The Electro-Osmotic Acceleration of Infiltration into the Subgrade of Pavements

By

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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and has not previously in its entirety or in part been submitted at any university for a degree.

……..
Signature:

…….
Date:

Abstract

The moisture content of road foundations plays an important role in the durability of the pavement and the driving comfort of the road. After a pavement has been completed, gradual moisture changes occur in the foundations until equilibrium conditions can be reached, and this can have negative results if expansive clays, for example, are present in the foundation. Pre-wetting of the foundation material is seen as a method to minimilize moisture changes after construction, but if the pavement was already completed, it would be very difficult to change or alter the moisture content in the foundation, because water could then only be applied to the shoulder areas of the road and horizontal infiltration in the soil is exceptionally slow.

The research which is reported in this account was undertaken to determine whether the process of electro-osmosis could be applied to accelerate water infiltration underneath covered areas, as in, for example, road foundation layers. Electro-osmosis, if found to be successful, has various advantages, of which the most important is that it can be applied without stopping the normal operations of the road.

This research was carried out on a mixture of G5 material (TRH14 classification) and fine material in the form of clay with a low plasticity. Firstly, tests were performed to determine the percentage of fines required. It was found that, if too little fines were present infiltration did not occur, because moisture could flow freely through the openings between the rough aggregate. Electro-osmosis also had no effect on the rate of flow. The allocated amount of fines required to fill sufficient openings was about 30% (TRH14 classification of mixture is G10). Free flow was stopped and true infiltration occurred. Simultaneously, the rate of infiltration could be accelerated with electro-osmosis.

Furthermore, a two-dimensional model of a road was constructed with electrodes placed on both sides, with the aim to determine the infiltration pattern controlled by electro-osmosis and what the effect of the initial moisture content would be on the process. Water was introduced to the one side of the model road and the wetting of the foundation was investigated. If the electric current for electro-osmosis was switched off, the infiltration was mainly vertical, as expected, but with the current switched on, there was an obvious acceleration of infiltration in the horizontal direction. As in the case of the initial tests, it was found that electro-osmosis was not very successful to accelerate horizontal infiltration at low percentages of fines. Furthermore, it was obvious that electro-osmosis was also more effective if the initial moisture content of the soil was low. Low amounts of fines and high initial moisture contents had rather the electro-osmotic flow of water passing underneath the road as a result instead of infiltration acceleration, with the result that the moisture content did not change much.

The research thus showed that electro-osmosis is a possible manner in which moisture could be conducted into the foundation layers of roads to increase the moisture content if the appropriate amount of fines and moisture content were present in the foundation material. Further research could still be carried out and the materials in each case should be practically evaluated before this method could be continued with.

Opsomming

Die voginhoud van padfondamente speel ’n belangrike rol in die duursaamheid van die plaveisel en die rygerief van die pad. Nadat ’n plaveisel voltooi is, vind daar geleidelike vogverandering in die fondamente plaas totdat ewewigstoestande bereik is, en dit kan nadelige gevolge inhou indien uitsettende kleie byvoorbeeld in die fundament teenwoordig is. Voorafbenatting van die fondamentmateriaal word gereken as ’n metode om vogveranderinge na konstruksie te minimeer, maar indien die plaveisel reeds voltooi is, is dit baie moeilik om die voginhoud in die fondament te verander of beheer omdat water dan slegs buite die skouerareas van die pad toegedien kan word en horisontale infiltrasie in grond uiters stadig is.

Die navorsing waaroor hierin verslag gedoen word, is onderneem om te bepaal of die proses van elektro-osmose aangewend kan word om waterinfiltrasie onder bedekte areas, soos byvoorbeeld padfondamentlae, te versnel. Elektro-osmose, indien dit suksesvol blyk te wees, hou verskeie voordele in, waarvan die belangrikste dat dit aangewend kan word sonder om die normale bedryf van die pad te staak.

Die ondersoek is uitgevoer op ’n mengsel van G5 materiaal (TRH14 klassifikasie) en fynstof in die vorm van klei met ’n lae plastisiteit. Eerstens is toetse uitgevoer om die persentasie fynstof wat nodig is, te bepaal. Daar is bevind dat, indien te min fynstof teenwoordig is, infiltrasie nie plaasvind nie aangesien water vryelik deur die openinge tussen die growwe aggregaat kan vloei. Elektro-osmose het ook geen effek op die vloeitempo gehad nie. Die aangewese hoeveelheid fynstof om genoegsame openinge te vul was ongeveer 30% (TRH14 klassifikasie van mengsel is G10). Vrye vloei is dan gestuit en ware infiltrasie het plaasgevind. Terselfdertyd kon die tempo van infiltrasie versnel word met elektro-osmose.

Voorts is ’n twee-dimensionele model van ’n pad gebou, met elektrodes aan weerskante geplaas, met die doel om te bepaal of die infiltrasiepatroon deur elektro-osmose beheer kon word en wat die effek van beginvoginhoud op die proses sal wees. Water is aan een kant van die modelpad ingevoer en die benatting van die fondament bestudeer. Indien die elektriese stroom vir elektro-osmose afgeskakel was, was die infiltrasie hoofsaaklik vertikaal, soos verwag, maar met die stroom aangeskakel was daar duidelike versnelling van infiltrasie in die horisontale rigting. Net soos in die geval van die aanvanklike toetse is bevind dat elektro-osmose nie baie suksesvol was om horisontale infiltrasie te versnel by lae persentasies fynstof nie. Dit het verder geblyk dat elektro-osmose ook meer effektief was indien die aanvanklike voginhoud van die grond laag was. Lae hoeveelhede fynstof en hoë aanvanklike voginhoude het eerder elektro-osmotiese deurvloei van water onderdeur die pad tot gevolg gehad as infiltrasieversnelling, met die gevolg dat die voginhoud nie veel verander het nie.

Die navorsing het dus getoon dat elektro-osmose ’n moontlike wyse is waarop water in die fondamentlae van paaie ingevoer kan word om die voginhoud te verhoog indien die geskikte hoeveelheid fynstof en voginhoud in die fondamentmateriaal teenwoordig is. Verdere navorsing kan nog uitgevoer word en die materiale van elke geval sal prakties evalueer moet word voordat met die metode voortgegaan kan word.

DEDICATION

This thesis is dedicated to my parents, Erich and Iris Glatz, whose support, encouragement and dedication to my career has been unfailing and way beyond the call of parental duty.

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List of Symbols

A = area

C = natural infiltration constant

D = soil water diffusivity

G_s = specific gravity

H = hydraulic head

h = pressure head

I = electric current intensity

i_e = electrical potential gradient

i_h = hydraulic gradient

K = Darcy's coefficient of permeability

K_e = coefficient of electro-osmotic hydraulic conductivity

K_h = coefficient of hydraulic conductivity

k_h = coefficient of hydraulic filtration

k_I = coefficient of electro-osmotic hydraulic conductivity in terms of current

L = distance separating total hydraulic heads at two points

n = porosity

P = power consumption

Q = volume flow rate

q = volume flow rate per unit area

t = time

v = discharge velocity

w = gravimetric moisture content

x = infiltrated distance

z = gravitational head

μ = viscosity

σ = charge density per unit area

σ_e = coefficient of electrical conductivity

σ_h = coefficient of electrical conductivity due to hydraulic flow

θ = volumetric moisture content

Φ = total potential

τ = zeta potential

ε = permittivity

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1. INTRODUCTION

1.1 INTRODUCTION

The foundation of a pavement is very important to the durability and strength of the pavement. In the past lots of attention was given to the changes in moisture content under pavements. The aim of the study was to investigate the application of electro-osmotic methods in the field of pavement engineering, to reach equilibrium moisture contents quicker and to exhibit homogeneous moisture characteristics.

1.2 BACKGROUND

In South Arfica the most important research on the observations and wetting of subgrade layers was done by Van der Merwe DH, Hugo F and Steyn AP (1980) and Emery (1985).

Van der Merwe DH, Hugo F and Steyn AP (1980) concentrated on the pretreatment of clay soils for road construction, especially in heaving clays. When a paved road is constructed on expansive clay soils the evaporation of water from the soil is prevented. The moisture content increases and the soil expands causing the road surface to become uneven. This also causes shear failures where the road cover is insufficient.

Pavement distortion, Kassiffe et al (1969), can be prevented by the replacement or improvement of the subgrade over the full active depth. This method is generally not economically feasible. Increasing the surcharge of the clay subgrade can also prevent pavement distortion, but is mostly not practical. The ideal condition would therefore be, when no deformation should occur, where the soil is at its fullest expanded condition before road construction.

This could be achieved by pre-wetting the subgrade. Tests done by Van der Merwe DH, Hugo F and Steyn AP (1980) showed that the initial high variation in moisture content of an expansive roadbed material had been eliminated by the wetting process. This limited road irregularities to movements caused by seasonal variations.

This wetting process was done by first covering the clay subgrade with a layer of sand. This sand layer minimised evaporation of moisture from the clay and acted as a reservoir during irrigation of the clay soil. The clay was irrigated through the sand blanket by means of perforated pipes. Fill was then brought onto the wet soil and sand layer by end tipping.

Emery (1985) concentrated on the prediction of moisture content under a pavement for use in pavement design. Once a pavement was constructed, moisture in the lower subgrade layers would gradually move upwards until moisture equilibrium is reached under the pavement. The distribution of moisture is usually not homogenous and gradual changes are possible depending on seasonal environmental conditions. The outer edges of the road can either be at a lower or higher moisture content than the middle part.

1.3 MOTIVATION FOR RESEARCH

From the work of Van der Merwe, Hugo and Steyn (1980) and Emery (1985) discussed above it is concluded that it would be beneficial if a way could be devised by which the moisture content in pavement subgrades could be increased within a limited period of time. It could serve as an alternative method of pre-wetting of expansive clay subgrades, or maintaining uniform moisture content in order to prevent relative movement. It could also be used to decrease the time required for equilibrium moisture content to be reached below newly paved areas or after long dry periods.

For the latter application, water can only be introduced to the areas to the sides of a pavement. Mere application of water to these areas is not very effective

since the natural tendency is for water to seep essentially downwards in course-grained soils, whilst the natural infiltration rate in fine-grained soils is very slow and increases with distance already infiltrated.

The method devised should ideally work in all subgrade materials, but if horizontal infiltration could be induced or accelerated in soils with a reasonable amount of fines, it would be a positive step.

It was therefore decided to embark on an experimental program to determine whether such a method could indeed be developed to accelerate infiltration into pavement subgrades in a horizontal direction, and to determine the factors that influence the efficiency of the method.

1.4 ELECTRO-OSMOSIS

It was decided to investigate the possibilities of electro-osmosis as a means of accelerating moisture infiltration into pavement subgrades. Electro-osmosis is the process in which an electrical gradient applied across a volume of saturated soil is capable of driving water away from the anode and towards the cathode.

Electro-osmosis can be used to treat a road without interfering with its normal operation. Treatment will not involve major construction procedures, thus it would not be necessary to completely close a road off if a road has to be treated, which can result in the saving of time for road-users and cutting costs in using staff to deviate traffic.

1.4.1 Electrokinetics

Electrokinetics is a common expression which includes all phenomena associated with the influence of an electrical gradient across porous media such as clay-water systems. Casagrande (1983) listed the following applications for electrokinetics: increasing the load capacity of steel friction piles; the chemical

cementation of soils by osmotic transport of a cementing agent; controlling seepage forces to permit excavation; stabilization of landslides; decreasing water contents of materials in disposal plants; increasing the strength of weak deposits to permit construction.

1.4.2 Electro-osmosis in unsaturated soil

De Wet (1995) proved that electro-osmosis did occur in unsaturated soil up to moisture contents as low as about 4.2%. He also proved that water can be made to infiltrate unsaturated clayey soils at a much higher rate than could be achieved by capillary action alone. The accelerated rate was constant over time and depended on the electric current intensity.

The equilibrium moisture content of subgrade layers in Cape Town is about 7% and in Durban about 10% (Emery, 1985). From the principles and applications of electro-osmosis mentioned above, it seems rational to investigate the possibilities of infiltrating the subgrade layers of roads with water to the equilibrium level.

Another possible application of electro-osmosis in unsaturated soil include the prevention of moisture penetration to ward off the swelling and maintaining moisture equilibrium below sensitive structures.

1.5 SCOPE OF RESEARCH

The intent was to expand the original work done by De Wet (1995) that reported on the feasibility of the process in unsaturated soil. Various soils can be present in pavement subgrades. G5 material (TRH14 classification) was used as the base material for the tests. This thesis deals specifically with the electro-osmotic acceleration into G5 material. One-dimensional and two-dimensional tests were performed on the material.

Sufficient clay material had to be added to to allow the process of electro-osmosis to occur. This in turn changed the classification to a G10 material (TRH14 classification). With such a high clay content, some G10 materials could tend towards a swelling soil, depending on the activity of the specific clay mineral present. In general, depending on the grading of the material and the type of clay mineral present, electro-osmosis might become feasible at other fines contents if other materials are used. The results found in this research could mean that electro-osmosis could also be a viable solution to the problem of moisture increase in clay foundations prior to construction of pavements, which was investigated by Van der Merve DH, Hugo F and Steyn AP (1980).

1.6 ORGANISATION OF THESIS

The phenomena of electrokinetics and electro-osmosis are given in Chapter 2. The qualitative models of electro-osmosis in unsaturated soil and of electro-osmotic infiltration are suggested in Chapter 3. The experimental work performed to meet with the research objectives is described in Chapter 4. The results of the one-dimensional tests are presented and discussed in Chapter 5. The results of the two-dimensional tests are presented and discussed in Chapter 6. Conclusions and recommendations for future research are given in Chapter 7.

2. LITERATURE REVIEW

2.1 INTRODUCTION

The literature review covers the topics relevant to the subject of this research. Firstly, the simultaneous flows of water, electric current and ions in unsaturated compacted soil under the influence of electrical gradients. Secondly, the rate and pattern of infiltration of moisture into unsaturated soil under the influence of an electrical gradient.

Electro-osmosis has not been studied in any great detail in soils at low moisture contents. Available literature is limited to saturated, natural soils and soils saturated by backpressure. De Wet (1995) did the first in depth study into electro-osmosis in soils at low moisture contents. The lowest value of moisture content in which electro-osmosis occurred was about 4,2%. At lower moisture contents the resistance was too high for the electric current to flow.

The natural infiltration of water into unsaturated soil is discussed to aid the development of a model of the combined effect of hydraulic and electrical gradients.

2.2 ELECTROKINETIC PHENOMENA IN FINE-GRAINED SOIL

Electrokinetic phenomena are several processes which are connected with an electric field and the relative motion of two types of phases in fine grained soil.

Yeung (1990 a and b) and Mitchell (1993) describe how the application of an electrical field will cause a tendency of relative translation at the interfaces between the negatively charged solid phase particles and the positively charged cations in the internal solution. Likewise, any forced relative translation between the two opposite charges will generate an electrical field. Electrophoresis,

streaming potential, sedimentation potential and electro-osmosis are examples of such electrokinetic phenomena.

ELECTROPHORESIS is the movement of loose or suspended solid phase particles with respect to a stationary fluid phase, both as a result of an applied electrical field. STREAMING POTENTIAL is the electrical field generated by movement of fluid and cations through the stationary solid phase. SEDIMENTATION POTENTIAL is generated by particles moving through a fluid under an external force, usually gravity. ELECTRO-OSMOSIS is the movement of the fluid phase relative to a rigid solid phase matrix.

The focus of this thesis is on the application of electro-osmosis, and thus more emphasis will be placed on this specific topic.

2.2.1 Electro-osmosis

When an electrical gradient is applied across a volume of saturated clay it is capable of driving water away from the anode and towards the cathode. This phenomenon was termed electro-osmosis, because of its similarity with the process of osmosis.

The first to demonstrate this phenomenon in an experiment was Reuss (1809), using a plug of quarts powder in a U-tube. He found that it is possible to induce flow with an electrical gradient, or balance a hydraulic gradient applied in the opposite direction. Wiedeman (see Yeung, 1990a and b) found that the induced flow was proportional to the electric current, the balanced hydraulic pressure difference was proportional to the applied electrical potential, and that both were independent of the plug dimensions.

The application of an electrical gradient to a stable mass of clay results in movement of cations in the internal solution towards the cathode. This exerts a frictional drag on the water, which tends to move it towards the cathode as well.

No net drag is developed in the outer solution however, because the concentrations of cations and anions are equal.

The phenomenon of electro-osmosis was described by several theories. A different distribution of cations in the double layers was assumed and different ratios of double layer thickness to pore size. It was commonly assumed that the clay pores could be treated as circular capillaries. Gray (1966) and Zaslavsky and Ravina (1965) gave excellent overviews of the most important of the developments and also repeated the relevant derivations. A brief summary follows below.

One of the earliest models based on the double layer theory by Helmholtz (1879) was developed by Smoluchowski (1914). He made the assumption that the capillary tubes were relatively large and that the cations were concentrated in a single layer, a small distance from the capillary walls. The mobile shell of cations dragged the water along, which resulted in a constant flow velocity across almost the entire capillary diameter. Winterkorn (1947) showed that these assumptions led to the result that the electro-osmotic flux was a function of the porosity of the clay matrix but not of the pore size. The theories of Helmholtz-Smoluchowski and related theories were found not applicable to soils with very high densities, and subsequently, low moisture content.

Schmid (1950) proposed a theory in which flow along micro capillaries was assumed, with the cations being distributed uniformly throughout the pores. This resulted in a parabolic flow distribution with zero velocity at the pore walls. When extended to flow through microporous clay, the electro-osmotic flux was a function of both pore size and porosity. Schmid's theory was not applicable to all clay systems as was concluded by Ballou (1955).

A frictional model to describe the mutual interaction of cations, anions and water, as well as their interactions with the matrix in permselective porous media was presented by Spiegler (1958). This theory was found useful in explaining observed effects of water content, pore size and the type of cation on electro-osmotic transport.

The various theories on electro-osmosis are not applicable to all soils. A practical approach is followed and the relationship between the volume flow rate, $\mathbf{Q_e}$, and the electrical gradient, $\mathbf{i_e}$, is given by

$$Q_e = K_e i_e A \qquad ....2.1$$

where $\mathbf{K_e}$ is the coefficient of electro-osmotic hydraulic conductivity and **A** is the cross-sectional area through which flow occurs.

