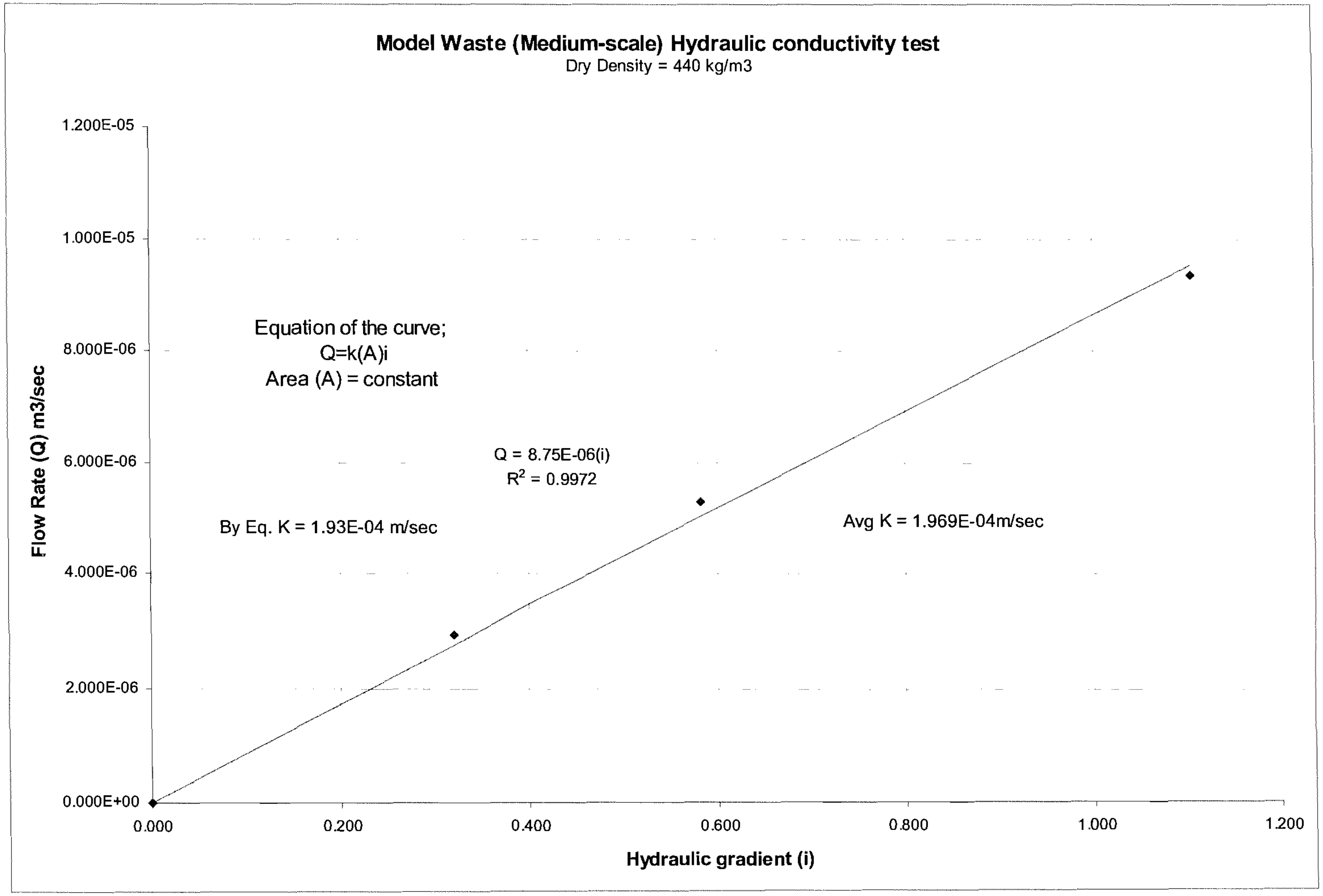


Figure C-2.3. Darcian relationship in model waste using medium-scale permeameter – constant head test (ρ_{dry} = 440kg/m^3)

Determination of Hydraulic conductivity of Model waste using Medium-scale permeameter - Constant Head Test

Dry density of waste = 480kg/m3

Observations & Calculations

Length of Sample = 0.29 m

X Area of Sample = 0.04524 m^2

											1 lit in								
Test run No	Hp1	Hp2	Hp3	Hp4	P(H1-H2)	P(H2-H3)	P(H1-H3)	Grad(12)	Grad(23)	Hgrad(13)	min	sec	Q = (m^3/s)	K (1-2)	K (2-3)	K (1-3)	Q	K	Hgrad(13)
	m	m	m	m	m	m	m							(m/sec)	(m/sec)	(m/sec)	(m^3/s)	(m/sec)	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	1.375	1.400	1.455	1.475	0.025	0.055	0.080	0.217	0.440	0.333	8	8	2.05E-06	2.0837E-04	1.0295E-04	1.3589E-04	2.05E-06	1.3589E-04	0.333
2	1.105	1.180	1.370	1.420	0.075	0.190	0.265	0.652	1.520	1.104	2	46	6.02E-06	2.0419E-04	8.7608E-05	1.2060E-04	6.02E-06	1.2060E-04	1.104
3	0.860	0.970	1.265	1.350	0.110	0.295	0.405	0.957	2.360	1.688	1	52	8.93E-06	2.0634E-04	8.3631E-05	1.1696E-04	8.93E-06	1.1696E-04	1.688
																	Avg k =	1.2448E-04	m/sec

Density of Waste

Volume of Waste Sample = X-sec Area x Length of Sample

= 0.04524 x 0.29

= 0.01312 m^3

Dry Density = Weight / Volume

Weight of Waste (Dry) = 6325 gms

= 482.103 kg/m^3

Table C-2.4. Hydraulic conductivity of model waste using medium-scale permeameter – constant head test (ρ_{dry} = 480kg/m^3)

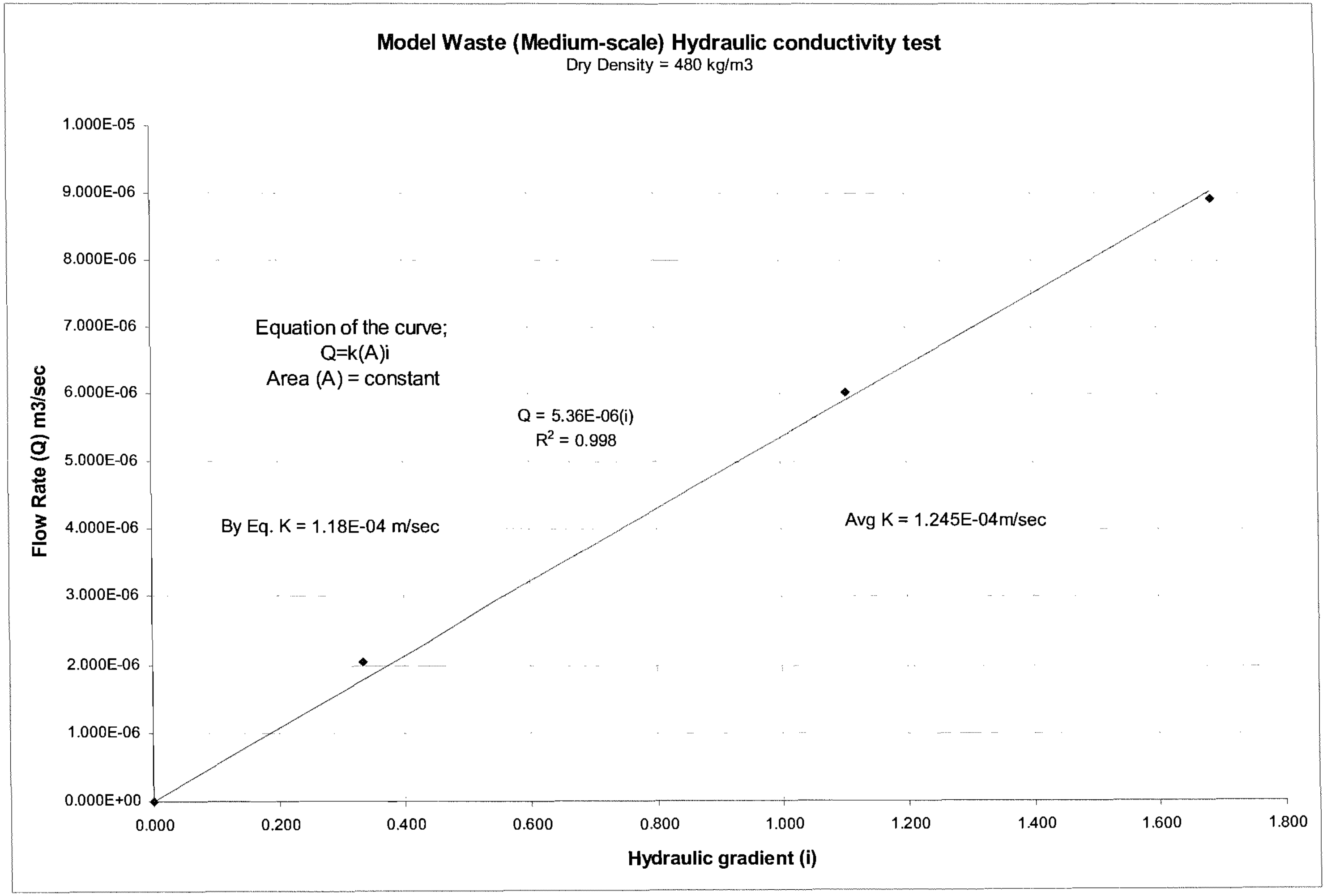


Figure C-2.4. Darcian relationship in model waste using medium-scale permeameter – constant head test (ρ_{dry} = 480kg/m^3)

Determination of Hydraulic conductivity of Model waste using Medium-scale permeameter - Constant Head Test

Dry density of waste = 275kg/m3

Observations & Calculations

Length of Sample = 0.33 m
X Area of Sample = 0.00636 m^2

											1 lit in								
Test run No	Hp1 m	Hp2 m	Hp3 m	Hp4 m	P(H1-H2) m	P(H2-H3) m	P(H1-H3) m	Grad(12)	Grad(23)	Hgrad(13)	min	sec	Q = (m^3/s)	K (1-2) (m/sec)	K (2-3) (m/scc)	K (1-3) (m/sec)	Q (m^3/s)	K (m/sec)	Hgrad(13)
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	1.490	1.530	1.550	1.560	0.040	0.020	0.060	0.400	0.200	0.300	4	9	4.02E-06	1.5786E-03	3.1573E-03	2.1049E-03	4.02E-06	2.1049E-03	0.300
2	1.420	1.495	1.525	1.535	0.075	0.030	0.105	0.750	0.300	0.525	2	36	6.41E-06	1.3439E-03	3.3597E-03	1.9198E-03	6.41E-06	1.9198E-03	0.525
3	1.160	1.315	1.410	1.418	0.155	0.095	0.250	1.550	0.950	1.250	1	13	1.37E-05	1.3896E-03	2.2672E-03	1.7231E-03	1.37E-05	1.7231E-03	1.250
																	Avg k =	1.9159E-03	m/scc