The power consumption, **P**, per unit volume flow rate, **Q**, is given by

$$P / Q = V\sigma_e / K_e \qquad ....2.2$$

where **V** is the applied voltage difference and $\boldsymbol{\sigma_e}$ is the electric conductivity of the soil. The factor $\mathbf{K_e/\sigma_e}$ can be regarded as a measure of the energy efficiency of driving water by an electrical gradient.

The coeffient of electro-osmotic hydraulic conductivity varies between $1x10^{-5}$ and $10x10^{-5}$ cm^2 per volt per second (Yeung 1990a and b). The value of $\mathbf{K_e}$ is apparently not very sensitive to moisture content, soil type and chemical composition of the fluid phase, but the power consumed by the process of electro-osmosis is very susceptible to fluctuations of these factors.

2.2.2 Applications of electro-osmosis

Electro-osmosis involves cation and anion movement and water flow, when an electrical gradient is applied to a particle-water system. This can be utilized to solve certain waste treatment, soil mechanics and other problems.

When fine grained soils have low hydraulic conductivities electro-osmosis is exceptionally useful to move water. It can be used for the dewatering of slimes, mine tailings and other suspensions (Butterfield and Johnson, 1980) and to increase the capacity of friction piles, decreasing pile friction during driving

(Spangler and King, 1949). Electro-osmosis is essentially used to remove water from saturated clay deposits to facilitate consolidation (Banarjee and Vitayasupakorn, 1984).

Gladwell (1965) reports on the stabilization of subgrades and sub-bases under pavements. Movement of water is used to stabilize embankments, slopes, excavations and dams, Chappell and Burton (1975). Cations and anions can be removed from or introduced into soil or waste to stabilize it. Densification can be achieved in slurries. Electro-osmosis can be used for the stabilization of unsaturated dispersive clay (De Wet, 1995). Chemicals can be injected to achieve cementation and contaminants can be removed.

Some side effects of electro-osmosis cannot be ignored. During prolonged electro-osmosis, electrolyte depletion near the anode and accumulation near the cathode will occur, which results in distortion of the electric field and the formation of a hydraulic head near the cathode, Miller (1955). Pressure fissures and shrinkage cracks developed in laboratory samples as reported by Bolt (1955). The following effects were listed by Mitchell (1970): ion diffusion, ion exchange, oxidation, reduction, hydrolysis, electrolysis, fabric changes, adsorption, mineral decomposition, precipitation of secondary minerals, desiccation from heat generated at electrodes and degeneration of osmotic and pH gradients.

De Wet (1995) also used electro-osmosis to accelerate the moisture infiltration into unsaturated soil.

2.3 UNSATURATED FLOW AND INFILTRATION

2.3.1 Principles of water movement in soil

Water at any given position in a soil is under the influence of a number of forces. This includes the weight of the water, interaction with the matrix of solid particles

in an unsaturated soil and the presence of solutes in the water. It is most convenient to work with potential energy of the water to facilitate the combination of these forces. All of these forces add to the total potential. The total potential is the work that must be done per unit quantity of water to transfer an infinitesimal quantity from a pool of pure water at a given elevation to the point under consideration.

The total potential, **Φ**, has several components. This depends on the influencing forces. The effect of gravity is termed gravitational potential, that of the solutes in the water is called osmotic potential and the contribution of water pressure is termed the pressure potential. Osmotic potential is always negative. Depending on whether the point of interest is submerged or not, the pressure potential can be positive or negative. A negative pressure potential arises from the interaction of water with the matrix of solid particles. This is termed matric potential. When submerged the positive potential is caused by the weight of water above the point.

Potential will have different units depending on the quantity on which the work is done. It is most common to use energy per unit weight, which leaves the potentials in units of length. Potential is also termed head. Capillary and surface adsorption causes matric potential and this varies over many orders of magnitude with changing moisture content, thus the unit of pF is sometimes used. This is the logarithm to base 10 of the matric head in cm.

Croney and Coleman (1960) reviewed techniques for measuring total and matric potential in unsaturated soils and the relationship with moisture content.

The sum of the pressure and gravitational heads is the hydraulic head, **H**, and this can differ from point to point in a porous medium. The water is then forced from positions of greater to those of lesser energy.
Darcy's law states that

$$v = Q / A = K(H_2 - H_1) / L_{12} \qquad ....2.3$$

Where **Q** is the rate of discharge of water through a cross-sectional area, **A**, normal to the direction of flow, **V** is the discharge velocity, **K** is a proportionally constant and $\mathbf{H_2}$ and $\mathbf{H_1}$ are total hydraulic heads at two points separated by a distance $\mathbf{L_{12}}$ parallel to the flow direction, with $\mathbf{H_2 > H_1}$. The constant **K**, is termed the hydraulic conductivity or coefficient of permeability and has units of $\mathbf{LT^{-1}}$. It is alleged by some researchers that Darcy's law is not valid for very low values of the discharge velocity, so that **K** is not a constant for a particular soil, while others did not find experimental proof of this.

The governing equation for flow in an incompressible soil is

$$\delta(K_x \delta H/\delta X)/\delta X + \delta(K_y \delta H/\delta Y)/\delta Y + \delta(K_z \delta H/\delta Z)/\delta Z = \delta\theta/\delta t \qquad ....2.4$$

where θ is the volumetric moisture content of the soil, **t** denotes time and δ**X**, δ**Y**, δ**Z** are the component vectors. The relevant boundary conditions must be taken into account when solving the above equation.

2.3.2 Unsaturated flow

As noted earlier on, Darcy's law may not be valid under all flow conditions in unsaturated flow. Kirkham and Powers (1972) have reported deviations from the linear behaviour implied by Darcy. They have suggested some physical reasons for non-linearity. Simultaneously, they state that basic theory for non-Darcy type flow does not exist and that there are many flow problems for unsaturated soil where the use of Darcy's law leads to valid results.

If osmotic potential is neglected and if Darcy-type flow is assumed, equation [2.4] becomes valid.

The sum of the pressure head, **h**, and the gravitational head, **z**, gives us the hydraulic head, **H**.

$$H = h + z \qquad ....2.5$$

Substituting [2.5] into [2.4] and assuming that the material is isotropic gives

$$\delta(K\delta h / \delta X) / \delta X + \delta(K\delta h / \delta Y) / \delta Y + \delta(K\delta h / \delta Z) / \delta Z + \delta K / \delta Z = \delta\theta / \delta t \qquad ....2.6$$

which gives the governing equation for flow in unsaturated soil. The hydraulic conductivity and pressure head (matric potential for unsaturated soil) were found to be single-valued functions, **K(θ)** and **h(θ)**, of the moisture content, **θ**, which in turn is a function of **x**, **y**, **z** and **t**.

The governing equation if flow is constrained to take place only in the horizontal direction, is

$$\delta[K(\theta)\delta h(\theta) / \delta X] / \delta X = \delta\theta / \delta t \qquad ....2.7$$

and in the vertical direction

$$\delta[K(\theta)\delta h(\theta) / \delta Z] / \delta Z + \delta[K(\delta)] / \delta Z = \delta\theta / \delta t \qquad ....2.8$$

The above equations for unsaturated flow can be extended to include osmotic potential or can be expressed in terms of total free energy.

2.3.3 Hydraulic conductivity and soil water diffusivity

When using any of the governing differential equations, reliable measurements of moisture content as well as variation of hydraulic conductivity and diffusivity with moisture content is required. Hysteresis has been observed in the relationship between matric potential, which is the driving force during unsaturated flow, and the moisture content. Most problems on unsaturated flow involve infiltration, thus only the wetting arm of a hysteresis loop is used.

The developments, accuracies, advantages and disadvantages of methods of in situ moisture determination, with sampling and oven drying, neutron scattering techniques and gamma ray methods are described by Marshall and Holmes (1979). These were found to be the most practical methods. Some indirect methods, including absorbent blocks and lysimeters and other methods that are discussed are those based on electrical conductivity, thermal conductivity and electrical capacity.

Marshall and Holmes (1979) published the typical values of permeability, **K**, and diffusivity, **D**, with varying moisture content and/or potential. The following conclusions can be reached:

1. **D** appears to vary less than **K** in materials studied.
2. For heavy clays **K** may be insensitive to moisture content.
3. For heavy clays $\delta h/\delta\theta$ may be insensitive to moisture content.
4. Neither $\delta h/\delta\theta$ nor **K** seem to be constant with moisture content in light textured soils.

Overburden pressures could influence **K** and **D**, fissured or non-homogeneous soils could pose problems, extremely sharp moisture gradients could occur in sandy soils and non-isothermal conditions could invalidate the equations.

2.3.4 Solutions to some unsaturated flow problems

The flow in unsaturated soils includes situations such as steady state and transient infiltration, evaporation and redistribution after infiltration. Transient infiltration will only be discussed for the purposes of this thesis.

The common approach followed by Green and Ampt (1911), (see Marshall and Holmes, 1979) is to assume a semi-infinitely long horizontal or vertical column of soil at a constant moisture content to which free water is introduced at one end at zero time. After some time has elapsed, the distribution of moisture in the soil is calculated. The boundary conditions can be mathematically stated as:

$$t = 0, \quad x \geq 0, \quad \theta = \theta_i$$

$$t > 0, \quad x = 0, \quad \theta = \theta_o \qquad ....2.9$$

where $\boldsymbol{\theta_i}$ is the initial moisture content, $\boldsymbol{\theta_o}$ is the constant moisture content at the point of infiltration, **x** is the distance along the tube and **t** denotes time.

When assuming a very steep wetting front in an initially dry soil the diffusion equations are avoided (Green and Ampt, 1911). The hydraulic potential at **x=0** is zero and the soil behind the wetting front is at constant moisture content, $\boldsymbol{\theta_o}$. The potential, $\mathbf{h_i}$, at the wetting front, is negative. When Darcy's law is applied to these assumed conditions, it leads to the following equation for horizontal infiltration:

$$xt^{-\frac{1}{2}} = -2Kh_i / n \qquad ....2.10$$

where **K** is the hydraulic conductivity at moisture content $\boldsymbol{\theta_o}$, and **n** is the porosity which will be filled by the advancing water. A similar equation was derived for vertical infiltration.

The Boltzmann transformation

$$\beta(\theta) = xt^{-\frac{1}{2}} \qquad ....2.11$$

was applied to the horizontal diffusion equation, thus converting it to an ordinary differential equation of the form

$$-d\theta / d\beta = 2/\beta \; d/d\beta(D \, d\theta / d\beta) \qquad ....2.12$$

An iterative mathematical procedure was derived to determine a curve of **β** versus **θ**. Equation [2.11] was again applied and this curve was transformed into curves of **θ** versus **x** for any desired time, **t**, which together constituted the solution of the horizontal infiltration problem. This solution is valid for finite columns of soil as well, provided that the wetting front has not reached the end of the column.

Phillip's method has the advantage over other mathematical solutions in that it takes the tail section of the infiltration curve near θ_i into account. Phillip (1957) reported good agreement between experimental infiltration curves and moisture curves.

It is most practical to use numerical solutions for infiltration. Numerical methods are readily adapted for computer use. They are not restricted to uniform initial moisture conditions as was the case for mathematical methods. Two-dimensional, anisotropic and non-homogeneous analyses are also possible.

Computer codes have been developed to solve diffusion equations for water, heat and contaminant flow. The finite difference analysis of two-dimensional infiltration at an experimental road site was reported by Richards (1965). Yeung (1990a and b) made use of the integrated finite difference method to model the movement of moisture and ions in an electrokinetic flow barrier.

The redistribution of moisture following infiltration was analysed by Youngs (1958). Watson (1965) studied the non-continuous unsteady flow in vertical soil columns. The redistribution of moisture under covered areas received attention from Russam and Dagg (1965). Marshall and Holmes (1979) treated the flow of moisture during evaporation and steady state infiltration to a shallow water table. Emery (1985) studied the prediction of moisture content for use in pavement design.

From this thesis the Green and Ampt equation is the most important equation, because it shows that the speed of infiltration decreases with distance that has already been infiltrated. In fine grained material the infiltration will virtually come to a stand still.

3. THEORETICAL INVESTIGATION

3.1 INTRODUCTION

This chapter deals with the background to the phenomena and processes involved in the experimental work done during the course of the research. Most of the topics covered here were already mentioned in the literature survey of Chapter 2. More detailed descriptions are required to establish a good understanding of the basic principles that are involved.

3.2 ELECTRO-OSMOSIS

Several theories have been proposed providing a basis for the prediction of flow rates.

3.2.1 Classical theories of electro-osmosis

The theory used by Helmholtz (1879) and Smoluchowski (1914) is the most widely used theory. This theory assumes that the soil pores can be modelled by single capillaries filled with liquid. The excess counterions are modelled as a single layer and the charge deficiency of the clay minerals is modelled as a layer of charges on the capillary surface. These two layers are a small distance apart. A capillary takes on the function of an electrical condenser. The water is dragged through the capillary as a plug flow by the mobile shell of counterions, which is set in motion by an electrical potential gradient. The flow velocity is zero against the capillary wall and a sharp velocity gradient exists over the double layer thickness. This can be seen in Figure 3.1.

The steady state flow can be determined by the balance between the electrical driving force on the counterions and the friction between the capillary wall and

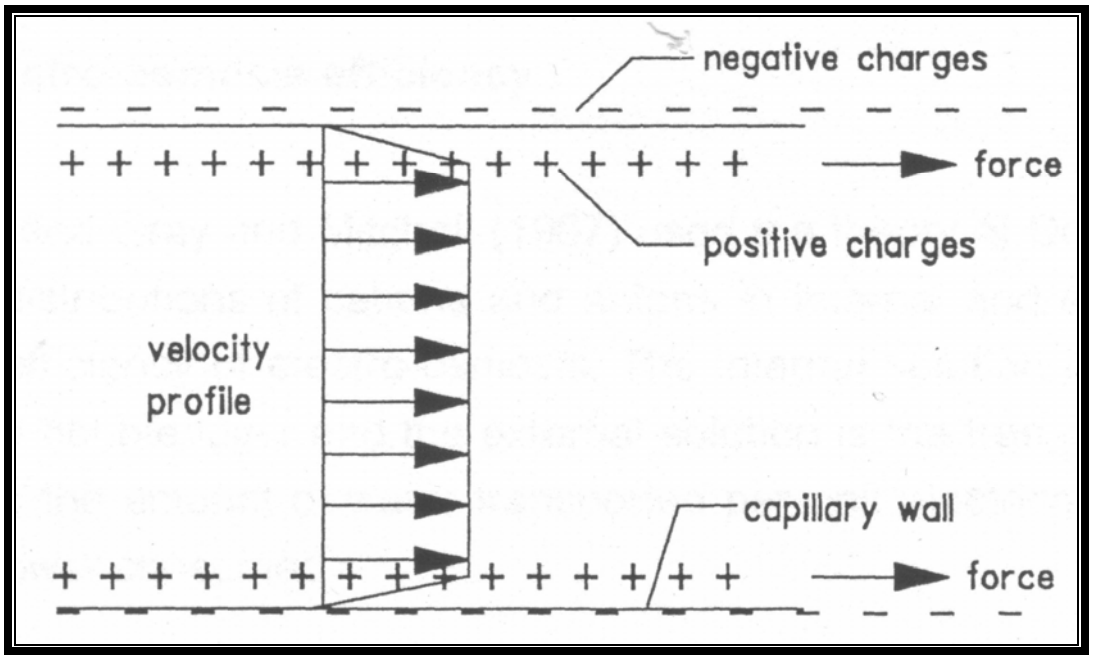

Figure 3.1 Helmholtz-Smoluchowski model for electro-osmotic flow velocity (from De Wet, 1995)

the liquid. The flow rate $\mathbf{Q_e}$ over an area **A** is given by

$$Q_e = K_e i_e A \qquad \text{....3.1}$$

where $\mathbf{i_e}$ is the electrical potential gradient.

The coefficient $\mathbf{K_e}$ is given by the Helmholtz Smoluchowski theory as

$$K_e = \tau\varepsilon n / \mu \qquad \text{....3.2}$$

where **n** is the porosity, ε is the permittivity of the pore fluid, μ is the viscosity of the pore fluid, τ is the potential across the condenser, or zeta potential. This equation is valid for saturated flow.

The equation

$$K_e = wG_s(1-n)\tau\varepsilon / \mu \qquad \text{....3.3}$$

is the Helmholtz-Smoluchowski theory adapted for unsaturated soils, where **w** is gravimetric moisture content and $\mathbf{G_s}$ is specific gravity.

3.2.2 Electro-osmotic efficiency

The definition of efficiency is the amount of water transported per unit electrical charge passed, or per unit of power consumed. Electro-osmotic efficiency depends on the water to cation ratio and is increased by a low cation exchange capacity, as well as a high water content. The theory of Donnan (1924) was used by Gray and Mitchell (1967) on the distributions of equilibrium of cations and anions in external and internal solutions to explain the efficiency of electro-osmosis. The external solution is the free pore fluid and the internal solution is within the domain of the diffuse double layer.

The efficiency depends on the degree to which anions are excluded from the internal solution, because of the frictional drag of the cations on the pore fluid, which is opposed by that of the anions moving in the opposite direction. There is no net drag in the external solution, because it is assumed that the numbers of anions and cations are equal. Donnan's theory indicates that anion exclusion is favoured by a high exchange capacity, low salinity in the external solution and a low water content.

The apparent above contradicting governing factors can be explained as follows:
In a low exchange capacity clay the volume of water transported per unit charge passed is higher than for a more active clay, if the salt concentration in the external solution is low. There is a more rapid anion invasion into the internal solution, as the external salt concentration increases. This results in the water transport decreasing at a higher rate than in the case of the high cation exchange capacity clay. The efficiency for both clays remain higher at higher water content. The effect of water content diminishes with increasing electrolyte concentration.

Mitchell (1993) expressed electro-osmotic transport efficiency by the following equation as volume flow rate of water per unit electric current, which is the same as the volume of water moved per unit charge passed.

$$k_I = Q_e / I \qquad \text{....3.4}$$

Where **I** is the electric current and $\mathbf{k_I}$ a transport coefficient related to $\mathbf{K_e}$.

$$k_I = K_e / \sigma_e \qquad \text{....3.5}$$

where $\boldsymbol{\sigma_e}$ is the specific conductivity of the soil-water system. A high conductivity $\boldsymbol{\sigma_e}$ means a low efficiency, because the electric current needed to remove water is high, which means a high power consumption. The theories above are applicable to clay soils at high moisture contents, seldom going below 25 percent moisture by weight, Mitchell (1993).

3.2.3 Electro-osmosis in drying compacted clay soil

The moisture content in a saturated compacted natural clay is likely to be below 20%. The diffuse double layer tends to be slightly compressed, taking on the shape of ion distribution curves marked **a** and **a′** in Figure 3.2. Using the theory of Helmholtz-Smoluchowski, the value of the coefficient of electro-osmotic hydraulic conductivity $\mathbf{K_e}$ can be determined. Anion invasion into the inner solution will be low, unless the salt content of the soil is high. According to Equation [3.5], a low specific conductivity can be expected which gives a comparatively high electro-osmotic efficiency.

The number of ions per unit of pore space remains constant, and this leads to an increase in the concentration of the free solution, if the moisture content of the soil is allowed to drop to below saturation. The double layer will be further compressed as shown by curves **b** and **b′** in Figure 3.2. The full cross sections of the capillaries will no longer be filled with water with the result that, even if the

velocity of the cation shell or the net drag is not affected, the discharge will decrease relative to the saturated case. Simultaneously the compression of the double layer will result in an increased invasion of anions. The value of $\mathbf{K_e}$ and of the efficiency coefficient $\mathbf{k_l}$ will be lower than that for the saturated case.

The annulus of water in each capillary becomes progressively thinner and the double layer becomes more and more compressed if the moisture content is further decreased until the water film and the double layer are about the same dimension as shown by curves **c** and **c′** in Figure 3.2. Now anion invasion into the double layer will be high. The percentage of capillary cross sectional area filled by water will be so low, that little water will be transported. The values of $\mathbf{K_e}$ and $\mathbf{k_l}$ will be lowered by the decrease in moisture content.

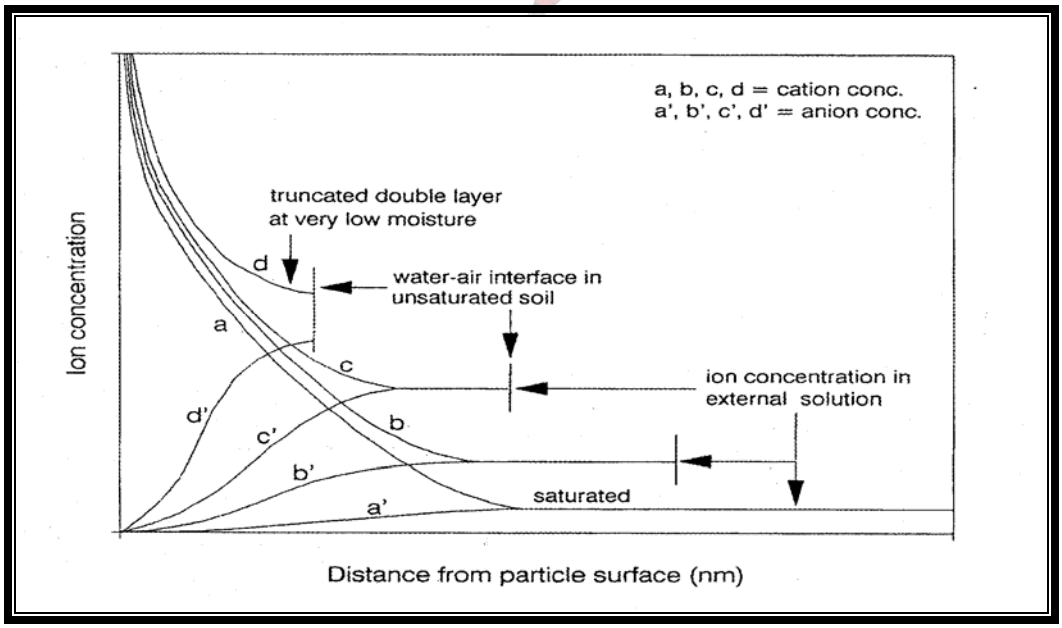

Figure 3.2 The diffuse double layer for decreasing moisture content in an unsaturated soil-water system (from De Wet, 1995)

The water film will become thinner still, with an additional decrease in moisture. This will force all of the anions and cations into a truncated diffuse double layer, which is no longer in equilibrium with an external solution, Bolt and Bruggenwert (1976), as can be seen in curves **d** and **d′** in Figure 3.2. Electro-osmosis will

stop if any further decrease in moisture content occurs, which will result in the water films in the capillaries to become discontinuous, leading to electrical conductivity becoming very low.

3.2.4 Factors that influence unsaturated electro-osmosis

A more quantitive description of the process of electro-osmosis can now be attempted.

$$K_e = wG_s(1-n)\tau\varepsilon/\mu \qquad \text{....3.3}$$

The zeta potential τ and the moisture content **w** determine the coefficient $\mathbf{K_e}$. The salt concentration in the outer solution has a direct influence on the zeta potential, Van Olphen (1977). Thus the only independent factor is the moisture content. $\mathbf{K_e}$ will be decreased by a lower moisture content. The lower moisture content also increases the outer solution concentration. This lowers the zeta potential and results in a further reduction in $\mathbf{K_e}$.

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An ideal situation will be a critical diameter above which the capillaries are no longer saturated and to which Equation [3.3] will apply. The smaller capillaries remain saturated and follow Equation [3.2]. The critical diameter becomes smaller as moisture loss proceeds, while at the same time the zeta potential decreases.

At moisture contents approaching compaction optimum the relationship between $\mathbf{K_e}$ and moisture content may approach linearity. The larger pores of the aggregate soil (Mitchell, 1993) will have the greater volume of fluid flow. It must be assumed that a more or less homogeneous degree of saturation may be valid and Equation [3.3] may be applied. The Helmholtz-Smoluchowski model does not apply when the process of electro-osmosis is confined to progressively smaller pores at lower moisture content values. At air-dried conditions the $\mathbf{K_e}$ is expected to approach zero in an asymptotic manner.

3.2.5 Electro-osmotic efficiency in unsaturated soils

Anion invasion into the double layer solution is favoured when the salt concentration of the external electrolite is increased. The ratio of water to cations will decrease. A lower electro-osmotic transport efficiency will be reached by both these effects. Less water will therefore be transported by a unit charge passed through the soil. The problem, to predict the exact relationship between moisture content and efficiency, is however, too involved.

3.3 DETERMINATION OF UNSATURATED ELECTRO-OSMOTIC SOIL PROPERTIES

A modified version of the electro-osmotic infiltration model has to be used, in order to evaluate the coefficients of $\mathbf{K_e}$ and $\mathbf{k_l}$. The only difference is that in this model the horizontal soil column is of finite length. The movement of moisture has to be monitored closely, close to and at the cathode end. Both versions of the model assume steep wetting fronts with no hydraulic gradient ahead of the wetting front, even though the soil is not dry ahead of the front.

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3.3.1 A model of coupled flow in a finite column of unsaturated soil

Moisture is moved by the electro-osmotic force towards the cathode and accumulates in the soil pores next to the cathode. Water cannot enter the soil from the cathode side, because there is no reservoir of water in contact with the cathode end. The increase in moisture leads to a hydraulic gradient in the soil opposing the electro-osmotic gradient. This process occurs until a moisture front similar to a wetting front is formed. Moisture will be driven from the soil if the cathode end is open, this occurs when the soil pores at the end of the soil column get close to saturation. The hydraulic gradient diminishes as the moisture content extends into the soil from the cathode. This leads to a stationary position when the constant electro-osmotic force balances the hydraulic force.

The moisture distribution shape in a finite horizontal column of soil, some time after coupled flow infiltration has commenced, can be seen in Figure (3.3). Three sections can be clearly identified. The first section is the wet section between the anode and the wetting front, the second section is the drier central section which is still at the initial moisture content, the third section is the wet section where water has accumulated in the pores on the cathode side. A combination of electro-osmotic and hydraulic gradients results in the entering of free water into the soil at the anode from a reservoir.

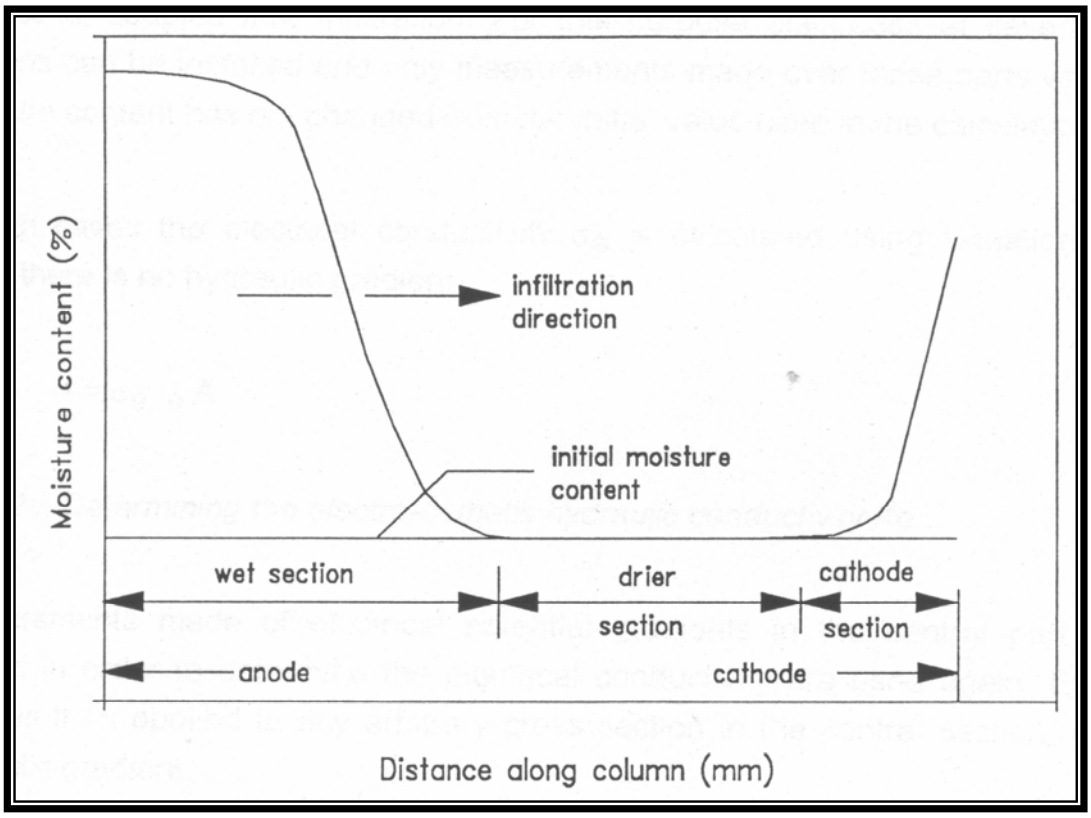

Figure 3.3 Moisture distribution in a finite column of unsaturated soil subject to coupled flow infiltration (from De Wet, 1995)

3.3.2 Calculating the unsaturated electro-osmotic coefficients

Assumptions have to be made before the electro-osmotic coefficients of the unsaturated material can be calculated. These are:

1. Hydraulic and electrical gradients are the only driving forces.
2. All material properties in the central section are unchanged from their initial values.
3. Electro-osmosis is the only driving force in the central section. (The hydraulic gradient is zero in that section, since there is no moisture content gradient).
4. All moisture in excess of the initial water content in the cathode section has been moved there by electro-osmosis through the central section. This also applies to any moisture that has accumulated in the empty cathode reservoir.

3.3.2.1 Determining the electrical conductivity

The electrical conductivity σ_e is calculated using

$$I = \sigma_e i_e A \qquad \text{....3.6}$$

where **I** is the electric current, $\mathbf{i_e}$ the electrical gradient and **A** the cross sectional area of the soil column.

The electrical conductivity can be measured by applying an alternating electrical potential gradient across the soil column and measuring the resulting alternating current. It can also be measured by measuring the potential gradient between two cross sections in the central portion of the soil column while the direct electric current is flowing during the process of coupled infiltration. This can be done by installing electrodes at several cross sections and only measurements made over those parts where the moisture content has not changed from the initial value used in the calculations.

3.3.2.2 Determining the electro-osmotic hydraulic conductivity K_e

The $\mathbf{K_e}$ is calculated by applying

$$Q = K_e i_e A \qquad \text{....3.1}$$

to a cross section in the central section, where **Q** is the water accumulated in the soil pores in the cathode section and the water that has left the soil at the cathode.

3.3.2.3 Determining the electro-osmotic hydraulic conductivity K_i

The $\mathbf{K_i}$ is calculated using

$$K_i = K_e / \sigma_e \qquad \text{....3.5}$$

3.4 THE INFILTRATION COEFFICIENT VERSUS DARCY'S LAW

Natural infiltration into a soil can be expressed in the form

$$C = \frac{x^2}{t} \qquad \text{....3.7}$$

Where **C** is the natural infiltration constant, **x** the infiltrated distance and **t** the time.

Water flows in one dimension through a fully saturated soil in accordance with Darcy's empirical law

$$Q = KiA \qquad \text{....3.8}$$

It is important to note that as the material approaches a state of little-to-no fines, Darcy's equation becomes more applicable. This means that infiltration is no longer being studied, but flow. It is important to keep this in mind as it is the most likely explanation for any deviations in the research data.

4. EXPERIMENTAL PROGRAM

4.1 OBJECTIVES

During the course of the experimental program it was attempted to study the relationship between the speed of moisture infiltration into a soil column and the percentage of fines present, at predetermined electric current and initial moisture content. The experimental work mainly involved the speed of infiltration into various samples of material. A wide range of samples were tested with varied fines content, electric currents and initial water contents. One-dimensional and two-dimensional tests were carried out on the material.

From the results of the experimental program it would be possible to determine whether the moisture distribution within a road's sugrade could be modified to, or maintained at, predetermined values, and whether moisture content changes could be achieved within reasonable time and financial limits.

The objectives of the tests were:

1. To determine the infiltration velocity of moisture into samples with various fines contents, electric currents and initial moisture contents in unsaturated compacted soil.
2. To perform one-dimensional tests, to determine how much fines is required to allow for the process of electro-osmosis to occur in G5 material. The one-dimensional experimental apparatus used was the same as designed by De Wet (1995).
3. To perform two-dimensional tests and to develop a two-dimensional experimental apparatus which permits an investigation into the electro-osmotic acceleration of infiltration into the subgrade of pavements.

4.2 EXPERIMENTAL APPARATUS

In the one-dimensional tests the soil was confined inside a perspex tube fixed horizontally. The two-dimensional tests were performed in a box, where electro-osmosis is permitted to occur in two-dimensions. A detailed description of the one-dimensional and two-dimensional and other components of the experimental apparatus is given in Sections 4.2.2 through 4.2.5.

4.2.1 Design criteria

The one-dimensional test components had to conform to the following criteria:

1. It must secure the sample against uncontrolled swelling and softening.
2. The electrodes must not engage in any exchange reaction with the soil, or must not ionize or produce ions capable of penetrating the soil.
3. All components must be leak proof and the soil must be able to be compacted directly within the apparatus.
4. The compacted sample is able to be brought to a semi-saturated condition through the application of partial vacuum.
5. Different solutions can be introduced to the two ends of the compacted sample. These can be changed and sampled at regular intervals.
6. All the components have to be electrically insulated.
7. The resulting electric current in the soil must be accurately measured.
8. A constant regulated DC electric current can be maintained through the sample. The resulting electrical potential is measured at fixed points along the length of the sample.
9. The apparatus must allow determination of the soil moisture content at regular intervals along the length of the sample.

All the above mentioned criteria also apply to the two-dimensional tests. Soil moisture gypsum blocks were used to determine the water content in different sections of the soil sample.

4.2.2 Design concepts

The determination of soil moisture content, to obtain infiltration speed as a function of time was an important aspect of the laboratory testing program. The electric current and potential difference were monitored continuously because of the inherent advantage that less samples have to be prepared in the apparatus. The major drawbacks are discussed below.

4.2.2.1 Moisture content monitoring

The electrical conductivity of partially saturated soil is determined by moisture content, as well as pore water chemistry and both these parameters change with time and position during the test. This results in neither being accurately measured by electrical conductivity. If moisture content varies over a short distance the electrical capacity and electrical conductivity can become unreliable indications of moisture content because the measurement at a relatively dry cross section is influenced by an approaching wet front still several millimeters away.

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In the two-dimensional tests soil moisture gypsum blocks are buried into the soil in the confined space of a box and this will interfere with the moisture flow patterns in the soil, rendering the results inaccurate. Because of this and other problems, the soil moisture gypsum blocks were later not used.

4.2.2.2 The method of sectioning

The method of sectioning was used to determine the moisture content at the end of an experiment. For the one-dimensional tests the soil column was sliced into thin sections to determine the distribution of the water content. A major advantage is that average values are obtained for the cross sections of moisture content as opposed to values at discreet points during continuous monitoring.

When taking moisture content samples of the two-dimensional tests the box was opened and samples were taken from 9 different areas.

The method of sectioning has its disadvantages. Instead of single test samples that can be used for continuous monitoring, sets of several test samples have to be compacted and subjected to the electrokinetic process. All the test samples within a set must have the same soil properties. It is virtually impossible to prepare five identical test samples and test them under perfectly identical conditions, thus quality control becomes a major issue when sets of test samples are used.

4.2.2.3 General considerations

One-dimensional and four two-dimensional apparatuses were manufactured and each provided with its own independent electrical system. A one-dimensional apparatus with independent power source can be seen in Figure 4.1. In this way test samples could be treated under identical conditions for different periods to study the effects of time or under different conditions to evaluate the effects of electric current density or voltage gradient on the infiltration process.