Density of Waste

Volume of Waste Sample = X-sec Area x Length of Sample
= 0.00636 x 0.33
= 0.00210 m^3

Weight of Waste (Dry) = 577.5 gms

Dry Density = Weight / Volume
= 275.157 kg/m^3

Table C-3.1. **Hydraulic conductivity of model waste using small-scale permeameter – constant head test ($\rho_{dry} = 275kg/m^3$)**

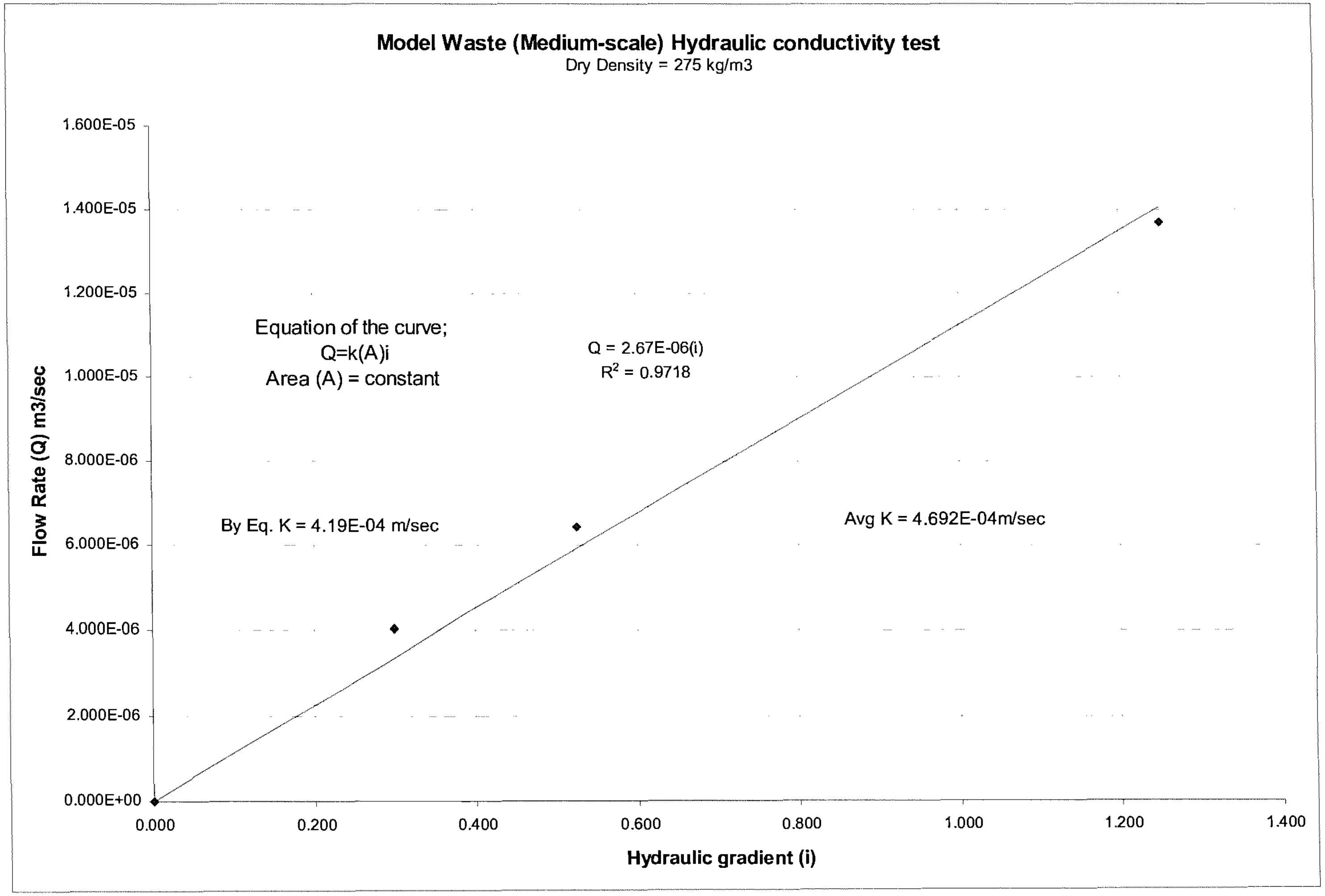


Figure C-3.1. Darcian relationship in model waste using small-scale permeameter – constant head test (ρ_{dry} = 275kg/m^3)

Determination of Hydraulic conductivity of Model waste using Small-scale permeameter - Constant Head Test

Dry density of waste = 355kg/m3

Observations & Calculations

Length of Sample = 0.33 m

X Area of Sample = 0.00636 m^2

											1 lit	in							
Test run No	Hp1	Hp2	Hp3	Hp4	P(H1-H2)	P(H2-H3)	P(H1-H3)	Grad(12)	Grad(23)	Hgrad(13)	min	sec	Q = (m^3/s)	K (1-2)	K (2-3)	K (1-3)	Q	K	Hgrad(13)
	m	m	m	m	m	m	m							(m/sec)	(m/sec)	(m/sec)	(m^3/s)	(m/sec)	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	1.475	1.555	1.585	1.590	0.080	0.030	0.110	0.800	0.300	0.550	4	38	3.60E-06	7.0698E-04	1.8853E-03	1.0283E-03	3.60E-06	1.0283E-03	0.550
2	1.250	1.465	1.545	1.550	0.215	0.080	0.295	2.150	0.800	1.475	2	10	7.69E-06	5.6255E-04	1.5119E-03	8.1999E-04	7.69E-06	8.1999E-04	1.475
3	0.950	1.330	1.470	1.475	0.380	0.140	0.520	3.800	1.400	2.600	1	19	1.27E-05	5.2376E-04	1.4216E-03	7.6550E-04	1.27E-05	7.6550E-04	2.600
																	Avg k =	8.7127E-04	m/sec

Density of Waste

Volume of Waste Sample = X-sec Area x Length of Sample

= 0.00636 x 0.33

= 0.00210 m^3

Dry Density = Weight / Volume

Weight of Waste (Dry) = 750 gms

= 357.347 kg/m^3

Table C-3.2. Hydraulic conductivity of model waste using small-scale permeameter – constant head test (ρ_{dry} = 355kg/m^3)

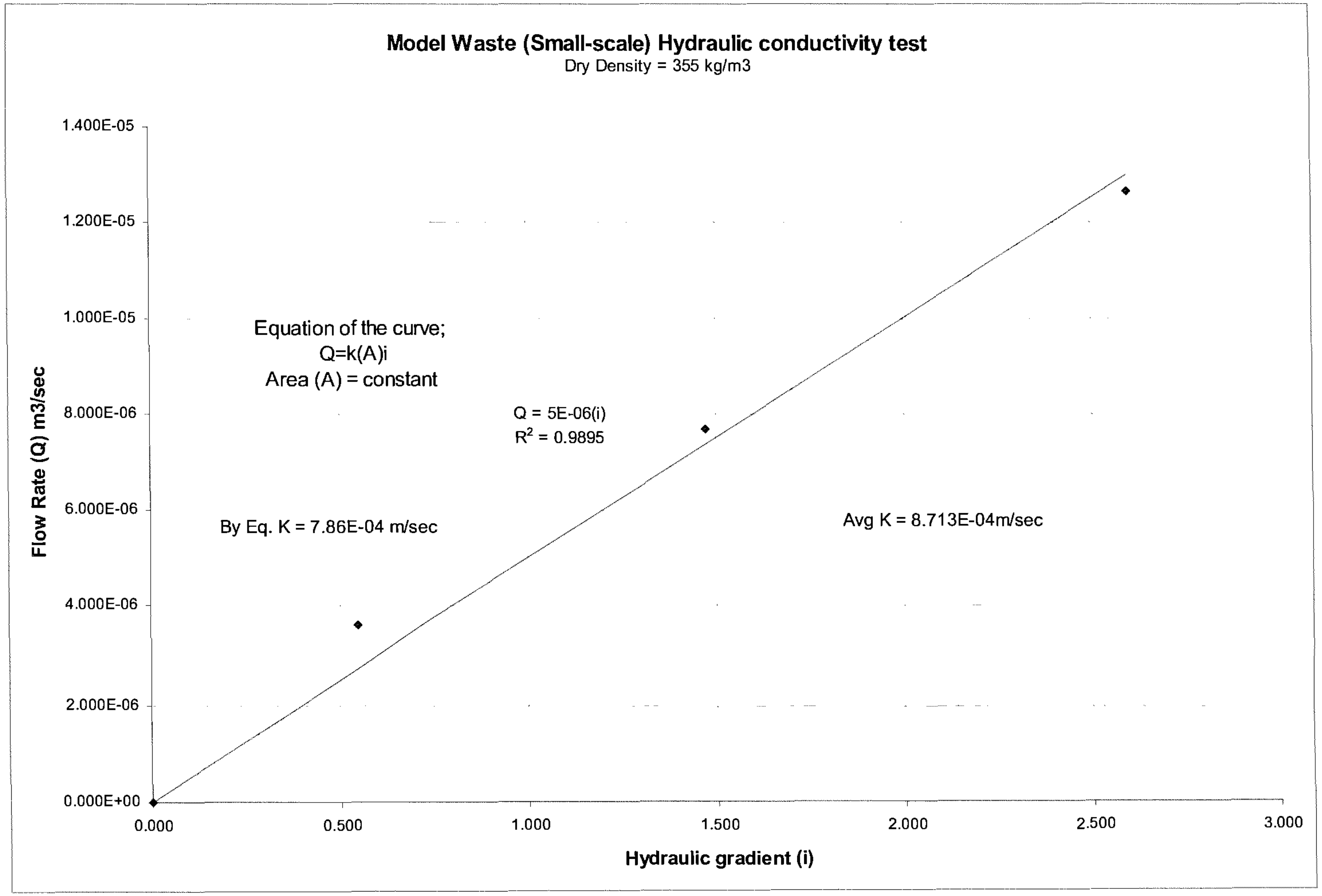


Figure C-3.2. Darcian relationship in model waste using small-scale permeameter – constant head test (ρ_{dry} = 355kg/m^3)

Determination of Hydraulic conductivity of Model waste using Small-scale permeameter - Constant Head Test