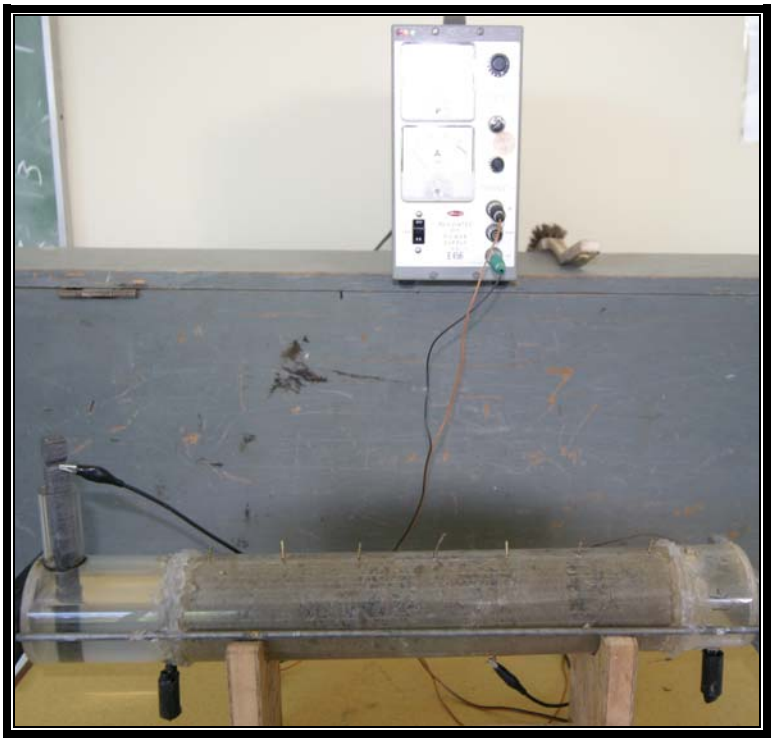

Figure4.1 One-dimensional apparatus with independent power source

The unsaturated test samples changed dramatically in electrical conductivity during the infiltration saturation process. The available regulated power sources was only able to supply current to one sample at a time during the initial stage of a test when the conductivity is very low.

A detailed description of the one-dimensional apparatus and two-dimensional apparatus and electrical system is presented in Sections 4.2.3 through 4.2.5.

4.2.2.4 The calcium chloride solution

Calcium chloride is dissolved in distilled water in a large bottle. Three grams of the calcium chloride is added per liter of distilled water. The 0.02 normal $CaCl_2$ solution was introduced to the soil in the vicinity of the anode in a controlled way. This provides known boundary conditions to the system.

4.2.3 The one-dimensional apparatus

A fixed wall cylindrical apparatus is advantageous for research of this nature. One-dimensional moisture infiltration is properly simulated during the test as well. At the same time moisture movement is perpendicular to the compaction layers. This avoids the possibility of increased migration rates along layer interfaces. The test samples are compacted directly into the apparatus. The soil can be recovered and sectioned with relative ease after completion of the test.

The apparatus has three cylindrical sections of the same diameter and is made of perspex. The middle section holds the soil sample and is open-ended. The two end sections, called the anode and cathode compartments respectively, have one closed end and one perforated end each. The perforations have a diameter of 8 millimeters and the perforated ends are recessed to fit inside the main section. This enables it to maintain proper contact with the soil and the stainless steel mesh electrodes. All three sections are clamped together and the joints are sealed with a silicone rubber compound. A schematic layout of the apparatus with its accompanying electrical system can be seen in Figure 4.2.

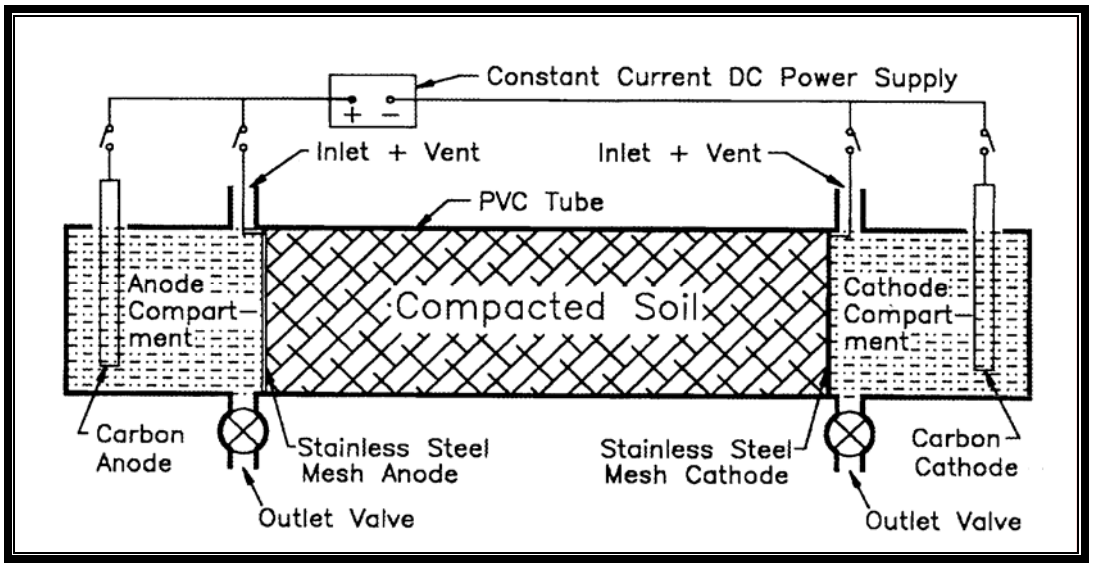

Figure 4.2 Schematic of one-dimensional and electrical system (from De Wet, 1995)

The apparatus is supported in a horizontal position. Secondary electrodes used for potential gradient determinations are installed in a series of 2 mm diameter openings at 50 mm spacing through the wall of the central section. These secondary electrodes are not shown in the schematic Figure 4.2 for the sake of simplicity. The openings also allow air in the soil to escape during infiltration. The infiltration process slows down without these openings, because a hydraulic gradient opposing the electro-osmotic gradient is induced by pore air pressure build-up.

The compartments of the anode and cathode are used as reservoirs for the solutions or the effluents. Each reservoir contains an inlet and outlet valve and an opening at the top, which serves as air vent and access for a carbon electrode. The anode and cathode reservoirs can be filled and emptied through the inlet and outlet valves.

The electrical system is presented in Section 4.2.5. To prevent contamination of the soil by metallic ions a carbon anode is used at all times. The stainless steel mesh anode shown in Figure 4.2 is not used. The other electrodes consist of stainless steel or copper. No other metallic objects are in contact with the soil during the test.

The apparatus was designed with a 60 mm diameter and 332 mm long soil column. Some difficulty was encountered in keeping these tubes intact during compaction, and resulted in quite a few tubes being broken. Replacement tubes were of 332 mm length, in order to get three tubes out of a meter of perspex, due to financial constraints. Detailed drawings of the one-dimensional components are given in Appendix A.

The end reservoirs were of the same diameter as the central section. The anode and cathode reservoirs had volumes of 0,3 and 0,15 liter respectively. The exact procedures followed during the different tests are given in more detail in Section 4.4.

4.2.4 The two-dimensional apparatus

The two-dimensional apparatus consisted of a box, which was made out of 20 mm shatterply wood. The apparatus had to be electrically insulated. Four boxes were made. One of the boxes had one side made out of perspex, which was also 20 mm thick. This was done to allow the water being moved across the soil test sample to be physically seen. Only one box had a perspex side due to limit costs. The boxes allowed for the proper simulation of two-dimensional moisture infiltration.

The samples were compacted directly into the box. Steel clamps were designed to prevent the wooden box from breaking during compaction. Chipboard screws were used to assemble the box. Silicone was also used in the corners of the box to ensure that the box was leakproof. The box could, therefore, be opened at the end of a test, this allowed sections to be taken and the soil test sample to be recovered. Soil moisture blocks were compacted into the box at 9 different areas. They were later not used, because they reduced the accuracy of the results. The soil moisture blocks had a diameter of 24 mm and a length of 35 mm. To strengthen the soil moisture blocks, a 24 mm diameter 5 mm thick piece of perspex was siliconed to the top of every block.

The dimensions of the boxes were 500 mm by 425 mm by 150 mm and they were open-ended at the top. A perspex sheet was used to model a road and was 300 mm by 150 mm by 3 mm. It was placed above the soil, leaving 100 mm either side of the road for the anode and cathode compartments. The compartments of the anode and cathode were used as reservoirs for the solutions or the effluents. A schematic of the apparatus can be seen in Figure 4.3.

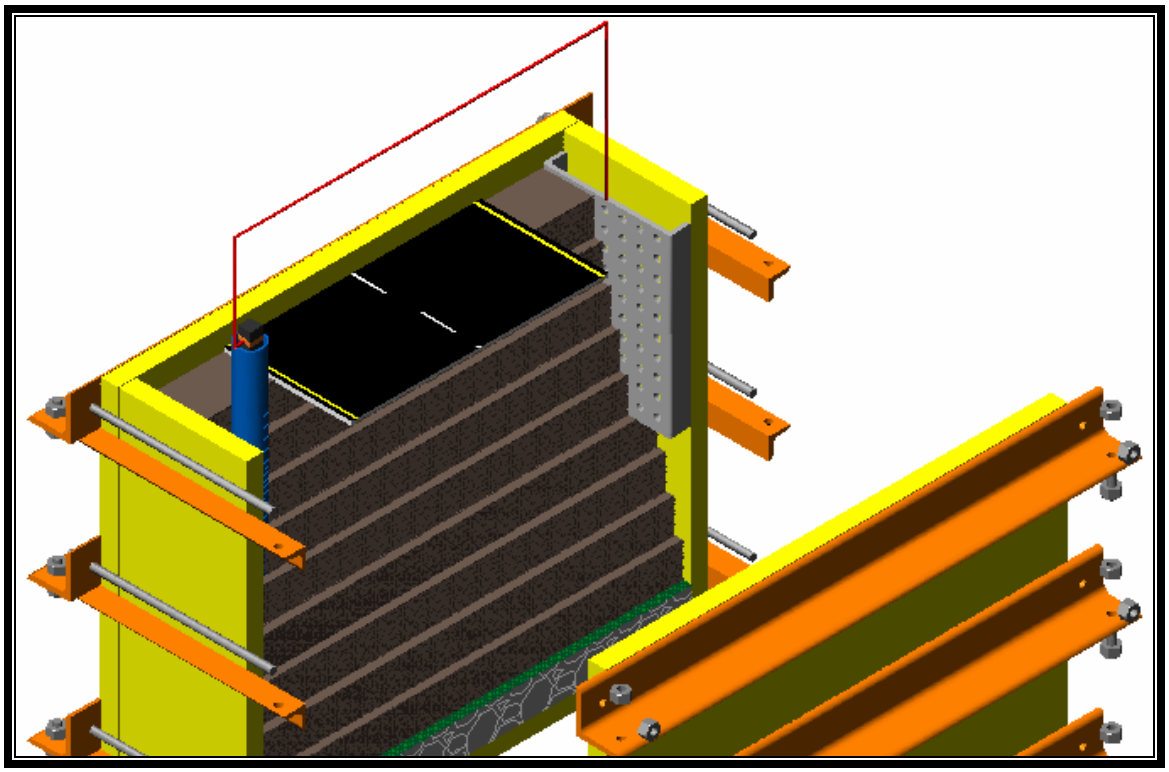

Figure 4.3 Schematic of the two-dimensional apparatus

The anode was a 32 mm PVC pipe with one side perforated to allow water to infiltrate the soil. Geotextile was used to cover the pipe to prevent the perforations from being clogged and therefore allowing water to infiltrate the soil. The pipe was 270 mm long and was buried 200 mm below the surface of the soil. It was open-ended to allow access for a carbon electrode. The cathode compartment was made out of a 5 mm thick perforated steel grid. It was 205 mm high and 149 mm wide and 25 mm thick. It had a steel cover underneath and was positioned against the wooden box to form the cathode compartment. A

gravel layer at the bottom of the box connected to an 11 mm outlet was provided for drainage. In this way the boundary condition imposed by the bottom of the box was removed.

The electrical system is presented in section 4.2.5. To prevent contamination of the test soil by metallic ions a carbon anode was used at all times. No other metallic objects were in contact with the test soil during the test. Detailed drawings of the two-dimensional components are given in Appendix A. The exact procedures followed during the different tests are given in more detail in Section 4.4.

4.2.5 The electrical system

In the one-dimensional and two-dimensional tests the anode reservoir was filled while the cathode compartment was primarily used to collect small volumes of effluent and to prevent evaporation from the end of the sample. The electric current was applied through the carbon anode and the stainless steel grid which served as a cathode. In the one-dimensional tests a thin layer of steel wool was placed between the steel grid that served as cathode and the soil, to provide for proper contact over the whole cross section.

In the one-dimensional and two-dimensional tests a constant electric current was passed through the soil. Three factors need to be taken into account before choosing between the regulated current or regulated voltage modes:

1. The samples were not compacted all with the same initial moisture contents and different electric currents will result from constant potential drops.
2. The electrical conductance of the soil changes drastically from the dry to the saturated state, meaning that the constant overall potential drop cannot be used over the whole period of testing.
3. The saturated length of the sample increases as the test proceeds. This increases the electrical conductivity over that length, and the length of low

moisture soil decreases. This means a fixed voltage drop across the sample will result in constantly varying potential gradients in the wet and dry sections and a variable electric current even if the electrokinetic properties within a section remains unchanged.

All samples were treated on a common basis in regulated current mode over all test periods, regardless of soil property differences or variations with time. The electrical potential gradient and the electrokinetic processes will remain at constant values and rates in any section of the soil column for which the electrokinetic properties do not change over any time period.

The current was set at a predetermined value, which the power source maintains regardless of a decrease in the total resistance of the test soil sample. The power source was able to supply the regulated current at potential drops of up to 350 volts. The magnitude of the current is monitored by means of a high impedance voltmeter in parallel with an in-line calibrated resistor or an in-line ammeter.

The electric current for several samples in succession can be monitored by using a digital multimeter. It can also be used to measure the potential differences between the secondary electrodes.

4.3 PROPERTIES OF THE TEST SOIL

The soil used in these experiments was crushed hornfels (G5-subase) with added fines in the form of yellowish grey clay. The G5 material was obtained from Lafarge Peak Quarry in Eersterivier, Western Cape Province. The results of CBR and grading tests done on the G5 material appear in Section 4.3.1 and 4.3.2.

The clay used in the one-dimensional experiments (to increase the fines content) was obtained from an embankment dam constructed on the farm De Clapmuts, next to the Elsenburg Agricultural Experiment Station in the Stellenbosch area, Western Cape Province. This clay will be referred to as De Clapmuts clay. The clay used in the two-dimensional experiments was obtained on the farm Môreson, next to the N1 highway in the Stellenbosch area, Western Cape Province. This clay will be referred to as Môreson clay. The properties determined of the De Clapmuts clay are presented in Sections 4.3.3 through 4.3.5. It was established that Môreson and De Clapmuts have virtually identical properties.

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4.3.1 The physical properties of the G5 material

Approximately three tons of G5 material was obtained from Lafarge at no extra cost for the purpose of research. One important aspect of the G5 material, as it relates to the research, is that the material had to have a plasticity index of 7 or 8. The material was placed into bags and transported to the laboratory. The material contained stones larger than 12.5 mm. These were sifted out and removed of, because of practical reasons. Compacting stones with such a large diameter into the apparatus was simply impossible and results obtained would be inconclusive. The sieved material is shown in Figure 4.4

The tests performed on the G5 material were done by Simlab for classification purposes. The physical properties of the G5 material are presented in Table 4.1.

Figure 4.4 Sieved G5 material stored in the laboratory

Table 4.1 Physical properties of the G5 material

Description of material		Crushed Hornfels (G5-Subbase)	
Soil mortar	Coarse sand		35
	Fine sand		36
	Material < 0.075 mm		29
Constants (Atterberg limits)	Liquid limit		22
	Plasticity index		7
	Linear shrinkage		3.0
Grading modulus			2.55
CBR determination	Modified AASHTO	Maximum dry density	2262
		Optimum moisture	5.0
		Compaction moisture	4.9
		% Density	100.9
		CBR	240
		Swell	0.01
	N.R.B.	% Density	95.2
		CBR	73
		Swell	0.02
	Proctor	% Density	91.0
		CBR	33
		Swell	0.03
CBR	At 100% Modified AASHTO		198
	At 98% Modified AASHTO		132
	At 95% Modified AASHTO		72
	At 93% Modified AASHTO		48
	At 90% Modified AASHTO		26
TRH14 Classification			G5

The plastic limit was determined according to USBR (1990c) and the determination of the liquid limit was performed according to USBR (1990b). The compaction procedure was performed according to ASTM (1982).

4.3.2 Particle size distribution of the G5 material

The particle size analysis was performed according to the procedures given by USBR (1990a). The particle size distribution curve of the G5 material is presented in Figure 4.5.