Dry density of waste = 425kg/m3

Observations & Calculations

Length of Sample = 0.33 m
X Area of Sample = 0.00636 m^2

											1 lit	in							
Test run	Hp1	Hp2	Hp3	Hp4	P(H1-H2)	P(H2-H3)	P(H1-H3)	Grad(12)	Grad(23)	Hgrad(13)	min	sec	Q = (m^3/s)	K (1-2)	K (2-3)	K (1-3)	Q	K	Hgrad(13)
No	m	m	m	m	m	m	m							(m/sec)	(m/sec)	(m/sec)	(m^3/s)	(m/sec)	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.830	1.095	1.440	1.520	0.265	0.345	0.610	2.650	3.450	3.050	2	11	7.63E-06	4.5292E-04	3.4790E-04	3.9352E-04	7.63E-06	3.9352E-04	3.050
2	1.205	1.330	1.510	1.550	0.125	0.180	0.305	1.250	1.800	1.525	3	38	4.59E-06	5.7700E-04	4.0069E-04	4.7295E-04	4.59E-06	4.7295E-04	1.525
3	1.390	1.450	1.545	1.570	0.060	0.095	0.155	0.600	0.950	0.775	6	15	2.67E-06	6.9881E-04	4.4135E-04	5.4102E-04	2.67E-06	5.4102E-04	0.775
																	Avg k =	4.6916E-04	m/sec

Density of Waste

Volume of Waste Sample = X-sec Area x Length of Sample
= 0.00636 x 0.33
= 0.00210 m^3

Dry Density = Weight / Volume

Weight of Waste (Dry) = 900 gms

= 428.816 kg/m^3

Table C-3.3. Hydraulic conductivity of model waste using small-scale permeameter – constant head test (ρ_{dry} = 425kg/m^3)

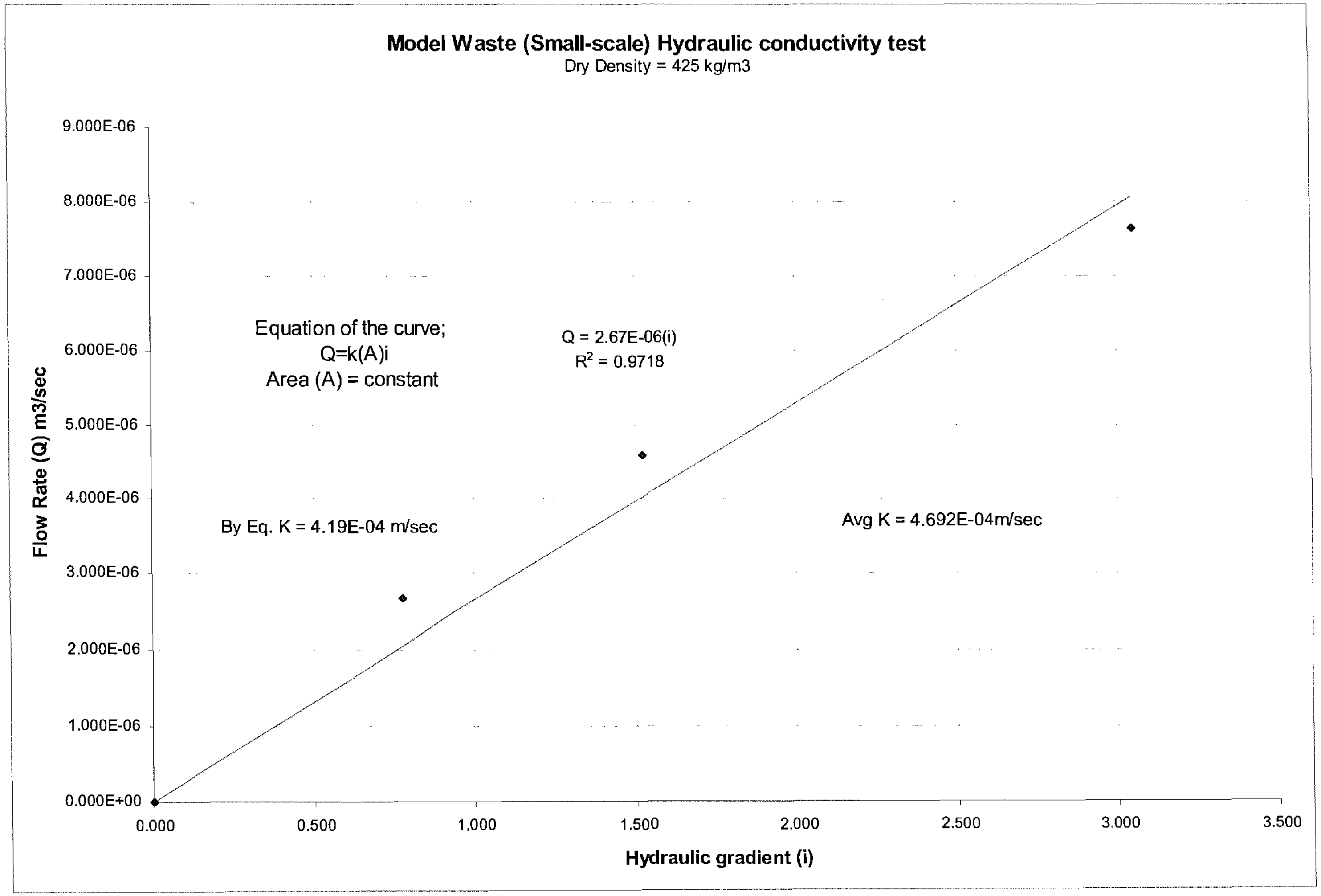


Figure C-3.3. Darcian relationship in model waste using small-scale permeameter – constant head test (ρ_{dry} = 425kg/m^3)

Appendix D

(Suction determination – Observations and Calculations sheets)

Determination of suction characteristics of Model waste

Dry Density of Sample Waste = 500 kg/m3

Mc	Top Fppr Mc	Bot Fppr Mc	Suction kPa	Suction kPa	Dif (log kPa)
0	0.45	1.37	201836.6	163305.2	-0.092
2	10.14	10.14	21677.0	21677.0	0.000
4	14.69	14.69	7603.3	7603.3	0.000
5	20.65	18.05	1927.52	3507.52	0.260
6	24.53	24.1	788.9	871.0	0.043
8	27.7	26.17	380.2	540.8	0.153
10	27.35	25.45	412.1	638.3	0.190
15	27.23	26.04	423.6	557.2	0.119
20	29.57	26.85	247.2	462.4	0.272

Avg Suction kPa	Bulk Density kg/m3
182570.92	500
21677.04	510
7603.26	520
2717.52	525
829.91	530
460.47	540
525.18	550
490.41	575
354.78	600

Determination of suction characteristics of Model waste

Dry Density of the waste sample = 750 kg/m3

Mc	Bot Fppr Mc	Top Fppr Mc	Suction kPa	Suction kPa	Dif (log kPa)
0	2.75	7.11	118850.2	43551.2	0.436
2	8.56	6.31	31188.9	52360.0	-0.225
4	14.28	12.88	8356.0	11534.5	-0.140
5	16.66	22.06	4830.59	1393.16	0.540
6	20.27	21.86	2103.8	1458.8	0.159
8	20.45	21	2018.4	1778.3	0.055
10	27.23	26.88	423.64	459.20	-0.035
15	28.44	27.83	320.63	368.98	-0.061
20	27.57	26.69	391.74	479.73	-0.088

Avg Suction kPa	Density kg/m3
81200.71	750
41774.47	765
9945.28	780
3111.87	790
1781.30	795
1898.32	810
441.42	825
344.80	863
435.74	900

Determination of suction characteristics of Model waste

Dry Density of Sample Waste = 1000 kg/m3

Mc	Bot Fppr Mc%	Top Fppr Mc%	Suction (kPa)	Suction (kPa)	Dif (log kPa)
0	3.65	4.72	96605.1	75509.2	-0.107
2	7.51	7.41	39719.2	40644.3	0.010
4	14.15	14.68	8609.9	7620.8	-0.053
5	15.13	16.17	6870.68	5407.54	-0.104
6	16.11	17.67	5482.8	3828.2	-0.156
8	19.82	17.45	2333.5	4027.2	0.237
10	21.3	23	1659.59	1122.02	-0.170
15	25.45	27.65	638.26	384.59	-0.220
20	25.23	26.4	671.43	512.86	-0.117

Avg Suction kPa	Bulk Density kg/m3
86057.16	1000
40181.74	1020
8115.36	1040
6139.11	1050
4655.51	1060
3180.31	1080
1390.80	1100
511.43	1150
592.15	1200

Table D-1.1. Determination of suction characteristics of model waste mix with varying dry density – preliminary tests

Determination of Model Waste Suction using Filter Paper method

Sample Designation : 1, 2, 3 & 4

Sampling Date : 5 -15th July 1999

Date of Analysis : 12 - 23rd July 1999

Method used (Contact or Non-Contact) Non-contact method

Other info :

Modified Dano waste suction determination.
Moisture content 5, 10, 15, 20, 30 & 50% dry weight basis

Sample # (Spec.)		#1	#1	#2	#2	#3	#3	#4	#4	#5	#5	#6	#6	Remarks
Moisture Tin No		#74	#67	#30	#28	#46	#52	#85	#45	#46	#28	#25	#97	
Top/Bottom Filter Paper (Fp)		T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	
Tin Tare (cold) Mass, gms	Tc	8.492	8.160	8.443	8.472	8.532	8.635	8.488	8.486	8.531	8.470	8.521	8.143	
Mass of (Wet Fp + Tare Tin cold), gms	M1	8.736	8.391	8.680	8.723	8.793	8.891	8.736	8.745	8.794	8.745	8.794	8.413	
Mass of (Dry Fp + Tare Tin hot), gms	M2	8.712	8.368	8.649	8.688	8.750	8.852	8.695	8.702	8.742	8.688	8.735	8.356	
Tin Tare (hot) Mass, gms	Th	8.488	8.156	8.440	8.468	8.528	8.631	8.485	8.483	8.528	8.467	8.517	8.139	
Mass of Dry Fp = (M2-Th), gms	Mf	0.224	0.212	0.209	0.220	0.222	0.221	0.210	0.219	0.214	0.221	0.218	0.217	
Mass of Water in Fp= (M1-M2-Tc+Th), gms	Mw	0.020	0.019	0.028	0.031	0.039	0.035	0.038	0.040	0.049	0.054	0.055	0.053	
Water Content of Filter paper = (Mw/Mf)	Wf	0.0893	0.0896	0.1340	0.1409	0.1757	0.1584	0.1810	0.1826	0.2290	0.2443	0.2523	0.2442	
Percentage of Moisture in Fp (%)	% Wf	8.93	8.96	13.40	14.09	17.57	15.84	18.10	18.26	22.90	24.43	25.23	24.42	
Avg Moisture in Fp (Avg Wf)			0.0895		0.1374		0.1670		0.1818	22.8972	24.4344	25.23	24.42	
Sample Moisture Content , %	Ws %	5	5	10	10	15	15	20	20	30	30	50	50	
Suction, kPa (for Wf < 0.3172)	ψ	28651.2	28429.8	10239.7	8727.89	3919.61	5838.34	3471.17	3338.23	1148.9	806.42	671.528	808.358	
Avg Suction, kPa (Top+Bot)/2 , if	log (ψ)	4.45714	4.45377	4.01029	3.94091	3.59324	3.76629	3.54048	3.52352	3.06028	2.90656	2.82706	2.9076	
|log (Top)-log(Bot)| < 0.5 log kPa	Diff.	-0.00337		-0.06938		0.17305		-0.01696		-0.15372		0.08054		
Avg Suction, kPa (Top+Bot)/2	Avg		28540.5		9483.79		4878.98		3404.7		977.657		739.943	
Vol. Water Cont. of Sample θω	θω													
Sample Bulk Density ρω (kg/m3)	ρω	276.3		292.2		304.4		316.6		254		293.3		

Table D-1.2. Determination of suction characteristics of Dano waste (modified) – exploratory test

Determination of Waste Suction using Filter Paper method

Sample Designation : 1A, 2A, 3A & 4A
Sampling Date : 4 - 5th Feb 2000
Date of Analysis : 13th Feb 2000

Method used (Contact or Non-Contact) Non - contact method
Other info :

Studying the effect of particle size on suction
Bulk density = 650 - 750 kg/m3
Dano waste residual fine particles (<10mm ø)

Sample # (Spec.)		Prtcl Dia < 1.18mm		1.18<P.dia<2.36mm		2.36< P.dia< 5mm		5 < P.dia< 10 mm				
Moisture Tin No		# 25	# 28	# 30	# 45	# 46	# 52	# 67	# 74	#	#	Remarks
Top/Bottom Filter Paper (Fp)		Bot	Top	Bot	Top	Bot	Top	Bot	Top	T / B	T / B	
Tin Tare (cold) Mass, gms	Tc	8.518	8.467	8.440	8.484	8.530	8.632	8.157	8.489			
Mass of (Wet Fp + Tare Tin cold), gms	M1	8.752	8.699	8.684	8.732	8.774	8.877	8.413	8.751			
Mass of (Dry Fp + Tare Tin hot), gms	M2	8.726	8.672	8.650	8.701	8.736	8.841	8.368	8.707			
Tin Tare (hot) Mass, gms	Th	8.515	8.464	8.437	8.481	8.527	8.629	8.155	8.486			
Mass of Dry Fp = (M2-Th), gms	Mf	0.211	0.208	0.213	0.220	0.209	0.212	0.213	0.221			
Mass of Water in Fp= (M1-M2-Tc+Th), gms	Mw	0.023	0.024	0.031	0.028	0.035	0.033	0.043	0.041			
Water Content of Filter paper = (Mw/Mf)	Wf	0.1090	0.1154	0.1455	0.1273	0.1675	0.1557	0.2019	0.1855			
Percentage of Moisture in Fp (%)	% Wf	10.90	11.54	14.55	12.73	16.75	15.57	20.19	18.55			
Sample Moisture Content , %	Ws %	10		10		10		10				
Suction, kPa (for Wf < 0.3172)	ψ	18195.02	15709.19	7845.144	11947.38	4735.424	6214.357	2143.98	3124.614			
Avg Suction, kPa (Top+Bot)/2 when	log (ψ)	4.259953	4.196154	3.894601	4.077273	3.675359	3.793396	3.331221	3.494796			
|log (Top)-log(Bot)| < 0.5 log kPa	Diff.	-0.0638		0.182672		0.118037		0.163576				
Avg Suction, kPa (Top+Bot)/2		16952.11		9896.263		5474.891		2634.297				
Vol. Water Cont. of Sample θω	θω											
Sample Bulk Density ρω (kg/m3)	ρω											

Table D-1.3. Determination of particle size effect on the waste suction characteristics

Determination of Model Waste Suction using Filter Paper method

Sample Designation : 1, 2, 3 & 4
Sampling Date : 17th June 2001
Date of Analysis : 26th - 27th June 2001

Method used (Contact or Non-Contact) Both
Other info :

Model Waste suction determination.
Moisture content 5, 10, 15, 20% by dry weight basis
Dry density = 300 kg/m3

Sample # (Spec.)		#1	#1	#2	#2	#3	#3	#4	#4	M#1	M#2	M#3	M#4	
Moisture Tin No		#25	#28	#30	#45	#46	#52	#67	#74	#85	#89	#97	#100	Remarks
Top/Bottom Filter Paper (Fp)		T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	
Tin Tare (cold) Mass, gms	Tc	8.514	8.463	8.432	8.483	8.529	8.628	8.156	8.487	8.486	8.458	8.138	8.486	
Mass of (Wet Fp + Tare Tin cold), gms	M1	8.765	8.709	8.701	8.751	8.799	8.897	8.442	8.778	8.607	8.601	8.270	8.639	
Mass of (Dry Fp + Tare Tin hot), gms	M2	8.735	8.682	8.647	8.698	8.744	8.846	8.378	8.710	8.591	8.575	8.239	8.595	
Tin Tare (hot) Mass, gms	Th	8.510	8.459	8.428	8.479	8.525	8.625	8.153	8.483	8.482	8.454	8.134	8.482	
Mass of Dry Fp = (M2-Th), gms	Mf	0.225	0.223	0.219	0.219	0.219	0.221	0.225	0.227	0.109	0.121	0.105	0.113	
Mass of Water in Fp= (M1-M2-Tc+Th), gms	Mw	0.026	0.023	0.050	0.049	0.051	0.048	0.061	0.064	0.012	0.022	0.027	0.040	
Water Content of Filter paper = (Mw/Mf)	Wf	0.1156	0.1031	0.2283	0.2237	0.2329	0.2172	0.2711	0.2819	0.1101	0.1818	0.2571	0.3540	
Percentage of Moisture in Fp (%)	% Wf	11.56	10.31	22.83	22.37	23.29	21.72	27.11	28.19	11.01	18.18	25.71	35.40	
Avg Moisture in Fp (Avg Wf)			0.1093		0.2260		0.2250		0.2765	11.0092	18.1818	25.71	35.40	
Sample Moisture Content , %	Ws %	5	5	10	10	15	15	20	20	5	10	15	20	
Suction, kPa (for Wf < 0.3172)	ψ	15647.5	20826.2	1166.53	1295.86	1050.11	1506.8	435.4	339.326	17745.3	3402.66	600.581	130.163	
Avg Suction, kPa (Top+Bot)/2 , if	log (ψ)	4.19444	4.31861	3.06689	3.11256	3.02123	3.17805	2.63889	2.53062	4.24908	3.53182	2.77857	2.11449	
|log (Top)-log(Bot)| < 0.5 log kPa	Diff.	0.12417		0.04566		0.15682		-0.10827						
Avg Suction, kPa (Top+Bot)/2	Avg		18236.8		1231.19		1278.45		387.363	17745.3	3402.66	600.581	130.163	
Vol. Water Cont. of Sample θω	θω													
Sample Bulk Density ρω (kg/m3)	ρω													

Table D-2.1. Determination of model waste suction characteristics using filter paper method – Phase 1 test (dry density = 300kg/m^3)

Determination of Waste Suction using Filter Paper method

Sample Designation : Nos. I, II, III and IV
Sampling Date : 15th May 2001
Date of Analysis : Redo (6th June 2001)

Method used (Contact or Non-Contact) Contact and Non-Contact both
Other info :

Dry Density of the sample = 350 kg/m3
All samples having same density and changing MC
Moisture content = 5%, 10%, 15% & 20% respectively

Sample # (Spec.)		#I	#I	#II	#II	#III	#III	#IV	#IV	M#I	M#II	M#III	M#IV	Remarks
Moisture Tin No		#25	#28	#30	#45	#46	#52	#67	#74	#85	#89	#97	#100	
Top/Bottom Filter Paper (Fp)		T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	
Tin Tare (cold) Mass, gms	Tc	8.515	8.465	8.436	8.484	8.530	8.630	8.157	8.488	8.486	8.460	8.139	8.488	
Mass of (Wet Fp + Tare Tin cold), gms	M1	8.762	8.715	8.697	8.744	8.808	8.890	8.447	8.773	8.625	8.616	8.284	8.681	
Mass of (Dry Fp + Tare Tin hot), gms	M2	8.723	8.677	8.653	8.697	8.745	8.834	8.378	8.705	8.602	8.581	8.243	8.609	
Tin Tare (hot) Mass, gms	Th	8.511	8.460	8.430	8.479	8.526	8.625	8.153	8.483	8.483	8.456	8.135	8.484	
Mass of Dry Fp = (M2-Th), gms	Mf	0.212	0.217	0.223	0.218	0.219	0.209	0.225	0.222	0.119	0.125	0.108	0.125	
Mass of Water in Fp= (M1-M2-Tc+Th), gms	Mw	0.035	0.033	0.038	0.042	0.059	0.051	0.065	0.063	0.020	0.031	0.037	0.068	
Water Content of Filter paper = (Mw/Mf)	Wf	0.1651	0.1521	0.1704	0.1927	0.2694	0.2440	0.2889	0.2838	0.1681	0.2480	0.3426	0.5440	
Percentage of Moisture in Fp (%)	% Wf	16.51	15.21	17.04	19.27	26.94	24.40	28.89	28.38	16.81	24.80	34.26	54.40	
Avg Moisture in Fp (Avg Wf)			15.8584		18.1532		25.6713		28.6336					
Sample Moisture Content , %	Ws %	5	5	10	10	15	15	20	20	5	10	15	20	
Suction, kPa (for Wf < 0.3172)	ψ	5001	6749.36	4425.52	2650.91	452.831	812.472	289.142	325.209	4670.12	741.31	136.226	60.8998	
Avg Suction, kPa (Top+Bot)/2 , if	log (ψ)	3.69906	3.82926	3.64596	3.42339	2.65594	2.90981	2.46111	2.51216					
|log (Top)-log(Bot)| < 0.5 log kPa	Diff.	0.13021		0.22257		-0.25387		0.05105						
Avg Suction, kPa (Top+Bot)/2	Avg		5875.18		3538.21		632.652		307.175	4670.12	741.31	136.226	60.900	
Vol. Water Cont. of Sample θω	θω													
Sample Bulk Density ρω (kg/m3)	ρω													

Table D-2.2. Determination of model waste suction characteristics using filter paper method – Phase 1 test (dry density = 350kg/m^3)

Determination of Model Waste Suction using Filter Paper method

Sample Designation : I, II, III & IV
Sampling Date : 13th June 2001
Date of Analysis : 21st - 22nd June 2001