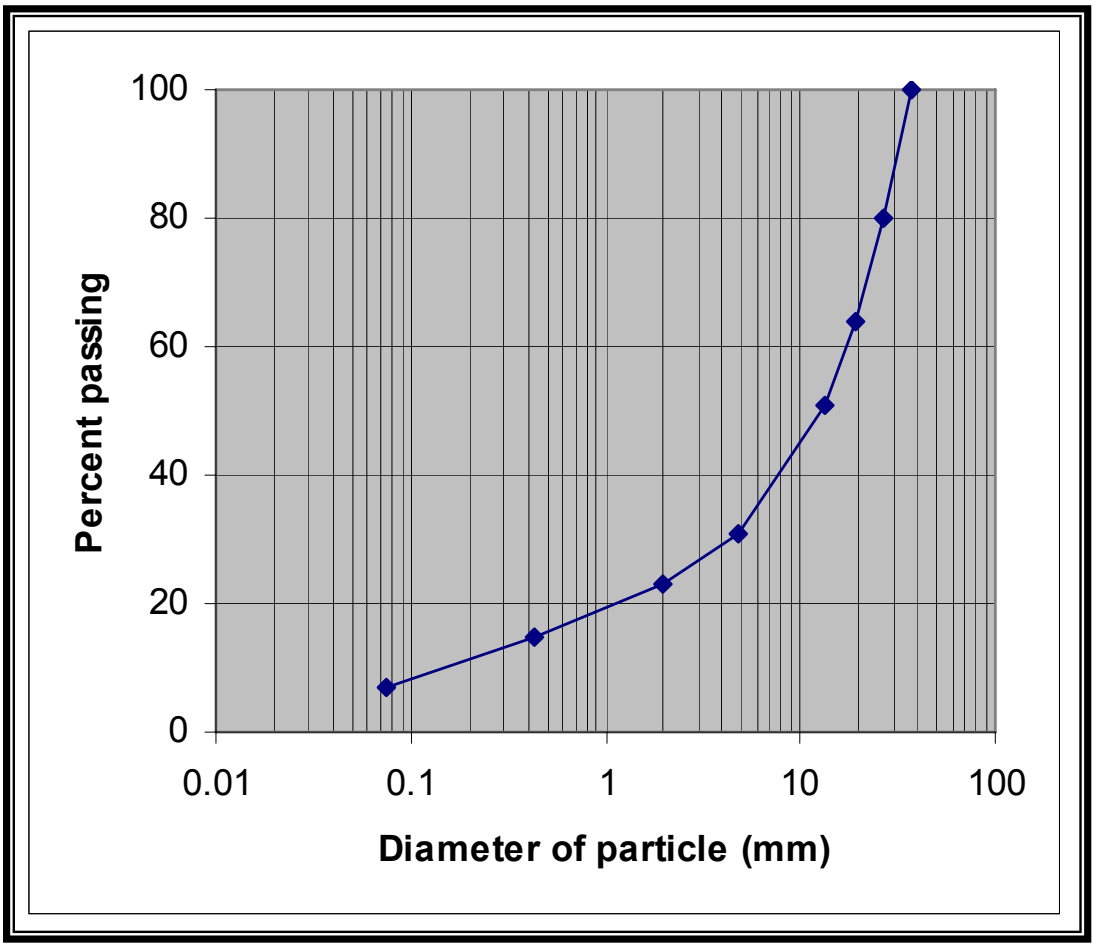

Figure 4.5 Particle size distribution of the G5 material

4.3.3 The physical properties of the De Clapmuts clay

The De Clapmuts clay was collected from deposits along the bank of the dam and placed in bags for easy transportation. In the laboratory it was air-dried for ten days and a Kango hammer and plate compactor were used to break up the clods in the dry material. Batches of the material was manually pulverized with a mortar and pestle and shaken through a 2.36 mm sieve prior to adding it to the G5 material as fines, as it was needed. The physical properties of the De Clapmuts clay are presented in Table 4.2.

Table 4.2 Physical properties of the De Clapmuts clay

Description of material			De Clapmuts clay
Constants (Atterberg limits)	Liquid limit		34
	Plasticity index		24
	Plastic limit		10
CBR determination	Modified AASHTO	Maximum dry density	1815
		Optimum moisture	13.4
Air dried moisture content			3.5
Specific gravity			2.601
Unified soil classification			CL

The plastic limit was determined according to USBR (1990c) and the determination of the liquid limit was performed according to USBR (1990b). The clay was classified according to the Unified Soil Classification, USBR (1990j). The specific gravity was determined according to USBR (1990d) and the compaction procedure according to ASTM (1982).

4.3.4 Particle size distribution of the De Clapmuts clay

The particle size analysis was performed according to the procedures given by USBR (1990a). The particle size distribution curve of the De Clapmuts is presented in Figure 4.6.

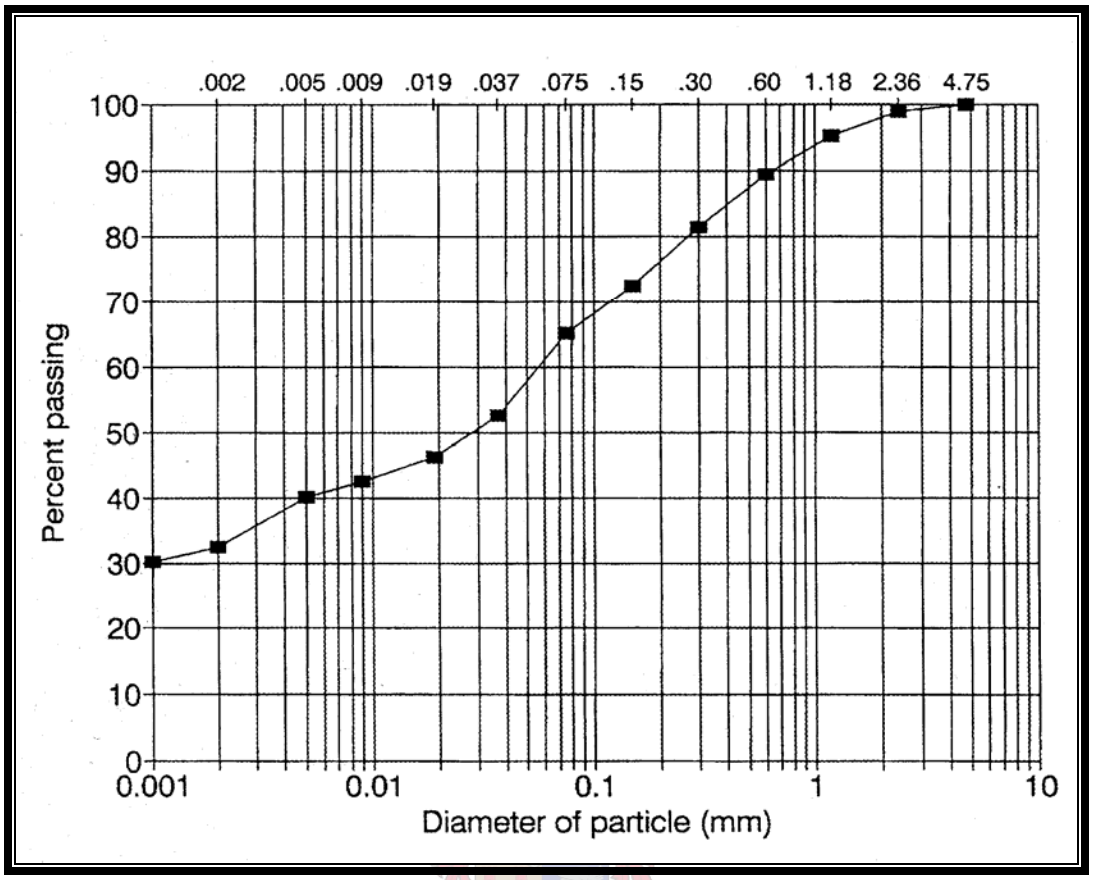

Figure 4.6 Particle size distribution of the De Clapmuts clay (from De Wet, 1995)

4.3.5 Permeability of the De Clapmuts clay

The falling head permeability test was done on samples after electrokinetic treatment. Erosion channels formed between the wall and the sample. As a result reliable values could not be obtained, but indications were that 3.6×10^{-7} mm/min may be a representative value. The coefficient of permeability is normally expressed in m/s, but the units of mm/min have been used in this thesis.

4.3.6 The physical properties of G5 material with 30% fines added

The properties of the 30% fines mixture were determined, because the electro-osmotic acceleration of infiltration process started to manifest in this mixture. The addition of fines to the G5 material would change the classification of the combined material. It was therefore important to classify the mixed material to see exactly with what type of material was being tested. The exact procedure of mixing the material is given in detail in Section 4.4.1. The physical properties of the 30% fines mixture is presented in Table 4.3. From the physical properties determined, the material was classified a G10 material. (TRH14 classification)

Table 4.3 Physical properties of the 30% fines mixture

Description of material		Crushed Hornfels (G5-Subbase)+ 30%Fines	
Constants (Atterberg limits)	Liquid limit		44
	Plasticity index		22
	Linear shrinkage		8.7
	Plastic limit		22
CBR determination	Modified AASHTO	Maximum dry density	2120
		Optimum moisture	10.2
		Swell (100% Mod. AASHTO)	0.63
		Swell (93% Mod. AASHTO)	0.35
CBR	At 93% Modified AASHTO		5.1
TRH14 Classification			G10

The plastic limit was determined according to USBR (1990c) and the determination of the liquid limit was performed according to USBR (1990b). The compaction procedure was performed according to ASTM (1982).

4.3.7 Particle size distribution of the 30% fines mixture

The particle size analysis was performed according to the procedures given by USBR (1990a). The particle size distribution curve of the G5 material with 30% fines is presented in Figure 4.7.

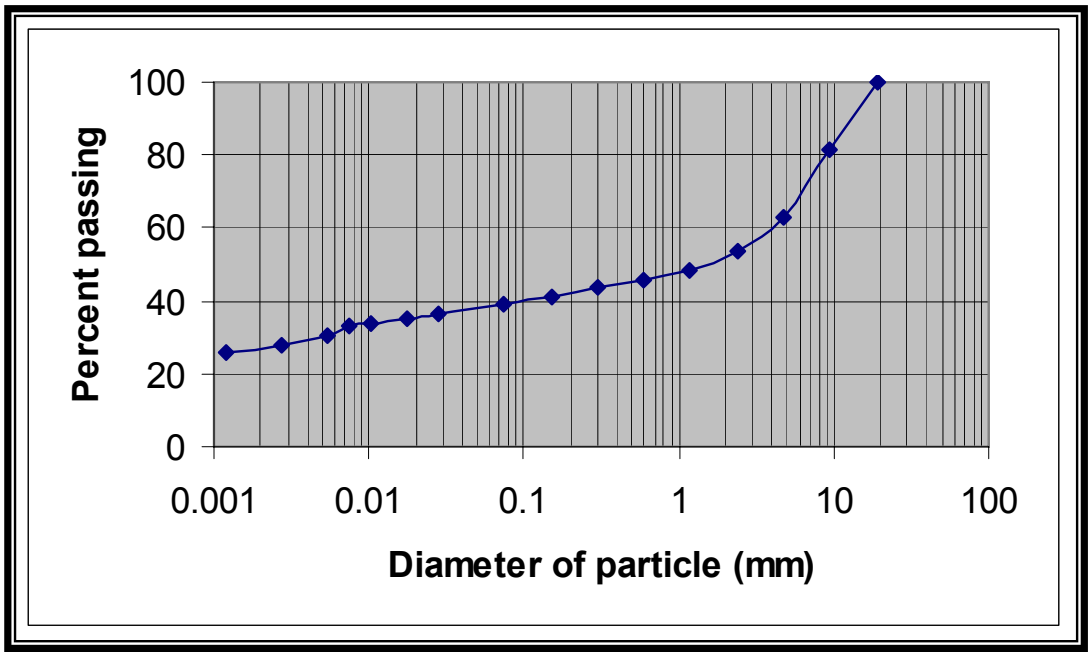

Figure 4.7 Particle size distribution of the 30% fines mixture

4.3.8 Permeability of the 30% fines and 20% fines mixtures

The falling head test was done on 30% and 20% fines samples compacted at 8% and 6% gravimetric moisture content. The values of the coefficient of permeability obtained are presented in Table 4.4.

As can be expected, the permeability of the 30% fines mixture was lower than that of the 20% fines mixture, because the reduced fines were not able to fill the voids between the coarse G5 particles.

Table 4.4 Coefficient of permeability of the 30% fines and 20% fines mixtures

Mixture	Coefficient of permeability (mm/min)
30%Fines-8%Water	0.000546
30%Fines-6%Water	0.000106
20%Fines-8%Water	0.298589
20%Fines-6%Water	0.225046

4.4 EXPERIMENTAL PROCEDURES

Described in this section are the procedures used to mix the different soils, to compact the soil into the respective compartments and to run the electro-osmosis experiments in such a way as to meet with the research objectives. Procedures to monitor the infiltration process and to determine the moisture content of the saturated sample after completion of the test are also discussed.

4.4.1 Mixing

The mass of soil needed for a batch of tests was removed from the bags. Then the clay had to be crushed by means of a pestle and put through the 2.36 mm sieve. The G5 and clay was then weighed and mixed in a drum mixer according to the desired ratio. The mixture was then placed back into the bags. A sample was oven-dried to determine the actual moisture content, and the following day the additional water was added to bring the soil mass to the required moisture content.

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The water was added by means of a fine spray while the mixer was running, ensuring homogeneous distribution of the water to bring it to the desired initial moisture content. This was a vital part of the process, since the initial moisture content had to be raised by only a few percent. Distilled water was used at all times. A problem encountered was that if large amounts of water had to be added, the soil tended to form wet lumps within the drier matrix if the rate of water addition was not sufficiently low.

Using a sample that “clotted” like this formed wet spots within the one-dimensional apparatus and made it very difficult to establish the position of the wetting front with the naked eye. To allow for evaporation during spraying and mixing the required mass of water was increased by 10 percent. After the addition of water, samples were oven dried to determine the actual moisture content.

4.4.1.1 One-dimensional test

The objective of the one-dimensional tests was to determine the relationship between the fines content and velocity of moisture infiltration into the soil column at different currents and different initial moisture contents. At first the tests were done using samples with 0%, 2%, 4%, 6%, 8% and 10% fines. The results were very close to each other and a larger spectrum of fines content had to be used to obtain conclusive results. It was then decided to add 20%, 30% and 50% fines content to the experimental program.

The ratio for mixing was 5:1 (5 parts G5 material to 1 part clay). This meant that if there were 10 kilograms of G5, and if a 20% mixture was wanted, 2 kilograms of clay was added. The initial moisture content was set at 3% and 6%, using a spray bottle to wet the material in a 20 litre drum mixer. This was a very tricky process and as a result, initial moisture content of different batches varied slightly. However this was not a problem, as the moisture water content of all the batches were measured separately by means of oven drying.

Batches of 10 kilograms per test were mixed in the 20 litre drum mixer. More difficulty was experienced in the one-dimensional tests, when attempting to obtain the required initial moisture content, because the 20 litre drum mixer did not mix as well as the 120 litre drum mixer used in the two-dimensional tests.

4.4.1.2 Two-dimensional test

Taking into account the results from the one-dimensional tests, it was decided to perform two-dimensional tests using samples with 20% and 30% fines. The ratio of G5 material to percentage fines mixing, used in the two-dimensional tests, was different to the one-dimensional mixing ratio. The ratio for two-dimensional mixing was 4:1 (4 parts G5 material to 1 part clay). This meant that 8 kilograms of G5 was added to 2 kilograms of clay to give us a 20% mixture.

The initial moisture content was set at 6% and 8%, using a spray bottle to wet the material in a 120 litre drum mixer. Batches of 60 kilograms per test were mixed in the 120 litre drum mixer.

4.4.2 Compaction

4.4.2.1 One-dimensional test

The Proctor 2.5 kg drop hammer was used to compact the samples, in layers, inside the cylindrical tube. The hammer fitted into the 60 mm tubes with very little clearance and all the blows were delivered virtually in the centre of the soil column. This meant that great care had to be taken to ensure that the soil along the walls of the tube was compacted sufficiently. Compaction was performed at moisture contents below the optimum and the confinement of the tubes favoured one-dimensional compaction instead of kneading, which usually resulted in a flocculated structure. The compaction process would therefore result in all soil columns having more or less the same fabric.

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It was necessary to maintain the same dry density along the soil column. To achieve this, the exact mass of soil to be compacted in each layer was put into the tube and compacted to the required layer thickness of 20 mm. The compaction of subsequent layers led to an increase in the densities of layers already in place by transmission of energy. The number of blows per layer was decreased for all layers except the last five to compensate for this increase in density. These last few layers received progressively more blows.

Moisture content samples were taken after compaction and the final average dry density of each column was determined. After the compaction process, ten millimetres of soil was removed from the ends of the column to allow for the steel wool and mesh electrodes to be placed in contact with the soil. The compartments were then assembled as discussed in section 4.2.3 and the brass electrodes inserted by penetration through the openings in the one-dimensional

apparatus wall. The carbon electrodes were then put into place inside the compartments.

4.4.2.2 Two-dimensional test

The Modified 4.536 kg drop hammer was used to compact the samples, in layers, inside the wooden box. Compaction was preformed at moisture contents below the optimum.

It was necessary to maintain the same dry density in the soil volume. To achieve this, the mass of soil to be compacted in each layer was put into the box and compacted to the required layer thickness of 40 mm. The compaction of subsequent layers led to an increase in the densities of layers already in place by transmission of energy. As in the one-dimensional tests, the last few layers received progressively more blows.

The box was first screwed together and the corners were then siliconed to ensure that the box was leakproof. The steel clamps were then used to reinforce the box. The first 30 mm of material which was placed into the box, is a 6 mm layer of gravel. A layer of geotextile was placed above the gravel layer to prevent fines from entering into the gravel. The gravel was there to allow water to move freely to the outlet. The test soil sample above the geotextile is 370 mm high.

Nine layers of 41 mm each were then compacted above the geotextile. At first three layers were compacted and then three 40 mm PVC pipes were placed onto this layer as shown in Figure 4.7. One more layer was compacted around these three PVC pipes and the anode and cathode compartments were placed onto this layer, as can be seen in Figure 4.8.

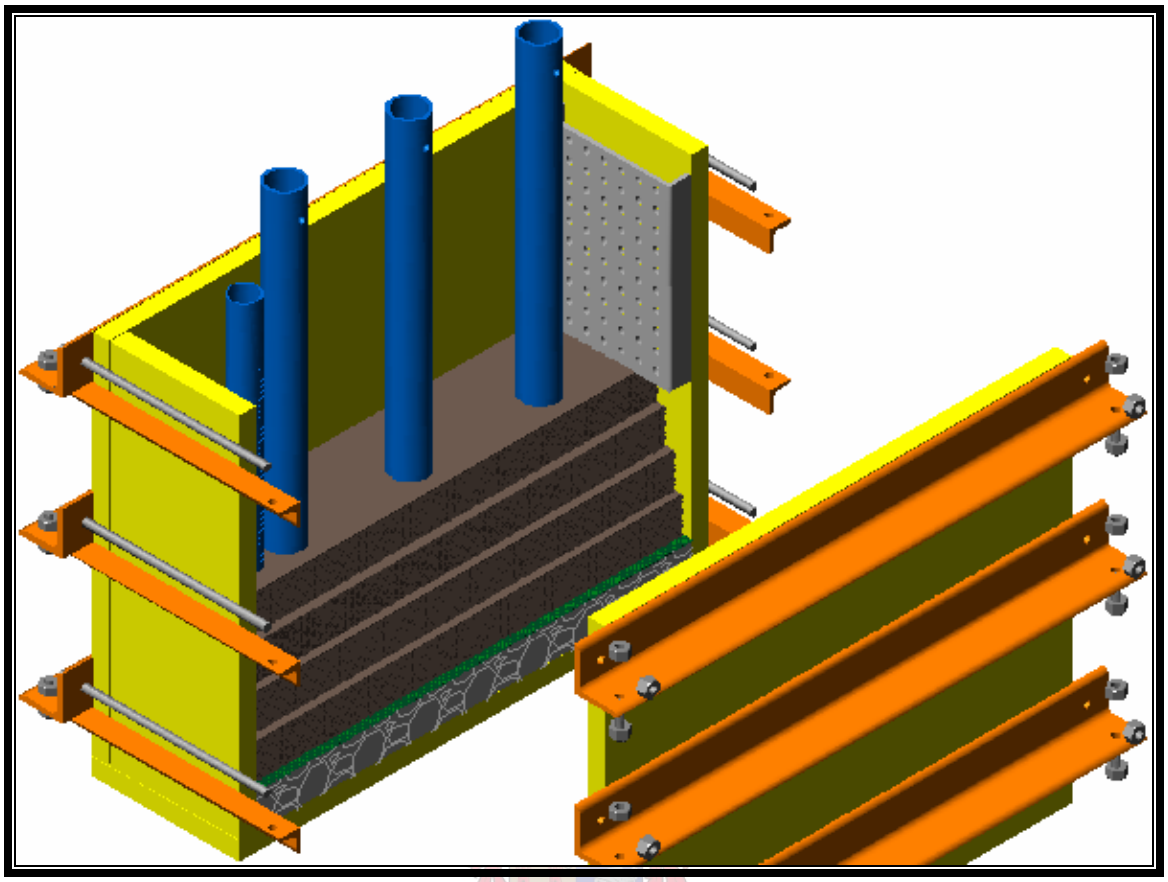


Figure 4.8 Schematic of compaction procedure

The last 5 layers were compacted around the anode and cathode compartments and the three 40 mm PVC pipes. There was a hole drilled at the top end of the three 40 mm PVC pipes and a steel bar was used to pull and twist the pipes out of the soil. The soil moisture blocks were then inserted into these holes. Three blocks were inserted into every hole and labelled areas 1 to 9 as can be seen in Figure 4.9.

After every block was inserted a steel pipe was used to compact fine clay material around the moisture blocks. The soil around the soil moisture blocks could not be compacted as solid as the surrounding soil and therefore the dry density in the whole sample would not be uniform. The difference in dry density would affect the rate of infiltration. This was another reason to leave the soil moisture blocks out in later experiments. Once the holes were filled, the perspex road was placed onto the soil surface. The carbon electrode was then placed into the anode compartment.

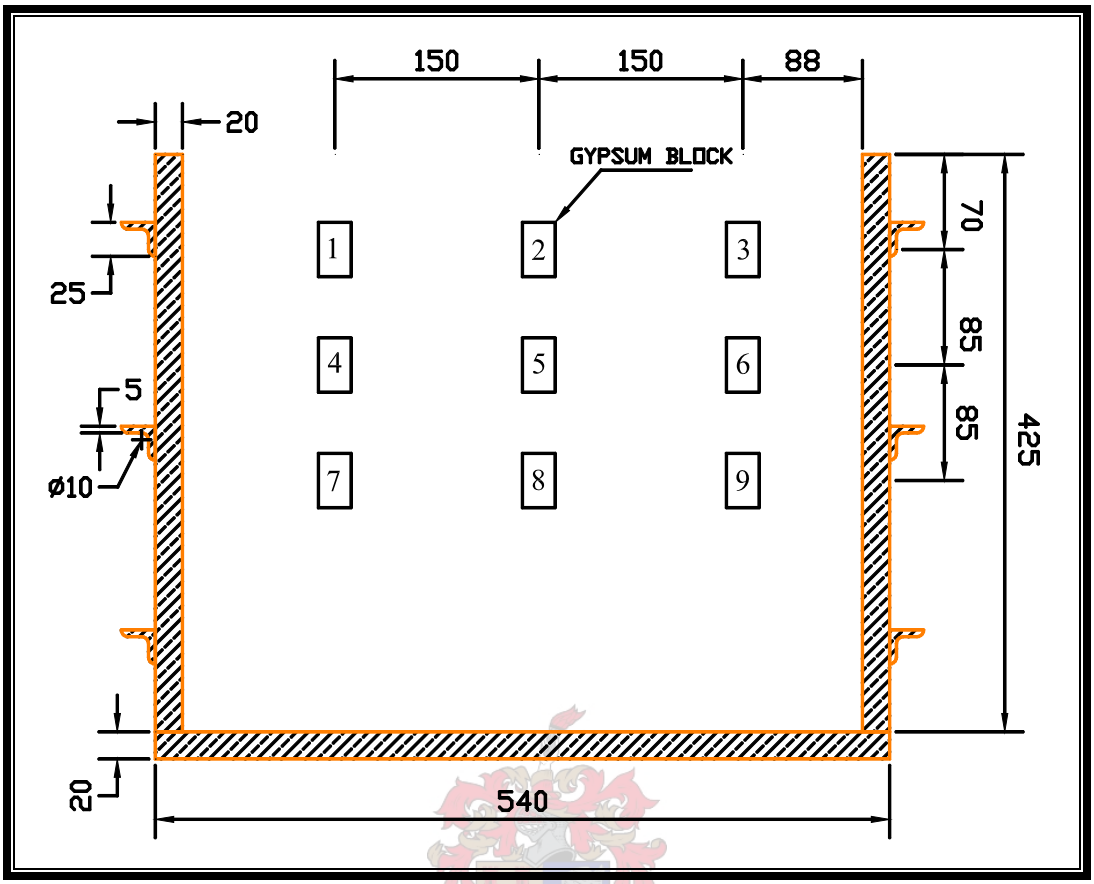


Figure 4.9 Labelling of section areas

4.4.3 Adding the chemical solutions

The object of the research was to study the rate of infiltration of moisture into a soil column given different fines compositions, through the method of electro-osmosis. A 0.02 normal $CaCl_2$ solution was prepared to use in the anode compartment. The solution was prepared in 20 litre batches and stored in a sealed bottle.

4.4.3.1 One-dimensional test

The compartments were emptied and refilled every 24 hours. Since the volume of pore fluid discharged from the cathode had to be accurately measured, the cathode compartments were sealed, except for small air ventilation openings,

and left empty. Pore fluid accumulated in these reservoirs and was drained and weighed only when the volume was substantial, about 10 ml. The water was also drained at the end of the test period.

4.4.3.2 Two-dimensional test

After the first test the chloride ions started corroding the gypsum soil moisture blocks. ph readings were taken and were found to be between 1 and 2. Therefore, potassium hydroxide was added to neutralise the solution. The potassium hydroxide made the solution more basic, but only for up to a time period of 4 hours. The addition of potassium hydroxide was stopped once the gypsum soil moisture blocks were omitted.

A constant level reservoir was used to ensure that the anode has water 24 hours a day. The calcium chloride solution infiltrated the soil quickly enough so that the solution did not have to be changed. Pore fluid accumulated in the cathode reservoir and was drained and weighed twice a day, because it would be undesirable for larger volumes of fluid to be left inside the compartments since that would alter the boundary conditions. The water was also drained at the end of the test period.

4.4.4 Fluid flow measurements

The inflow was determined indirectly by sectioning and moisture content determination of the test soil. In the one-dimensional tests a row of small openings was drilled in the wall of the perspex, in order to ensure that air does not become trapped inside the soil column. These openings do not only serve as ventilation holes, but also to allow secondary electrodes to be inserted into the soil column. As sections of the sample became semi-saturated while the electro-osmotic process was under way, fluid pressure built up and the result was that the pore fluid tended to ooze out of the ventilation openings. This was

undesirable and as soon as there were signs of this occurring, the holes were plugged up with silicone rubber.

4.4.5 Electrical measurements

The regulated power source was first switched on so that the electrokinetic processes commenced as soon as the solutions were introduced into the anode compartment. The addition of the calcium chloride solution closed the electric circuit.

A multimeter was used to measure voltages and current strength. The current strength was adjusted when necessary. In the one-dimensional tests, the potential drops between the stainless steel and closest copper electrodes and between the copper electrodes spaced at 50 mm along the soil column length were measured. One-dimensional tests were performed at current intensities of 0 mA, 15 mA and 25mA.

In the two-dimensional tests, the current strength of 200 mA had to be constant and was therefore constantly monitored to prevent any large deviations. Two-dimensional tests were first performed at current intensities of 0 mA, 70 mA, 150 mA and 200 mA. There was not a great difference between the 0 mA, 70 mA and 150 mA tests, and was therefore decided to perform the remaining tests at 0mA and 200 mA. An even higher current was desirable, but the available power sources were limited to 200 mA.

4.4.6 Removing samples for moisture content determination

4.4.6.1 One-dimensional test

When the reservoirs were empty, the current was switched off and the apparatus was dismantled as quickly as possible. The central section of the apparatus, which contained the soil sample, was placed inside a specially designed frame

and the soil pushed out by means of a manually operated hydraulic jack. The piston of the jack was fitted with a removable end plate just smaller than the inside diameter of the tube and the soil was always pushed from the cathode end, as the soil was firmer there.

There were some problems encountered with this process, as quite a few of the tubes were broken. This is attributed to the fact that the clay fines that were added tended to swell when saturated and as pressure was applied at the one end, by means of the hydraulic jack, the clay pushed outward against the wall. This caused it to break and was only a problem however with samples consisting of great portions of fines, 20%, 30% and 50% mixtures. Circular clamps were then used to reinforce the tubes. The specially designed frame and hydraulic jack can be seen in Figure 4.10.

Figure 4.10 Specially designed frame and hydraulic jack

The wet and dry sections of the soil column could be distinguished visually by means of the difference in colour. The removal of the soil from the tube was done at 20 mm intervals until the vicinity of the wetting front was reached. The section size was then reduced to 10 mm for the rest of the column. For those tests that did not use an electric current, the saturated part of the sample was

sectioned at 20 mm intervals, until the wetting front was close and 10 mm until there was only dry material left. The rest of the material was taken as one section. Each section was immediately placed into a numbered tin, weighed and put into the oven to dry at 105°C in order to determine the moisture content of the particular section following the procedures of USBR (1990h). Fresh soil was used for every test.

4.4.6.2 Two-dimensional test

At the end of the test period the reservoirs were drained of all the effluent, which was measured. When the reservoirs were empty, the steel clamps were removed and the boxes were unscrewed. The 6 mm gravel layer was then separated from the sample and a hammer and a chisel were used to chisel the sample into sub-samples. The removal of moisture content test soil samples were taken at the 9 areas described in Figure 4.9. These were immediately placed into numbered tins, weighed and put into the oven to dry at 105°C in order to determine the moisture content of the particular sub-sample following the procedures of USBR (1990h).

The remaining soil was air-dried and re-used in the following tests. The soil could only be used a maximum of four times, where after fresh material had to be crushed and mixed, because the soil properties would change too much if it would be used over and over.

5. RESULTS OF ONE-DIMENSIONAL TESTS

5.1 INTRODUCTION

The experimental work was carried out in two phases. The first phase included all the tests that were concerned with one-dimensional infiltration and will be discussed in this chapter. The second phase included all the tests that related to two-dimensional infiltration. This is discussed in the next chapter.

The experimental work for the one-dimensional tests mainly involved the determination of infiltration speed into different samples of material. The tests were done over a wide range of samples, with varied fines content as discussed in Section 4.4.1.1, as well as different electric currents as discussed in Section 4.4.5.

The objectives of these tests were:

1. To determine the infiltration velocity of moisture into samples with various fines contents, electric currents and initial moisture contents in unsaturated compacted soil.
2. To determine the effects of different current intensities applied to the sample at different fines contents.
3. To perform one-dimensional tests, to determine how much fines is required to allow for the process of electro-osmosis to occur in G5 material. This would then give a starting point to perform the two-dimensional tests.

Table 5.1 is a summary of the various tests performed together with relevant factors such as percentage fines, compaction moisture content, electric current intensity, treatment period, infiltration constants and effluents weighed in the cathode compartments. The individual tests results are presented in tabulated

and graphical form in Appendix B. Various results from the tests will be combined and discussed in the subsequent sections of this chapter.

Table 5.1 Summary of one-dimensional test parameters

Test no.	Fines (%)	Gravimetric moisture content (%)	Electric current (mA)	Treatment period (hours)	Incremental velocity (mm/min)	Constant (x^2/t)	Reservoir (g)
1	0	3.05	0	22.1	0.120	40	0.0
2	2	1.37	0	10.2	0.229	65	0.0
3	4	2.55	0	4.9	0.305	82	0.0
4	4	3.39	15	19.8	0.427	N/A	38.2
5	4	3.39	25	30.3	0.347	N/A	32.2
6	6	3.03	0	27.7	0.263	126	0.0
7	6	3.03	15	18.7	0.122	N/A	12.8
8	6	3.03	25	31.5	0.126	N/A	32.2
9	8	3.82	0	31.5	0.225	65	0.0
10	8	3.45	15	34.7	0.186	N/A	43.1
11	8	3.45	25	13.2	0.190	N/A	20.7
12	10	2.45	0	12.2	0.222	66	0.0
13	10	3.06	15	47.7	0.118	N/A	8.2
14	10	2.64	25	46.9	0.130	N/A	30.4
15	10	5.60	0	8.5	0.149	75	0.0
16	10	4.26	15	34.2	0.119	N/A	27.3
17	15	4.20	0	8.3	0.258	101	0.0
18	20	3.43	0	9.3	0.205	101	0.0
19	20	2.19	15	196.9	0.049	N/A	21.0
20	20	2.03	25	72.3	0.040	N/A	8.2
21	20	3.93	0	23.1	0.065	19	0.0
22	20	3.59	15	47.8	0.180	N/A	13.8
23	20	3.43	25	66.3	0.140	N/A	44.6
24	25	3.91	0	23.4	0.114	42	0.0
25	30	3.45	0	73.6	0.010	4	0.0
26	30	4.03	15	92.1	0.074	N/A	16.5
27	30	4.96	0	110.3	0.015	4	0.0
28	30	4.96	15	187.7	0.060	N/A	1.0
29	30	4.96	25	158.9	0.018	N/A	9.6
30	40	5.96	0	124.9	0.018	2	0.0
31	50	4.50	0	172.3	0.011	4	0.0
32	50	4.50	15	168.2	0.041	N/A	3.9
33	50	4.50	25	143.7	0.050	N/A	13.9
34	50	6.50	0	235.6	0.021	2	6.0
35	50	6.50	15	116.1	0.020	N/A	6.9
36	50	6.50	25	380.0	0.044	N/A	2.6

Detail on sample preparation, compaction and the actual test particulars were described in Chapter 4. The electric current was applied by means of a carbon anode in contact with the calcium chloride solution and a stainless steel grid with

steel wool cathode in close contact with the soil. Tests were performed at current strengths of 0 mA, 15 mA and 25 mA. Electrical potential drops over the sections between the secondary electrodes were monitored on a daily basis. All samples were carefully sectioned after the tests to determine the moisture distributions as discussed in Section 4.4.6.1

5.2 GENERAL CONSIDERATIONS

5.2.1 Darcy's Law

When looking at the data, the first thing that stands out, is that below 20% fines content the effects of electro-osmosis are minimal. Above the 20% mark however, a clear pattern emerges, which will be discussed in detail in Section 5.3.

This clear "lack of pattern" can only be attributed to Darcy's Law. In Section 3.4 I discussed Darcy's Law of Hydraulic flow. The influence was plain to see, as it was clear that samples with low fines content gave sporadic results. This led to the conclusion that below 20% fines content, the natural infiltration theory in Section 3.4 no longer applied. The water no longer infiltrated into the soil sample, it simply flowed through the large voids. Even the electric current was affected, as it no longer travelled through the clay fines (to initiate ion movement), but rather through the voids filled with water.

5.2.2 Compaction

The compaction is discussed in Section 4.4.2.1. It proved to be somewhat of a problem. The sample was a mix between G5 material and added fines as discussed in Section 4.4.1. This meant that during the compaction process the fines tended to settle at concentrated areas. The clay particles tended to migrate to the top.

Every added layer also formed a thin film at the top after the compaction hammer was used. This meant that essentially there was not one homogeneous sample, but different layers making up the soil column. This could also be the cause of some discrepancies in the data.

5.2.3 Wetting front

The wetting fronts were in some cases of such a nature that the end points were difficult to determine visually. This could also be the cause of some discrepancies in the data. The wetting front from the anode and cathode sides can be seen in Figure 5.1.

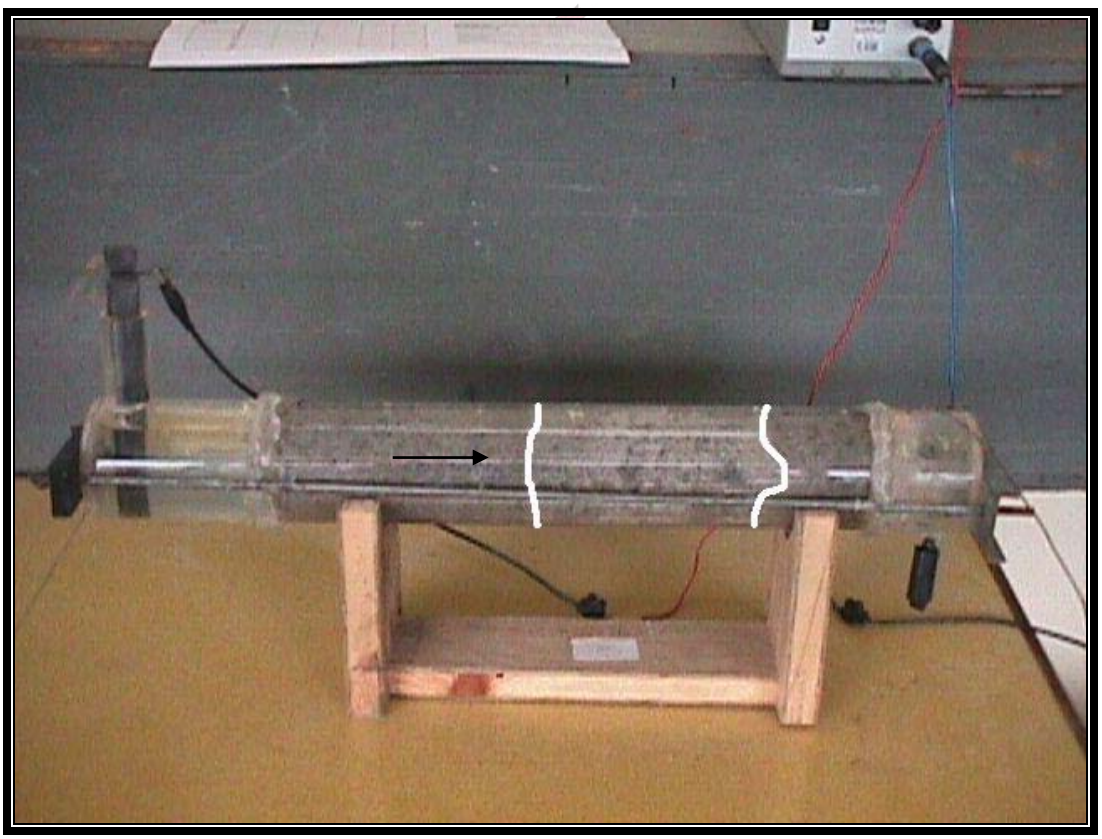


Figure 5.1 Wetting fronts in the one-dimensional test

Distance from anode end versus volumetric moisture content graphs were drawn for the tests where many sections were taken. Some tests were allowed to run

until the soil column was fully saturated. Only the results from tests no. 18 and no. 10 are shown in Figures 5.2 and 5.3 respectively to aid in the discussion.