Method used (Contact or Non-Contact) Both
Other info :

Model Waste suction determination.
Moisture content 5, 10, 15, 20% by dry weight basis
Dry density = 400 kg/m3

Sample # (Spec.)		I	I	II	II	III	III	IV	IV	M#I	M#II	M#III	M#IV	Remarks
Moisture Tin No		#25	#28	#30	#45	#46	#52	#67	#74	#85	#89	#97	#100	
Top/Bottom Filter Paper (Fp)		T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	
Tin Tare (cold) Mass, gms	Tc	8.514	8.464	8.434	8.482	8.529	8.629	8.156	8.487	8.486	8.458	8.138	8.486	
Mass of (Wet Fp + Tare Tin cold), gms	M1	8.763	8.708	8.690	8.728	8.802	8.908	8.434	8.767	8.612	8.602	8.295	8.639	
Mass of (Dry Fp + Tare Tin hot), gms	M2	8.737	8.680	8.654	8.693	8.745	8.853	8.375	8.711	8.595	8.577	8.256	8.601	
Tin Tare (hot) Mass, gms	Th	8.510	8.460	8.430	8.478	8.525	8.625	8.152	8.483	8.482	8.455	8.134	8.483	
Mass of Dry Fp = (M2-Th), gms	Mf	0.227	0.220	0.224	0.215	0.220	0.228	0.223	0.228	0.113	0.122	0.122	0.118	
Mass of Water in Fp= (M1-M2-Tc+Th), gms	Mw	0.022	0.024	0.032	0.031	0.053	0.051	0.055	0.052	0.013	0.022	0.035	0.035	
Water Content of Filter paper = (Mw/Mf)	Wf	0.0969	0.1091	0.1429	0.1442	0.2409	0.2237	0.2466	0.2281	0.1150	0.1803	0.2869	0.2966	
Percentage of Moisture in Fp (%)	% Wf	9.69	10.91	14.29	14.42	24.09	22.37	24.66	22.81	11.50	18.03	28.69	29.66	
Avg Moisture in Fp (Avg Wf)			0.1030		0.1435		0.2323		0.2374	11.5044	18.0328	28.69	29.66	
Sample Moisture Content , %	Ws %	5	5	10	10	15	15	20	20	5	10	15	20	
Suction, kPa (for Wf < 0.3172)	ψ	24034.6	18159	8345.04	8093.56	872.789	1297.65	764.949	1173	15832.8	3521.45	302.794	242.046	
Avg Suction, kPa (Top+Bot)/2 , if	log (ψ)	4.38084	4.25909	3.92143	3.90814	2.94091	3.11316	2.88363	3.0693	4.19956	3.54672	2.48115	2.3839	
|log (Top)-log(Bot)| < 0.5 log kPa	Diff.	-0.12175		-0.01329		0.17225		0.18567						
Avg Suction, kPa (Top+Bot)/2	Avg		21096.8		8219.3		1085.22		968.975	15832.8	3521.45	302.794	242.046	
Vol. Water Cont. of Sample θω	θω													
Sample Bulk Density ρω (kg/m3)	ρω													

Table D-2.3. Determination of model waste suction characteristics using filter paper method – Phase 1 test (dry density = 400kg/m^3)

Determination of Model waste suction using Filter Paper Method

Sample Designation: 3-A, 3-B & 3-C
Sampling Date: 19-Nov-02
Testing Date: 27-Nov-02

Sample Density: 300 kg/m3
Other information: Non Contact Method
5, 10 & 15% moisture content

Moisture Tin No		25	28	30	45	46	52						
Sample Designation / Dry density (kg/m3)		3-A 400	400 3-A	3-B 300	300 3-B	3-C 300	300 3-C						
Cold Tare Mass, g	T_c	8.510	8.458	8.507	8.454	8.427	8.478						
Mass of Wet Filter paper Cold Tare Mass, g	M_1	8.756	8.707	8.763	8.724	8.713	8.755						
Mass of Dry Filter paper Hot Tare Mass, g	M_2	8.721	8.670	8.714	8.676	8.646	8.685						
Hot Tare Mass, g	T_h	8.506	8.454	8.502	8.450	8.422	8.473						
Mass of Dry Filter (M_2-T_h)	M_f	0.215	0.216	0.212	0.226	0.224	0.212						
Mass of Water in Filter (M_1-M_2-T_c+T_h)	M_w	0.031	0.033	0.044	0.044	0.062	0.065						
Water Content of Filter paper, g (M_w/M_f)	W_f	0.144	0.153	0.208	0.195	0.277	0.307						
Suction, kPa	ψ	8094	6641	1882	2530	382	192						
Sample Moisture Content W_s	W_s	0.050	0.050	0.100	0.100	0.150	0.150						
Volumetric Water Content of Sample (θ_w)	θ_w												
Sample Bulk Density ρ_w (kg/m^3)	ρ_w												

Table D-3.1. Determination of model waste suction characteristics using filter paper method – Phase 2 test (Glass) (ρ_{dry} = 300kg/m^3)

Determination of Model waste suction using Filter Paper Method

Sample Designation: 2-A, 2-B & 2-C
Sampling Date: 30-Oct-02
Testing Date: 07-Nov-02

Sample Density: 350 kg/m3
Other information: Non Contact Method
5, 10 & 15% moisture content

Moisture Tin No		67	74	85	89	97	100						
Sample Designation / Dry density (kg/m3)		2-A 350	350 2-A	2-B 350	350 2-B	2-C 350	350 2-C						
Cold Tare Mass, g	T_c	8.153	8.484	8.483	8.452	8.135	8.482						
Mass of Wet Filter paper Cold Tare Mass, g	M_1	8.407	8.744	8.743	8.710	8.412	8.745						
Mass of Dry Filter paper Hot Tare Mass, g	M_2	8.373	8.710	8.702	8.669	8.356	8.695						
Hot Tare Mass, g	T_h	8.151	8.480	8.480	8.449	8.131	8.477						
Mass of Dry Filter (M_2-T_h)	M_f	0.222	0.230	0.222	0.220	0.225	0.218						
Mass of Water in Filter $(M_1-M_2-T_c+T_h)$	M_w	0.032	0.030	0.038	0.038	0.052	0.045						
Water Content of Filter paper, g (M_w/M_f)	W_f	0.144	0.130	0.171	0.173	0.231	0.206						
Suction, kPa	ψ	8101	11108	4348	4195	1094	1931						
Sample Moisture Content W_s	W_s	0.050	0.050	0.100	0.100	0.150	0.150						
Volumetric Water Content of Sample (θ_w)	θ_w												
Sample Bulk Density ρ_w (kg/m^3)	ρ_w												

Table D-3.2. Determination of model waste suction characteristics using filter paper method – Phase 2 test (Glass) (ρ_{dry} = 350kg/m^3)

Determination of Model waste suction using Filter Paper Method

Sample Designation: 1-A, 1-B & 1-C
Sampling Date: 30-Oct-02
Testing Date: 07-Nov-02

Sample Density: 400 kg/m3
Other information: Non Contact Method
5, 10 & 15% moisture content

Moisture Tin No		25	28	30	45	46	52						
Sample Designation / Dry density (kg/m3)		1-A 400	400 1-A	1-B 400	400 1-B	1-C 400	400 1-C						
Cold Tare Mass, g	T_c	8.511	8.458	8.430	8.480	8.528	8.626						
Mass of Wet Filter paper Cold Tare Mass, g	M_1	8.767	8.719	8.694	8.750	8.790	8.907						
Mass of Dry Filter paper Hot Tare Mass, g	M_2	8.730	8.685	8.645	8.698	8.738	8.852						
Hot Tare Mass, g	T_h	8.507	8.454	8.426	8.475	8.524	8.623						
Mass of Dry Filter (M_2-T_h)	M_f	0.223	0.231	0.219	0.223	0.214	0.229						
Mass of Water in Filter $(M_1-M_2-T_c+T_h)$	M_w	0.033	0.030	0.045	0.047	0.048	0.052						
Water Content of Filter paper, g (M_w/M_f)	W_f	0.148	0.130	0.205	0.211	0.224	0.227						
Suction, kPa	ψ	7416	11254	1973	1747	1279	1200						
Sample Moisture Content W_s	W_s	0.050	0.050	0.100	0.100	0.150	0.150						
Volumetric Water Content of Sample (θ_w)	θ_w												
Sample Bulk Density ρ_w (kg/m^3)	ρ_w												

Table D-3.3. Determination of model waste suction characteristics using filter paper method – Phase 2 test (Glass) (ρ_{dry} = 400kg/m^3)

Determination of Model waste suction using Filter Paper Method

Sample Designation: 1&I, 2&II, 3&III
Sampling Date: 21-Oct-02
Testing Date: 31-Oct-02

Sample Density: 300 kg/m3
Other information: Non Contact Method
5, 10 & 15% moisture content

Moisture Tin No		25	28	30	45	46	52	67	74	85	89	97	100
Sample Designation / Dry density (kg/m3)		1 300	300 1	I 300	300 I	2 300	300 2	II 300	300 II	3 300	300 3	III 300	300 III
Cold Tare Mass, g	T_c	8.512	8.459	8.431	8.481	8.528	8.626	8.154	8.485	8.484	8.453	8.136	8.484
Mass of Wet Filter paper Cold Tare Mass, g	M_1	8.761	8.708	8.677	8.723	8.783	8.886	8.420	8.730	8.749	8.706	8.402	8.755
Mass of Dry Filter paper Hot Tare Mass, g	M_2	8.726	8.673	8.642	8.693	8.738	8.841	8.377	8.690	8.696	8.657	8.348	8.699
Hot Tare Mass, g	T_h	8.507	8.454	8.426	8.476	8.523	8.623	8.150	8.481	8.479	8.450	8.132	8.479
Mass of Dry Filter (M_2-T_h)	M_f	0.219	0.219	0.216	0.217	0.215	0.218	0.227	0.209	0.217	0.207	0.216	0.220
Mass of Water in Filter (M_1-M_2-T_c+T_h)	M_w	0.030	0.030	0.030	0.025	0.040	0.042	0.039	0.036	0.048	0.046	0.050	0.051
Water Content of Filter paper, g (M_w/M_f)	W_f	0.137	0.137	0.139	0.115	0.186	0.193	0.172	0.172	0.221	0.222	0.231	0.232
Suction, kPa	ψ	9553	9553	9143	15773	3087	2651	4285	4241	1374	1342	1084	1076
Sample Moisture Content W_s	W_s	0.050	0.050	0.050	0.050	0.100	0.100	0.100	0.100	0.150	0.150	0.150	0.150
Volumetric Water Content of Sample (θ_w)	θ_w												
Sample Bulk Density ρ_w (kg/m³)	ρ_w												

Table D-3.4. Determination of model waste suction characteristics using filter paper method – Phase 2 test (Plastic) (ρ_{dry} = 300kg/m^3)

Determination of Model waste suction using Filter Paper Method

Sample Designation:	1&I, 2&II, 3&III	Sample Density:	350 kg/m3
Sampling Date:	22-Nov-02	Other information:	Non Contact Method
Testing Date:	01-Dec-02		5, 10 & 15% moisture content

Moisture Tin No		25	28	30	45	46	52	67	74	85	89	97	100
Sample Designation / Dry density (kg/m3)		1 350	350 1	I 350	350 I	2 350	350 2	II 350	350 II	3 350	350 3	III 350	400 III
Cold Tare Mass, g	T_c	8.506	8.455	8.426	8.478	8.527	8.623	8.153	8.483	8.482	8.450	8.134	8.480
Mass of Wet Filter paper Cold Tare Mass, g	M_1	8.759	8.700	8.679	8.711	8.776	8.880	8.412	8.732	8.762	8.720	8.397	8.744
Mass of Dry Filter paper Hot Tare Mass, g	M_2	8.728	8.671	8.650	8.683	8.740	8.842	8.375	8.695	8.702	8.661	8.349	8.696
Hot Tare Mass, g	T_h	8.502	8.450	8.422	8.473	8.523	8.619	8.149	8.479	8.478	8.445	8.130	8.476
Mass of Dry Filter (M_2-T_h)	M_f	0.226	0.221	0.228	0.210	0.217	0.223	0.226	0.216	0.224	0.216	0.219	0.220
Mass of Water in Filter $(M_1-M_2-T_c+T_h)$	M_w	0.027	0.024	0.025	0.023	0.032	0.034	0.033	0.033	0.056	0.054	0.044	0.044
Water Content of Filter paper, g (M_w/M_f)	W_f	0.119	0.109	0.110	0.110	0.147	0.152	0.146	0.153	0.250	0.250	0.201	0.200
Suction, kPa	ψ	14299	18367	17927	17979	7505	6689	7759	6641	708	708	2192	2239
Sample Moisture Content W_s	W_s	0.050	0.050	0.050	0.050	0.100	0.100	0.100	0.100	0.150	0.150	0.150	0.150
Volumetric Water Content of Sample (θ_w)	θ_w												
Sample Bulk Density ρ_w (kg/m^3)	ρ_w												

Table D-3.5. Determination of model waste suction characteristics using filter paper method – Phase 2 test (Plastic) (ρ_{dry} = 350kg/m^3)

Determination of Model waste suction using Filter Paper Method

Sample Designation: 1&I, 2&II, 3&III
Sampling Date: 02-Nov-02
Testing Date: 22-Nov-02

Sample Density: 400 kg/m3
Other information: Non Contact Method
5, 10 & 15% moisture content

Moisture Tin No		25	28	30	45	46	52	67	74	85	89	97	100
Sample Designation / Dry density (kg/m3)		1 400	400 1	I 400	400 I	2 400	400 2	II 400	400 II	3 400	400 3	III 400	400 III
Cold Tare Mass, g	T_c	8.509	8.457	8.427	8.479	8.528	8.624	8.154	8.484	8.482	8.451	8.134	8.481
Mass of Wet Filter paper Cold Tare Mass, g	M_1	8.749	8.701	8.667	8.726	8.787	8.882	8.418	8.733	8.754	8.728	8.416	8.751
Mass of Dry Filter paper Hot Tare Mass, g	M_2	8.718	8.667	8.637	8.696	8.746	8.840	8.369	8.689	8.693	8.669	8.356	8.693
Hot Tare Mass, g	T_h	8.502	8.451	8.423	8.475	8.523	8.620	8.150	8.480	8.478	8.446	8.130	8.477
Mass of Dry Filter (M_2-T_h)	M_f	0.216	0.216	0.214	0.221	0.223	0.220	0.219	0.209	0.215	0.223	0.226	0.216
Mass of Water in Filter (M_1-M_2-T_c+T_h)	M_w	0.024	0.028	0.026	0.026	0.036	0.038	0.045	0.040	0.057	0.054	0.056	0.054
Water Content of Filter paper, g (M_w/M_f)	W_f	0.111	0.130	0.121	0.118	0.161	0.173	0.205	0.191	0.265	0.242	0.248	0.250
Suction, kPa	ψ	17334	11316	13647	14912	5441	4195	1973	2730	500	848	745	708
Sample Moisture Content W_s	W_s	0.050	0.050	0.050	0.050	0.100	0.100	0.100	0.100	0.150	0.150	0.150	0.150
Volumetric Water Content of Sample (θ_w)	θ_w												
Sample Bulk Density ρ_w (kg/m^3)	ρ_w												

Table D-3.6. Determination of model waste suction characteristics using filter paper method – Phase 2 test (Plastic) (ρ_{dry} = 400kg/m^3)

Determination of Model waste suction using Filter Paper method

Sample Designation : #1, #A, #A&B

Sampling Date : 22nd June 2001

Date of Analysis : 9th - 13th July 2001

Method used (Contact or Non-Contact) Contact and Non-Contact both

Other info :

Dry Density of the sample = 350 kg/m3
Sample #1&2 = Blank (no solute), #A&B = With Solute
Solute concentration = 0.5Molar of NaCl

Sample # (Spec.)		#1	#1	(Matric)	#A	#A	(Matric)	#2	#2	(Matric)	#B	#B	(Matric)
Moisture Tin No		#25	#28	#85	#30	#45	#89	#46	#52	#97	#67	#74	#100
Top/Bottom Filter Paper (Fp)		T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B
Tin Tare (cold) Mass, gms	Tc	8.513	8.463	8.486	8.432	8.483	8.458	8.529	8.628	8.138	8.155	8.487	8.486
Mass of (Wet Fp + Tare Tin cold), gms	M1	8.730	8.691	8.604	8.659	8.712	8.576	8.759	8.867	8.257	8.388	8.710	8.609
Mass of (Dry Fp + Tare Tin hot), gms	M2	8.718	8.678	8.597	8.645	8.699	8.568	8.739	8.846	8.246	8.374	8.697	8.599
Tin Tare (hot) Mass, gms	Th	8.509	8.459	8.482	8.428	8.478	8.453	8.525	8.625	8.134	8.152	8.484	8.482
Mass of Dry Fp = (M2-Th), gms	Mf	0.209	0.219	0.115	0.217	0.221	0.115	0.214	0.221	0.112	0.222	0.213	0.117
Mass of Water in Fp= (M1-M2-Tc+Th), gms	Mw	0.008	0.009	0.003	0.010	0.008	0.003	0.016	0.018	0.007	0.011	0.010	0.006
Water Content of Filter paper = (Mw/Mf)	Wf	0.0383	0.0411	0.0261	0.0461	0.0362	0.0261	0.0748	0.0814	0.0625	0.0495	0.0469	0.051
Percentage of Moisture in Fp (%)	% Wf	3.83	4.11	2.61	4.61	3.62	2.61	7.48	8.14	6.25	4.95	4.69	5.128
Avg Moisture in Fp (Avg Wf)			3.9687			4.1141			7.8107	0.0720		0.05	0.049
Sample Moisture Content , %	Ws %	~0	~0	~0	~0	~0	~0	~0	~0	~0	~0	~0	~0
Suction, kPa (for Wf < 0.3172)	ψ	92731	86904.3	122781	77476.6	97276.7	122781	40025.5	34317.9	53088.4	71532.7	75948	68735.2
Avg Suction, kPa (Top+Bot)/2 , if	log (ψ)	4.96722	4.93904		4.88917	4.98801		4.60234	4.53552		4.8545	4.88052	4.837
|log (Top)-log(Bot)| < 0.5 log kPa	Diff.	-0.02818			0.09884			-0.06682			0.02601		
Avg Suction, kPa (Top+Bot)/2	Avg		89817.6	122781		87376.7	122781		37171.7	53088.4		73740.3	68735.2
Sample Bulk Density ρω (kg/m3)													

Table D-4.1. Investigation into sensitivity of filter paper method – preliminary test (no added moisture)

Determination of Model waste suction using Filter Paper method

Sample Designation : #1, #A, #2, #B
Sampling Date : 10th May 2001
Date of Analysis : 21st May 2001

Method used (Contact or Non-Contact) Contact and Non-Contact both
Other info :

Dry Density of the sample = 350 kg/m3
Sample #1 = Blank (no solute), Sample #A = With Solute
Solute concentration = 0.5Molar of NaCl

Sample # (Spec.)		#1	#1	(Matric)	#A	#A	(Matric)	#2	#2	(Matric)	#B	#B	(Matric)
Moisture Tin No		#25	#28	#52	#46	#45	#30	#67	#74	# 30	#85	#97	# 52
Top/Bottom Filter Paper (Fp)		T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B
Tin Tare (cold) Mass, gms	Tc	8.516	8.466	8.631	8.528	8.482	8.438	8.157	8.489	8.437	8.488	8.141	8.631
Mass of (Wet Fp + Tare Tin cold), gms	M1	8.787	8.740	8.788	8.789	8.739	8.617	8.427	8.750	8.593	8.755	8.402	8.800
Mass of (Dry Fp + Tare Tin hot), gms	M2	8.729	8.680	8.742	8.743	8.696	8.566	8.372	8.696	8.546	8.701	8.354	8.758
Tin Tare (hot) Mass, gms	Th	8.512	8.461	8.627	8.526	8.478	8.434	8.153	8.484	8.432	8.482	8.135	8.627
Mass of Dry Fp = (M2-Th), gms	Mf	0.217	0.219	0.115	0.217	0.218	0.132	0.219	0.212	0.114	0.219	0.219	0.131
Mass of Water in Fp= (M1-M2-Tc+Th), gms	Mw	0.054	0.055	0.042	0.044	0.039	0.047	0.051	0.049	0.042	0.048	0.042	0.038
Water Content of Filter paper = (Mw/Mf)	Wf	0.2488	0.2511	0.3652	0.2028	0.1789	0.3561	0.2329	0.2311	0.3684	0.2192	0.1918	0.290
Percentage of Moisture in Fp (%)	% Wf	24.88	25.11	36.52	20.28	17.89	35.61	23.29	23.11	36.84	21.92	19.18	29.008
Avg Moisture in Fp (Avg Wf)			24.9995			19.0832			23.2004	0.2998		0.21	0.241
Sample Moisture Content , %	Ws %	10	10	10	10	10	10	10	10	10	10	10	10.000
Suction, kPa (for Wf < 0.3172)	ψ	726.977	689.58	124.446	2100.63	3639.23	129.086	1050.11	1093.15	122.863	1439.52	2705.15	281.343
Avg Suction, kPa (Top+Bot)/2 , if	log (ψ)	2.86152	2.83858	2.09498	3.32235	3.56101	2.11088	3.02123	3.03868	2.08942	3.15822	3.43219	2.449
|log (Top)-log(Bot)| < 0.5 log kPa	Diff.	-0.02294			0.23866			0.01745			0.27397		
Avg Suction, kPa (Top+Bot)/2	Avg		708.278	124.446		2869.93	129.086		1071.63	122.863		2072.34	281.343
Sample Bulk Density ρω (kg/m3)													

Table D-4.2. Investigation into sensitivity of filter paper method – preliminary test (moisture content = 10%)

Determination of Waste Suction using Filter Paper method

Sample Designation : Nos. 1, A, 2, B
Sampling Date : 31st May 2001
Date of Analysis : 8-11th June 2001

Method used (Contact or Non-Contact) Contact and Non-Contact both
Other info :

Dry Density of the sample = 350 kg/m3
#1 & 2, having blank solvent. #A & B having 0.5M solution of brine
Moisture content = 20% (kept constant in all samples).