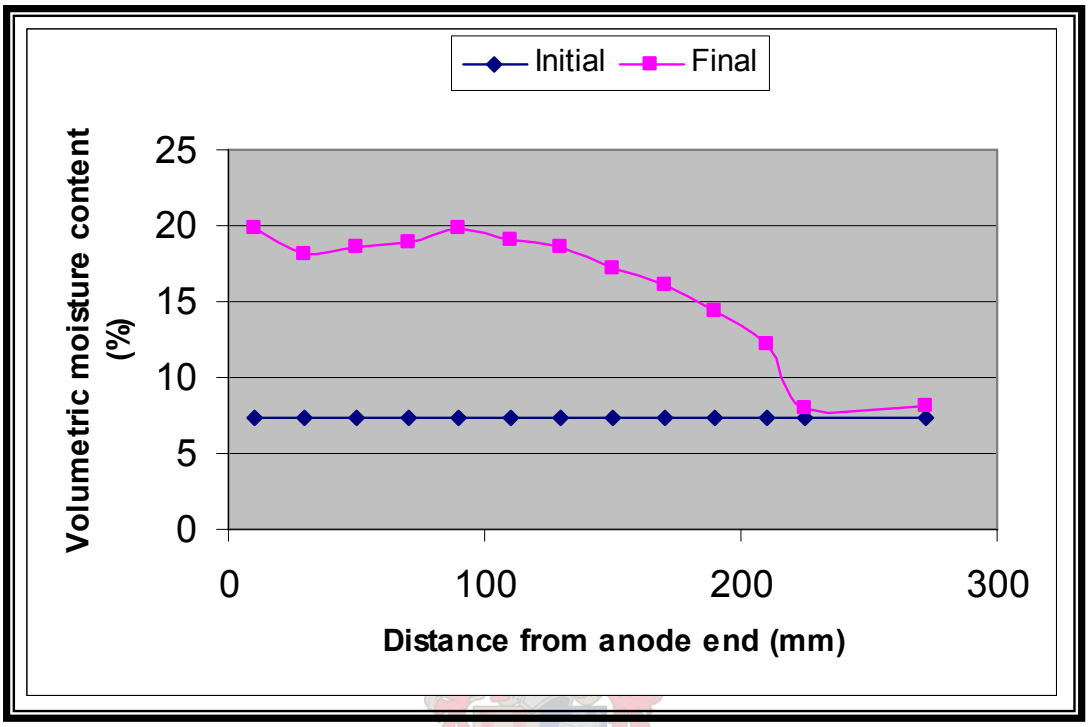


Figure 5.2 Volumetric moisture content graph, Test no. 18 (20% fines, 3% moisture content, 0 mA)

In Figure 5.2 it can be seen that the wetting front is about 237 mm from the anode end. The soil column had not been fully saturated, and the test was stopped at this point in time. The test was stopped after 9.3 hours and had an initial volumetric moisture content of 7.39%. The moisture content of the material just ahead of the wetting front remained similar to the initial moisture content.

In Figure 5.3 the soil column has been fully saturated. The moisture content at the anode is similar to the moisture content at the cathode. The line is not perfectly straight, because of the presence of small stones in the G5 material and the non-homogeneity described in Section 5.2.2. Water stayed within the fines fraction. One section could have more stones, and would therefore have less water. The test was stopped after 34.7 hours and had an initial volumetric moisture content of 5.79%.

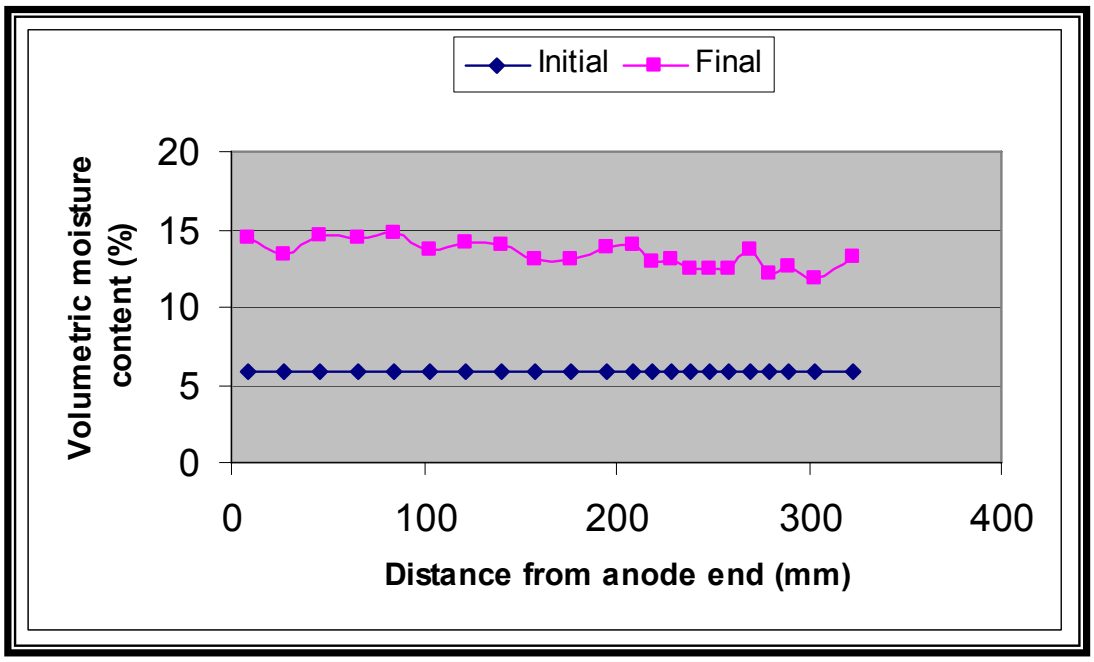


Figure 5.3 Volumetric moisture content graph, Test no. 10 (8% fines, 3% moisture content, 15 mA)

5.3 INFILTRATION VELOCITY

The incremental velocity, which is the maximum velocity reached, was calculated for every test. The results were varied and inconclusive with samples consisting of less than 20% fines. No real infiltration occurred in samples consisting of less than 20% fines. Moisture entered through the openings because the sample was confined in a perspex tube. The results are displayed graphically in Figure 5.4.

With no current applied, the velocity of moisture infiltration decreased with added fines. At high fines content the velocity of infiltration slowed drastically and in some cases the infiltration did not penetrate the whole sample. This occurs because there are less voids in the sample for the infiltration of moisture. It is also important to note that at fines contents at 30% and above, the velocity of infiltration is much faster when an electrical current is applied across the sample. Below 30% fines electro-osmosis did not work.

The material classification of the 30% fines mixture was determined to be G10 as discussed in Section 4.3.6.

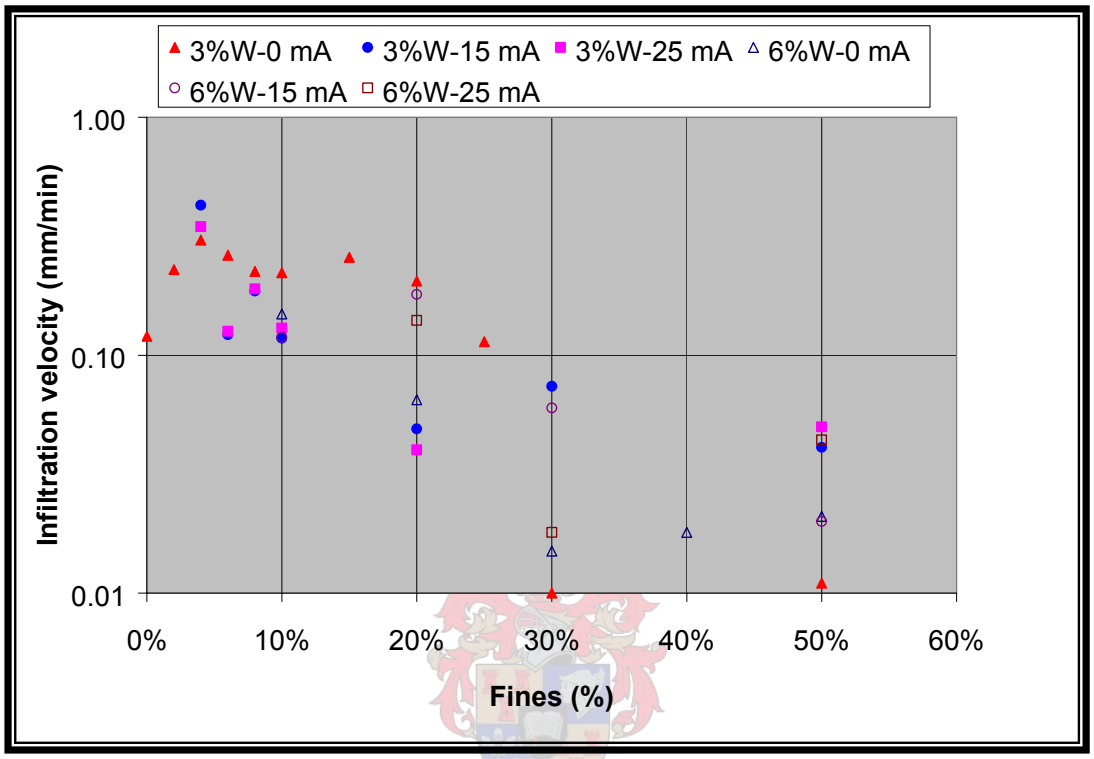


Figure 5.4 Incremental velocities in fines content at different electric current intensities

5.4 EFFECT OF THE ELECTRIC CURRENT

For natural flow, the infiltration constants in Equation 3.7 were determined for the different samples and are displayed graphically in Figure 5.5. Looking at the figure it can be concluded that the natural infiltration of water decreases with added clay fines. The high values at low fines were influenced by free flow as described in 5.2.1.

The time-distance graph for two sets of samples from the 30% fines content (3% moisture, 0 mA; and 3% moisture, 15 mA) was drawn up and the results compared. The results are displayed graphically in Figure 5.6. It is clear from

this figure that the influence of an electric current caused the moisture to infiltrate into the material at a constant speed. This infiltration at a constant velocity was

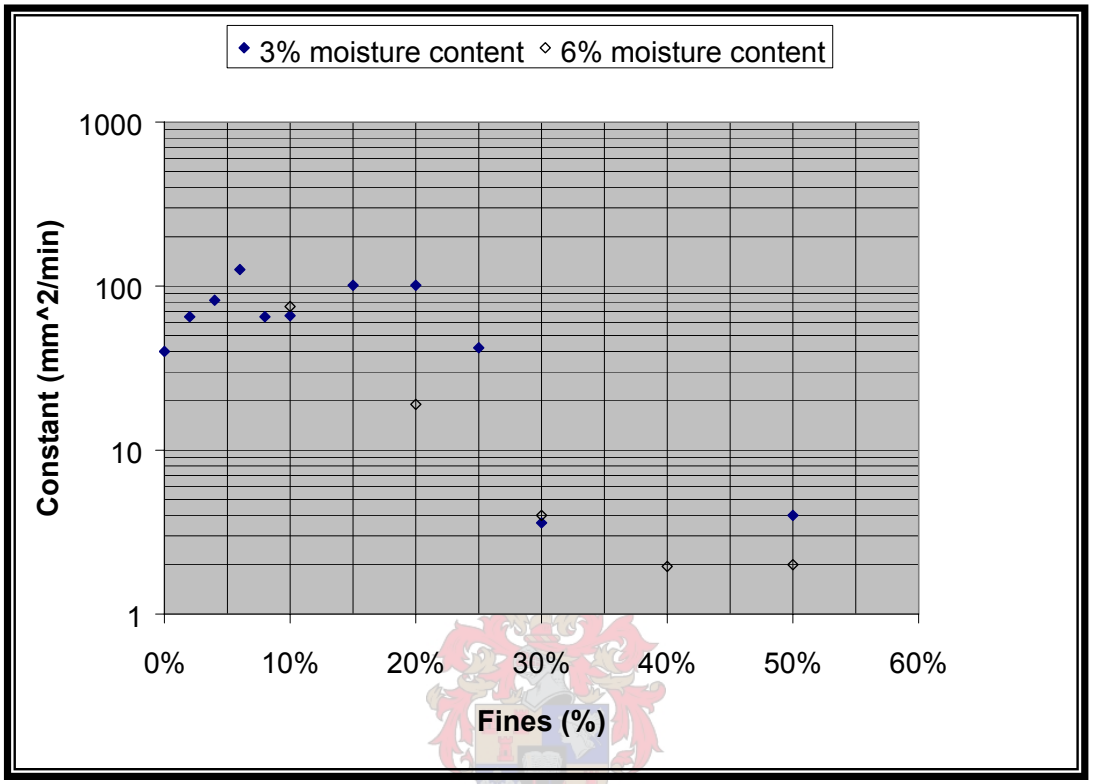


Figure 5.5 Natural infiltration constants at different fines contents

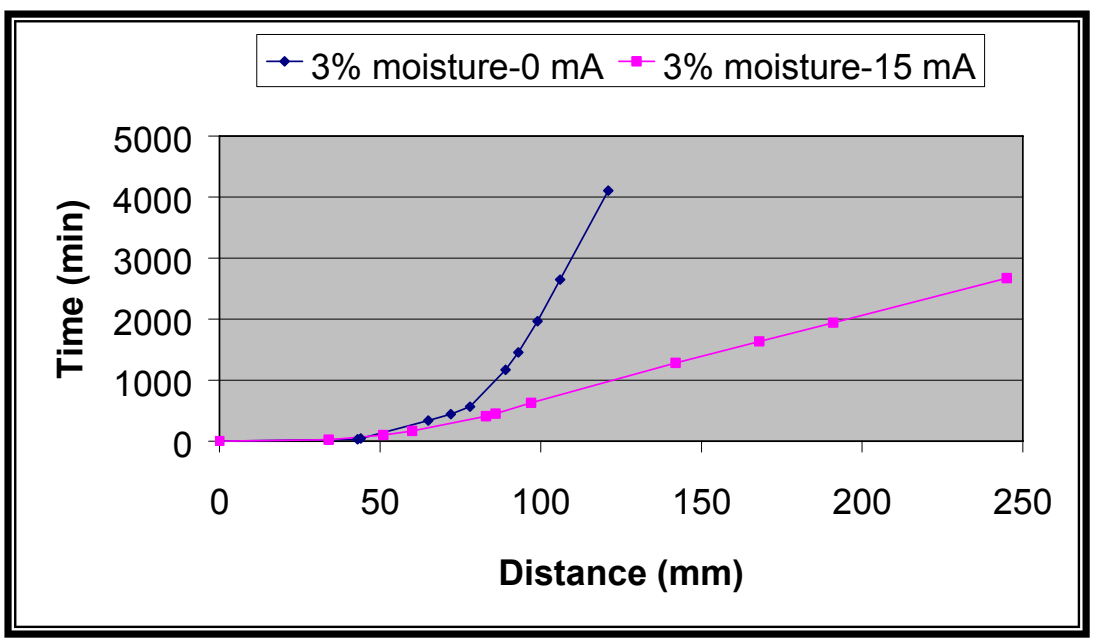


Figure 5.6 Effects of electric current on infiltration, 30% fines

much faster in the sample with an electric current. It can therefore be concluded that an electric current increased the rate of infiltration.

This is even more apparent on a graph depicting the infiltration behaviour of material with 50% fines. The effects of 0 mA, 15 mA and 25 mA were all plotted together in Figure 5.7. Here it can be seen that moisture infiltrated much faster with more intense currents, and without an electric current the infiltration rate tends to decrease with time.

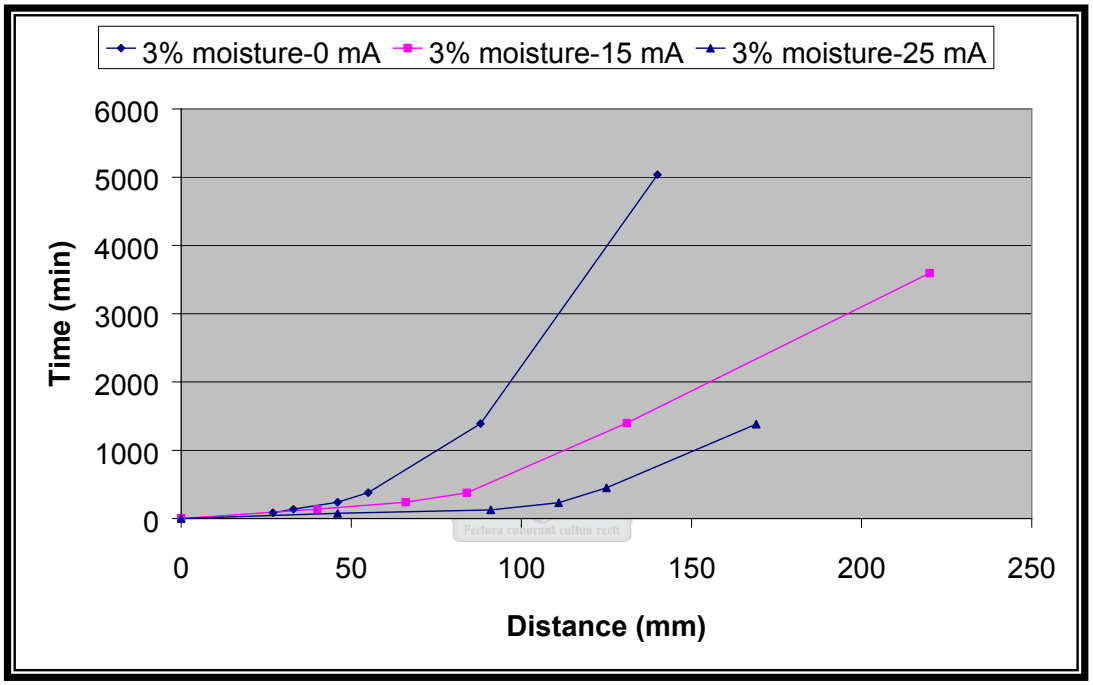


Figure 5.7 Effects of electric current on infiltration, 50% fines

It is clear from this figure that the influence of an electric current caused the moisture to infiltrate into the material at a constant velocity. If the lines for 15 mA and 25 mA currents were extended, it was evident that they do not have the same gradient. The 25 mA series was indeed faster than the 15 mA series. It can therefore be concluded that an increase in current intensity, increased the rate of infiltration. It can be concluded that with an adequate amount of fines in the material, the infiltration process can be sped up with the application of an electric current.