Sample # (Spec.)		#1	#1	#A	#A	#2	#2	#B	#B	M#1	M#A	M#2	M#B
Moisture Tin No		#25	#28	#30	#45	#46	#52	#67	#74	#85	#89	#97	#100
Top/Bottom Filter Paper (Fp)		T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B	T / B
Tin Tare (cold) Mass, gms	Tc	8.514	8.464	8.434	8.483	8.529	8.628	8.155	8.486	8.486	8.138	8.459	8.488
Mass of (Wet Fp + Tare Tin cold), gms	M1	8.796	8.748	8.694	8.750	8.804	8.906	8.418	8.753	8.672	8.310	8.642	8.685
Mass of (Dry Fp + Tare Tin hot), gms	M2	8.731	8.679	8.651	8.706	8.739	8.847	8.370	8.708	8.608	8.263	8.584	8.614
Tin Tare (hot) Mass, gms	Th	8.510	8.459	8.430	8.479	8.525	8.625	8.152	8.482	8.482	8.134	8.454	8.483
Mass of Dry Fp = (M2-Th), gms	Mf	0.221	0.220	0.221	0.227	0.214	0.222	0.218	0.226	0.126	0.129	0.130	0.131
Mass of Water in Fp= (M1-M2-Tc+Th), gms	Mw	0.061	0.064	0.039	0.040	0.061	0.056	0.045	0.041	0.060	0.043	0.053	0.066
Water Content of Filter paper = (Mw/Mf)	Wf	0.2760	0.2909	0.1765	0.1762	0.2850	0.2523	0.2064	0.1814	0.4762	0.3333	0.4077	0.5038
Percentage of Moisture in Fp (%)	% Wf	27.60	29.09	17.65	17.62	28.50	25.23	20.64	18.14	47.62	33.33	40.77	50.38
Avg Moisture in Fp (Avg Wf)			28.3464		17.6341		26.8649		19.3919	47.6190	33.3333	40.7692	50.3817
Sample Moisture Content , %	Ws %	20	20	20	20	20	20	20	20	20	20	20	20
Suction, kPa (for Wf < 0.3172)	ψ	388.883	276	3848.52	3871.56	315.888	672.167	1930.99	3434.32	79.8607	141.362	105.014	71.5112
Avg Suction, kPa (Top+Bot)/2 , if	log (ψ)	2.58982	2.44091	3.58529	3.58789	2.49953	2.82748	3.28578	3.53584				
|log (Top)-log(Bot)| < 0.5 log kPa	Diff.	-0.14891		-0.00259		-0.32794		0.25006					
Avg Suction, kPa (Top+Bot)/2	Avg		332.442		3860.04		494.028		2682.65	79.8607	141.362	105.014	71.5112
Sample Bulk Density ρω (kg/m3)													

Table D-4.3. Investigation into sensitivity of filter paper method – preliminary test (moisture content = 20%)

Determination of Model waste suction using Filter Paper Method

Sample Designation: I-1, I-2, I-3
Sampling Date: 05-Nov-02
Testing Date: 19-Nov-02

Sample Density: 400 kg/m3
Other information: Non Contact Method (Blank)
5, 10 & 15% moisture content

		I 1		I 2		I 3							
Moisture Tin No		25	28	46	52	85	89						
Sample Designation / Dry density (kg/m3)		400	400	400	400	400	400						
Cold Tare Mass, g	T_c	8.509	8.457	8.528	8.624	8.482	8.451						
Mass of Wet Filter paper Cold Tare Mass, g	M_1	8.761	8.717	8.795	8.915	8.778	8.736						
Mass of Dry Filter paper Hot Tare Mass, g	M_2	8.723	8.681	8.738	8.847	8.709	8.672						
Hot Tare Mass, g	T_h	8.505	8.454	8.524	8.621	8.478	8.447						
Mass of Dry Filter (M_2-T_h)	M_f	0.218	0.227	0.214	0.226	0.231	0.225						
Mass of Water in Filter (M_1-M_2-T_c+T_h)	M_w	0.034	0.033	0.053	0.065	0.065	0.060						
Water Content of Filter paper, g (M_w/M_f)	W_f	0.156	0.145	0.248	0.288	0.281	0.267						
Suction, kPa	ψ	6171	7875	747	298	344	482						
Sample Moisture Content W_s	W_s	0.050	0.050	0.100	0.100	0.150	0.150						
Volumetric Water Content of Sample (θ_w)	θ_w												
Sample Bulk Density ρ_w (kg/m^3)	ρ_w												

Table D-4.3. Investigation into sensitivity of filter paper method – auxiliary test – 1 (determination of total suction with Blank)

Determination of Model waste suction using Filter Paper Method

Sample Designation: I-1, I-2, I-3
Sampling Date: 25-Nov-02
Testing Date: 03-Dec-02

Sample Density: 400 kg/m3
Other information: Non Contact Method (Blank)
5, 10 & 15% moisture content

		I 1		I 2		I 3							
Moisture Tin No		25	28	46	52	85	89						
Sample Designation / Dry density (kg/m3)		400	400	400	400	400	400						
Cold Tare Mass, g	T_c	8.506	8.454	8.526	8.623	8.482	8.448						
Mass of Wet Filter paper Cold Tare Mass, g	M_1	8.755	8.693	8.791	8.892	8.769	8.742						
Mass of Dry Filter paper Hot Tare Mass, g	M_2	8.726	8.663	8.739	8.840	8.704	8.675						
Hot Tare Mass, g	T_h	8.501	8.450	8.522	8.619	8.477	8.444						
Mass of Dry Filter (M_2-T_h)	M_f	0.225	0.213	0.217	0.221	0.227	0.231						
Mass of Water in Filter (M_1-M_2-T_c+T_h)	M_w	0.024	0.026	0.048	0.048	0.060	0.063						
Water Content of Filter paper, g (M_w/M_f)	W_f	0.107	0.122	0.221	0.217	0.264	0.273						
Suction, kPa	ψ	19201	13469	1374	1507	509	419						
Sample Moisture Content W_s	W_s	0.050	0.050	0.100	0.100	0.150	0.150						
Volumetric Water Content of Sample (θ_w)	θ_w												
Sample Bulk Density ρ_w (kg/m^3)	ρ_w												

Table D-4.4. Investigation into sensitivity of filter paper method – auxiliary test – 2 (determination of total suction with Blank)

Determination of Model waste suction using Filter Paper Method

Sample Designation: A-1, A-2, A-3
Sampling Date: 05-Nov-02
Testing Date: 19-Nov-02

Sample Density: 400 kg/m3
Other information: Non Contact Method (Solute concentration)
5, 10 & 15% moisture content

		A 1		A 2		A 3							
Moisture Tin No		30	45	67	74	97	100						
Sample Designation / Dry density (kg/m3)		400	400	400	400	400	400						
Cold Tare Mass, g	T_c	8.429	8.480	8.153	8.484	8.135	8.482						
Mass of Wet Filter paper Cold Tare Mass, g	M_1	8.666	8.724	8.407	8.742	8.386	8.730						
Mass of Dry Filter paper Hot Tare Mass, g	M_2	8.638	8.696	8.372	8.706	8.351	8.694						
Hot Tare Mass, g	T_h	8.425	8.475	8.149	8.480	8.131	8.477						
Mass of Dry Filter (M_2-T_h)	M_f	0.213	0.221	0.223	0.226	0.220	0.217						
Mass of Water in Filter (M_1-M_2-T_c+T_h)	M_w	0.024	0.023	0.031	0.032	0.031	0.031						
Water Content of Filter paper, g (M_w/M_f)	W_f	0.113	0.104	0.139	0.142	0.141	0.143						
Suction, kPa	ψ	16720	20383	9117	8592	8728	8345						
Sample Moisture Content W_s	W_s	0.050	0.050	0.100	0.100	0.150	0.150						
Volumetric Water Content of Sample (θ_w)	θ_w												
Sample Bulk Density ρ_w (kg/m³)	ρ_w												

Table D-4.5. Investigation into sensitivity of filter paper method – auxiliary test – 1 (determination of total suction with Solute)

Determination of Model waste suction using Filter Paper Method

Sample Designation: A-1, A-2, A-3
Sampling Date: 25-Nov-02
Testing Date: 03-Dec-02

Sample Density: 400 kg/m3
Other information: Non Contact Method (Solute concentration)
5, 10 & 15% moisture content

		A 1		A 2		A 3							
Moisture Tin No		30	45	67	74	97	100						
Sample Designation / Dry density (kg/m3)		400	400	400	400	400	400						
Cold Tare Mass, g	T_c	8.425	8.477	8.153	8.483	8.133	8.479						
Mass of Wet Filter paper Cold Tare Mass, g	M_1	8.669	8.709	8.398	8.735	8.388	8.736						
Mass of Dry Filter paper Hot Tare Mass, g	M_2	8.646	8.685	8.365	8.703	8.352	8.701						
Hot Tare Mass, g	T_h	8.422	8.473	8.150	8.478	8.129	8.475						
Mass of Dry Filter (M_2-T_h)	M_f	0.224	0.212	0.215	0.225	0.223	0.226						
Mass of Water in Filter (M_1-M_2-T_c+T_h)	M_w	0.020	0.020	0.030	0.027	0.032	0.031						
Water Content of Filter paper, g (M_w/M_f)	W_f	0.089	0.094	0.140	0.120	0.143	0.137						
Suction, kPa	ψ	28651	25504	9008	14125	8223	9513						
Sample Moisture Content W_s	W_s	0.050	0.050	0.100	0.100	0.150	0.150						
Volumetric Water Content of Sample (θ_w)	θ_w												
Sample Bulk Density ρ_w (kg/m^3)	ρ_w												

Table D-4.6. Investigation into sensitivity of filter paper method – auxiliary test – 2 (determination of total suction with Solute)

Determination of Model waste suction using Filter Paper Method

Sample Designation: I-1, A-1, I-2, A-2, I-3, A-3
Sampling Date: 05-Nov-02
Testing Date: 20-Nov-02

Sample Density: 400 kg/m3
Other information: Contact Method (Matric suction)
5, 10 & 15% moisture content

		I-1	A-1	I-2	A-2	I-3	A-3						
Moisture Tin No		25	28	30	45	46	52						
Sample Designation / Dry density (kg/m3)		400	400	400	400	400	400						
Cold Tare Mass, g	T_c	8.509	8.457	8.427	8.479	8.528	8.624						
Mass of Wet Filter paper Cold Tare Mass, g	M_1	8.762	8.701	8.707	8.727	8.843	8.916						
Mass of Dry Filter paper Hot Tare Mass, g	M_2	8.726	8.673	8.644	8.693	8.747	8.847						
Hot Tare Mass, g	T_h	8.504	8.453	8.423	8.475	8.523	8.620						
Mass of Dry Filter (M_2-T_h)	M_f	0.222	0.220	0.221	0.218	0.224	0.227						
Mass of Water in Filter (M_1-M_2-T_c+T_h)	M_w	0.031	0.024	0.059	0.030	0.091	0.065						
Water Content of Filter paper, g (M_w/M_f)	W_f	0.140	0.109	0.267	0.138	0.406	0.286						
Suction, kPa	ψ	8987	18159	479	9416	106	307						
Sample Moisture Content W_s	W_s	0.050	0.050	0.100	0.100	0.150	0.150						
Volumetric Water Content of Sample (θ_w)	θ_w												
Sample Bulk Density ρ_w (kg/m^3)	ρ_w												

Table D-4.7. Investigation into sensitivity of filter paper method – auxiliary test – 1 (Matric suction with Solute & Blank)

Determination of Model waste suction using Filter Paper Method

Sample Designation: I-1, A-1, I-2, A-2, I-3, A-3
Sampling Date: 25-Nov-02
Testing Date: 03-Dec-02

Sample Density: 400 kg/m3
Other information: Contact Method (Matric suction)
5, 10 & 15% moisture content

		I-1	A-1	I-2	A-2	I-3	A-3						
Moisture Tin No		25	28	30	52	46	45						
Sample Designation / Dry density (kg/m3)		400	400	400	400	400	400						
Cold Tare Mass, g	T_c	8.505	8.453	8.425	8.622	8.526	8.477						
Mass of Wet Filter paper Cold Tare Mass, g	M_1	8.745	8.696	8.692	8.860	8.794	8.725						
Mass of Dry Filter paper Hot Tare Mass, g	M_2	8.716	8.673	8.645	8.829	8.739	8.689						
Hot Tare Mass, g	T_h	8.500	8.448	8.421	8.619	8.521	8.473						
Mass of Dry Filter (M_2-T_h)	M_f	0.216	0.225	0.224	0.210	0.218	0.216						
Mass of Water in Filter (M_1-M_2-T_c+T_h)	M_w	0.024	0.018	0.043	0.028	0.050	0.032						
Water Content of Filter paper, g (M_w/M_f)	W_f	0.111	0.080	0.192	0.133	0.229	0.148						
Suction, kPa	ψ	17334	35481	2694	10391	214	7388						
Sample Moisture Content W_s	W_s	0.050	0.050	0.100	0.100	0.150	0.150						
Volumetric Water Content of Sample (θ_w)	θ_w												
Sample Bulk Density ρ_w (kg/m^3)	ρ_w												

Table D-4.8. Investigation into sensitivity of filter paper method – auxiliary test – 2 (Matric suction with Solute & Blank)

Determination of Degree of Saturation

Model waste, dry density = **500 kg/m3** Specific gravity (G_s) = 1.625

Volume of Sample (V) = 2.94E-04 m3 Unit weight water (γ_w) = 9.79E+03 kN/m3

$V_s = W_s / (G_s \gamma_w)$, $S = W_w / (\gamma_w V_v)$ and $V = V_s + V_v$

Sample # 2					
Wet weight of sample (W) =	154.35 gm				
Moisture content (w) =	0.05				
Wet weight of water (Ww) =	7.35 gm	=	7.207E-02 N		
Weight of solid (Ws) =	147 gm	=	1.441E+00 N		
Volume of solid (Vs) =	9.06E-05 m3				
Volume of voids (Vv) =	2.03E-04 m3				
Degree of saturation (S) =	**3.62E-02**			**Suction =**	**2718 kPa**

Sample # 3					
Wet weight of sample (W) =	161.7 gm				
Moisture content (w) =	0.1				
Wet weight of water (Ww) =	14.7 gm	=	1.441E-01 N		
Weight of solid (Ws) =	147 gm	=	1.441E+00 N		
Volume of solid (Vs) =	9.06E-05 m3				
Volume of voids (Vv) =	2.03E-04 m3				
Degree of saturation (S) =	**7.24E-02**			**Suction =**	**525 kPa**

Sample # 4					
Wet weight of sample (W) =	169.05 gm				
Moisture content (w) =	0.15				
Wet weight of water (Ww) =	22.05 gm	=	2.162E-01 N		
Weight of solid (Ws) =	147 gm	=	1.441E+00 N		
Volume of solid (Vs) =	9.06E-05 m3				
Volume of voids (Vv) =	2.03E-04 m3				
Degree of saturation (S) =	**1.09E-01**			**Suction =**	**490 kPa**

Sample # 5					
Wet weight of sample (W) =	176.4 gm				
Moisture content (w) =	0.2				
Wet weight of water (Ww) =	29.4 gm	=	2.883E-01 N		
Weight of solid (Ws) =	147 gm	=	1.441E+00 N		
Volume of solid (Vs) =	9.06E-05 m3				
Volume of voids (Vv) =	2.03E-04 m3				
Degree of saturation (S) =	**1.45E-01**			**Suction =**	**355 kPa**

Table 5.1. Determination of degree of saturation in model waste samples (ρ_{dry}= 500kg/m^3)

Determination of Degree of Saturation

Model waste, dry density = 750 kg/m3 Specific gravity (G_s) = 1.625

Volume of Sample (V) = 2.94E-04 m3 Unit weight water (γ_w) = 9.79E+03 kN/m3

$V_s = W_s / (G_s \gamma_w)$, $S = W_w /(\gamma_w V_v)$ and $V = V_s + V_v$

Sample # 2A				
Wet weight of sample (W) =	232.26 gm			
Moisture content (w) =	0.05			
Wet weight of water (Ww) =	11.06 gm	=	1.085E-01 N	
Weight of solid (Ws) =	221.2 gm	=	2.169E+00 N	
Volume of solid (Vs) =	1.36E-04 m3			
Volume of voids (Vv) =	1.58E-04 m3			
Degree of saturation (S) =	**7.03E-02**		**Suction =**	**3112 kPa**

Sample # 3A				
Wet weight of sample (W) =	242.55 gm			
Moisture content (w) =	0.1			
Wet weight of water (Ww) =	22.05 gm	=	2.162E-01 N	
Weight of solid (Ws) =	220.5 gm	=	2.162E+00 N	
Volume of solid (Vs) =	1.36E-04 m3			
Volume of voids (Vv) =	1.58E-04 m3			
Degree of saturation (S) =	**1.40E-01**		**Suction =**	**648 kPa**

Sample # 4A				
Wet weight of sample (W) =	253.7 gm			
Moisture content (w) =	0.15			
Wet weight of water (Ww) =	33.09 gm	=	3.245E-01 N	
Weight of solid (Ws) =	220.61 gm	=	2.163E+00 N	
Volume of solid (Vs) =	1.36E-04 m3			
Volume of voids (Vv) =	1.58E-04 m3			
Degree of saturation (S) =	**2.10E-01**		**Suction =**	**569 kPa**

Sample # 5A				
Wet weight of sample (W) =	264.6 gm			
Moisture content (w) =	0.2			
Wet weight of water (Ww) =	44.1 gm	=	4.324E-01 N	
Weight of solid (Ws) =	220.5 gm	=	2.162E+00 N	
Volume of solid (Vs) =	1.36E-04 m3			
Volume of voids (Vv) =	1.58E-04 m3			
Degree of saturation (S) =	**2.79E-01**		**Suction =**	**719 kPa**

Table 5.2. Determination of degree of saturation in model waste samples (ρ_{dry}= 750kg/m^3)

Determination of Degree of Saturation

Model waste, dry density = 1000 kg/m3 Specific gravity (Gs) = 1.625

Volume of Sample (V) = 2.94E-04 m3 Unit weight water (γ_w) = 9.79E+03 kN/m3

$V_s = W_s / (G_s \gamma_w)$, $S = W_w / (\gamma_w V_v)$ and $V = V_s + V_v$

Sample #1				
Wet weight of sample (W) =	308.7 gm			
Moisture content (w) =	0.05			
Wet weight of water (Ww) =	14.7 gm	=	1.441E-01 N	
Weight of solid (Ws) =	294 gm	=	2.883E+00 N	
Volume of solid (Vs) =	1.81E-04 m3			
Volume of voids (Vv) =	1.13E-04 m3			
Degree of saturation (S) =	**1.31E-01**		**Suction =**	**2806 kPa**

Sample # 2				
Wet weight of sample (W) =	323.4 gm			
Moisture content (w) =	0.1			
Wet weight of water (Ww) =	29.4 gm	=	2.883E-01 N	
Weight of solid (Ws) =	294 gm	=	2.883E+00 N	
Volume of solid (Vs) =	1.81E-04 m3			
Volume of voids (Vv) =	1.13E-04 m3			
Degree of saturation (S) =	**2.61E-01**		**Suction =**	**1391 kPa**

Sample # 3				
Wet weight of sample (W) =	338.1 gm			
Moisture content (w) =	0.15			
Wet weight of water (Ww) =	44.1 gm	=	4.324E-01 N	
Weight of solid (Ws) =	294 gm	=	2.883E+00 N	
Volume of solid (Vs) =	1.81E-04 m3			
Volume of voids (Vv) =	1.13E-04 m3			
Degree of saturation (S) =	**3.92E-01**		**Suction =**	**511 kPa**

Sample # 4				
Wet weight of sample (W) =	352.8 gm			
Moisture content (w) =	0.2			
Wet weight of water (Ww) =	58.8 gm	=	5.766E-01 N	
Weight of solid (Ws) =	294 gm	=	2.883E+00 N	
Volume of solid (Vs) =	1.81E-04 m3			
Volume of voids (Vv) =	1.13E-04 m3			
Degree of saturation (S) =	**5.22E-01**		**Suction =**	**592 kPa**

Table 5.3. Determination of degree of saturation in model waste samples (ρ_{dry}= 750kg/m^3)