6. RESULTS OF TWO-DIMENSIONAL TESTS

6.1 INTRODUCTION

This section discusses the two-dimensional infiltration tests.

It had been verified in the previous chapter that at low fines content, smaller than 20% fines, electro-osmosis does not occur. At high fines content, bigger than 20% fines, the application of electro-osmosis seemed to have a telling effect on the velocity of moisture infiltration, increasing it drastically. It was therefore decided to perform the two-dimensional tests at 20% and 30% fines content, as discussed in Section 4.4.1.2. The addition of the fines to the G5 material to make the 30% mixture, would change the classification of the material. The 30% fines mixture would be classified a G10 material.

With the high clay content, the modified G5 material could tend towards a swelling soil, depending on the activity of the specific clay mineral present. The results found in this research could mean that electro-osmosis could be a solution to the problem of moisture increase in clay foundations prior to construction of pavements, which was investigated by Van der Merve DH, Hugo F and Steyn AP (1980).

Two-dimensional tests were first performed at current intensities of 0 mA, 70 mA, 150 mA and 200 mA. There was not a great difference between the 0 mA, 70 mA and 150 mA tests, and it was therefore decided to perform the remaining tests at 0mA and 200 mA only.

The objectives of these tests were:

1. To perform two-dimensional tests and to develop a two-dimensional experimental apparatus which permits an investigation into the electro-osmotic acceleration of infiltration into the subgrade of pavements.

2. To evaluate the viability of the electro-osmotic acceleration of infiltration into the subgrade of pavements.

Table 6.1 below is a summary of the various tests performed together with relevant factors such as percentage fines, compaction moisture content, electric current intensity, treatment period, energy consumption, effluents weighed in the cathode compartments and whether or not soil moisture blocks were present in the test. The individual tests are presented in tabulated and graphical form in Appendix C. Various results from the tests will be combined and discussed in the subsequent sections of this chapter.

Table 6.1 Summary of two-dimensional test parameters

Test no.	Fines (%)	Gravimetric moisture content (%)	Aimed moisture content (%)	Electric current (mA)	Treatment period (days)	Energy consumption (Wh)	Reservoir (g)	Soil moisture blocks
1	30	8.76	8.00	0	3	N/A	0.0	Yes
2	30	7.01	8.00	0	5	N/A	0.0	Yes
3	30	7.66	8.00	0	7	N/A	0.0	Yes
4	30	8.34	8.00	0	10	N/A	0.0	Yes
5	30	8.51	8.00	0	15	N/A	0.0	No
6	30	8.95	8.00	70	3	101.061	0.0	Yes
7	30	8.95	8.00	150	3	381.611	67.2	Yes
8	30	8.95	8.00	200	3	669.320	263.2	Yes
9	30	8.03	8.00	200	5	878.891	334.5	Yes
10	30	8.04	8.00	200	7	1520.982	725.4	Yes
11	30	7.73	8.00	200	10	1896.012	852.3	Yes
12	30	8.83	8.00	200	15	3360.669	1278.4	Yes
13	30	5.80	6.00	0	7	N/A	0.0	No
14	30	6.11	6.00	0	10	N/A	0.0	No
15	30	6.14	6.00	0	14	N/A	0.0	No
16	30	5.46	6.00	200	7	2207.151	0.0	No
17	30	6.53	6.00	200	10	2402.672	152.3	Yes
18	30	5.46	6.00	200	15	4614.446	327.7	No
19	20	8.39	8.00	0	7	N/A	0.0	No
20	20	8.45	8.00	0	10	N/A	0.0	No
21	20	7.63	8.00	0	15	N/A	0.0	No
22	20	7.32	8.00	200	7	1476.485	820.8	No
23	20	8.46	8.00	200	10	3289.620	1065.2	No
24	20	8.13	8.00	200	15	5490.132	1343.2	No
25	20	6.28	6.00	0	7	N/A	0.0	No
26	20	6.22	6.00	0	10	N/A	0.0	No
27	20	6.29	6.00	0	15	N/A	0.0	No
28	20	6.31	6.00	200	7	1784.311	489.0	No
29	20	5.88	6.00	200	10	2071.046	1120.2	No
30	20	5.52	6.00	200	15	6601.552	303.9	No

Detail on sample preparation, compaction and the actual test particulars were described in Chapter 4. The electric current was applied by means of a carbon anode in contact with the calcium chloride solution and a stainless steel grid cathode in close contact with the soil. All samples were carefully sectioned after the tests to determine the moisture distributions as discussed in Section 4.4.6.2.

6.2 GENERAL CONSIDERATIONS

6.2.1 Compaction

The compaction is discussed in Section 4.4.2.2. It proved to be somewhat of a problem. The sample was a mix between G5 material and added fines as discussed in Section 4.4.1. This meant that during the compaction process the fines tended to settle at concentrated areas. Every added layer also formed a thin film at the top after the compaction hammer was used. This meant that essentially there was not one homogeneous sample, but different layers making up the test soil sample. It was virtually impossible to compact a perfectly homogeneous sample. This could be the cause of some discrepancies in the data.

6.2.2 Wetting front

The wetting fronts were in some cases of such a nature that the end points were difficult to determine. The wetting front from the 30% fines, 8% initial moisture content, 0 mA, 7 days test can be seen in Figure 6.1. It clearly shows, that when no electric current is applied, the water from the anode compartment infiltrated the soil sample downwards. The water moved downwards because of gravity. Hardly any horizontal infiltration had taken place.

The wetting front, from the anode and cathode sides, from the 30% fines, 6% initial moisture content, 200 mA, 15 days test can be seen in Figure 6.2. A photo was taken every day, except day 13, to show the procession of the

Figure 6.1 Wetting front for 30% fines, 8% water, 0 mA, 7 days test

wetting front. It clearly shows that, when an electric current is applied, two-dimensional infiltration took place. In fact, the horizontal component of infiltration is larger than the vertical component.

Day 1

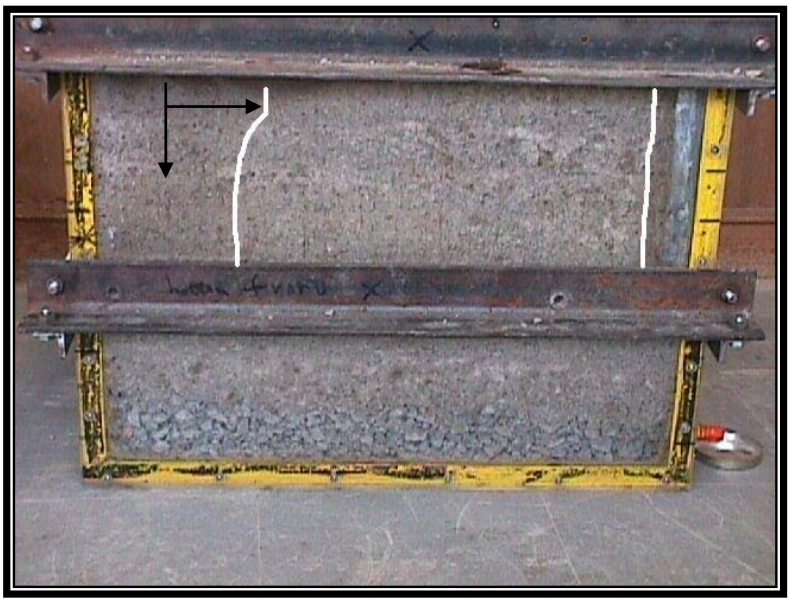
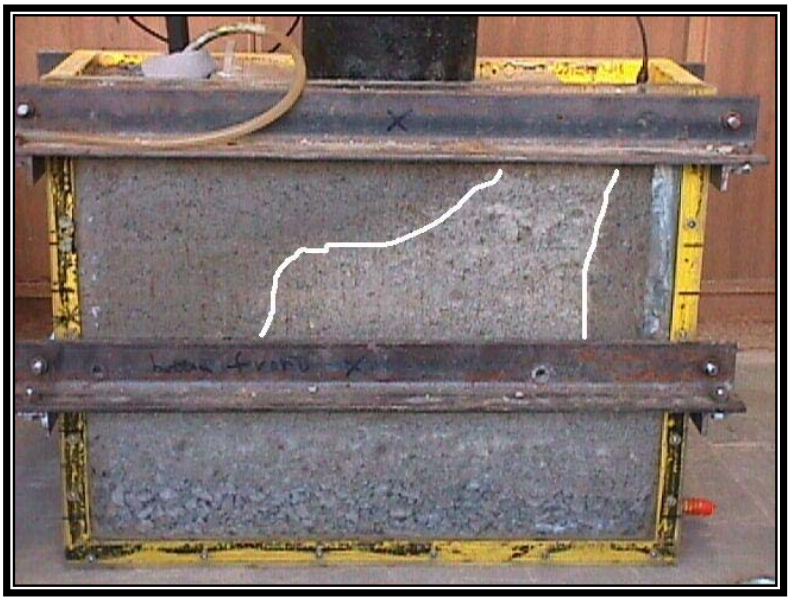


Figure 6.2a Wetting front for 200 mA test (Day 1)

Day 2

Day 3



Day 4

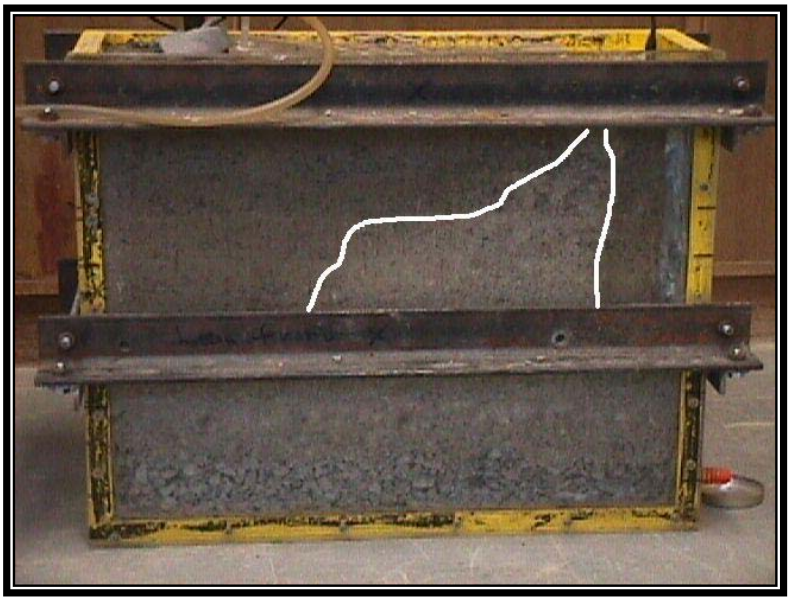
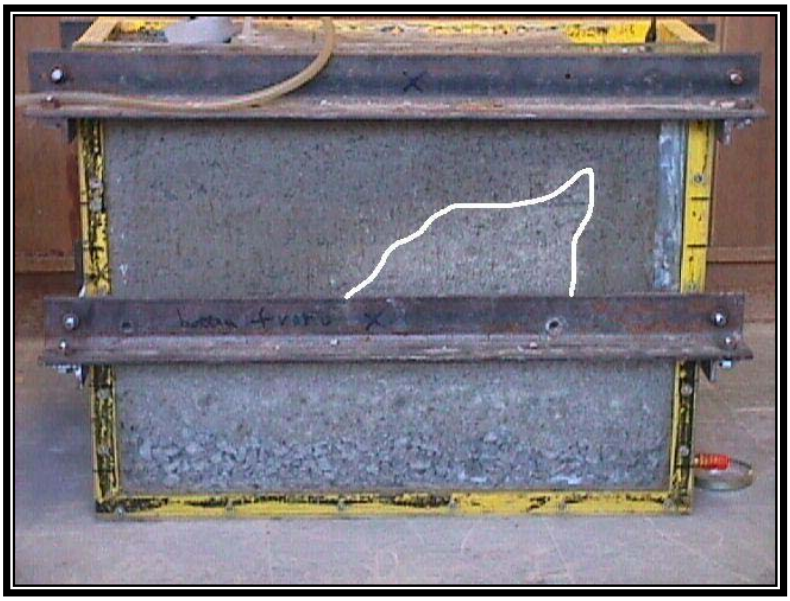
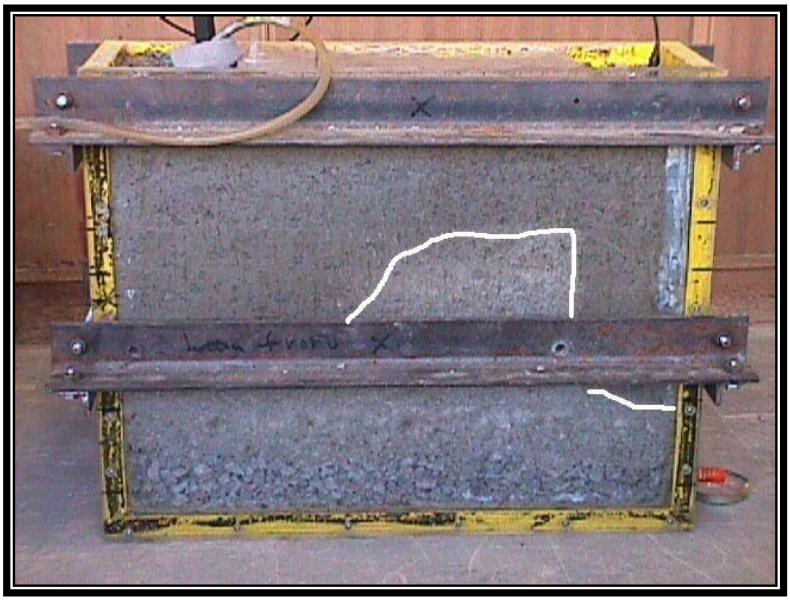


Figure 6.2b Wetting front for 200 mA test (Day 2, 3, 4)

Day 5



Day 6



Day 7

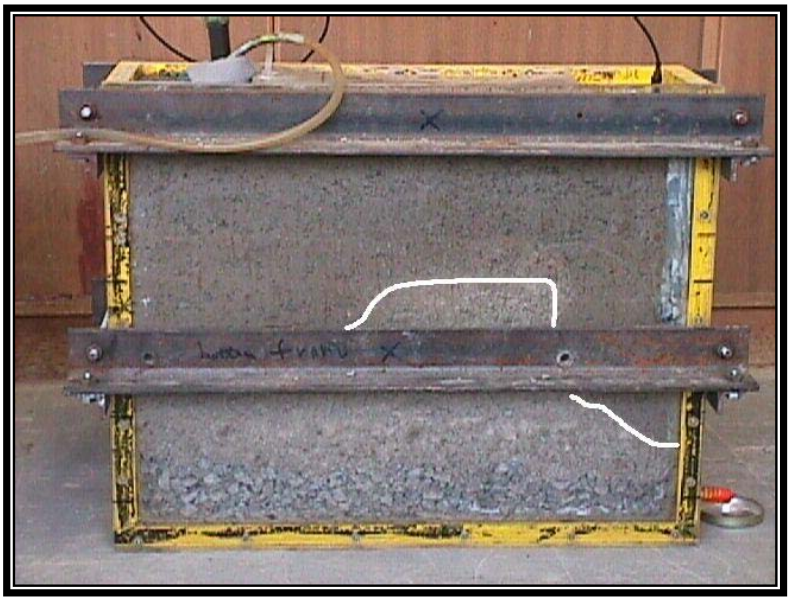
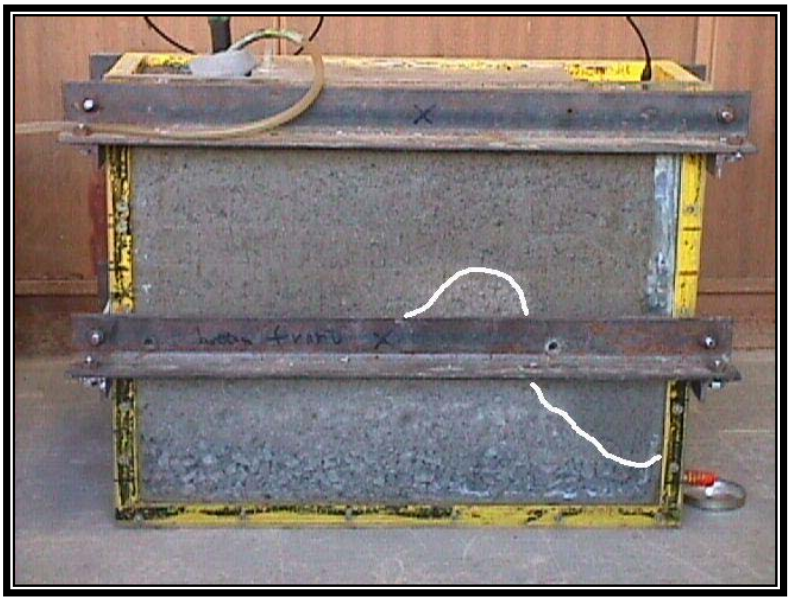
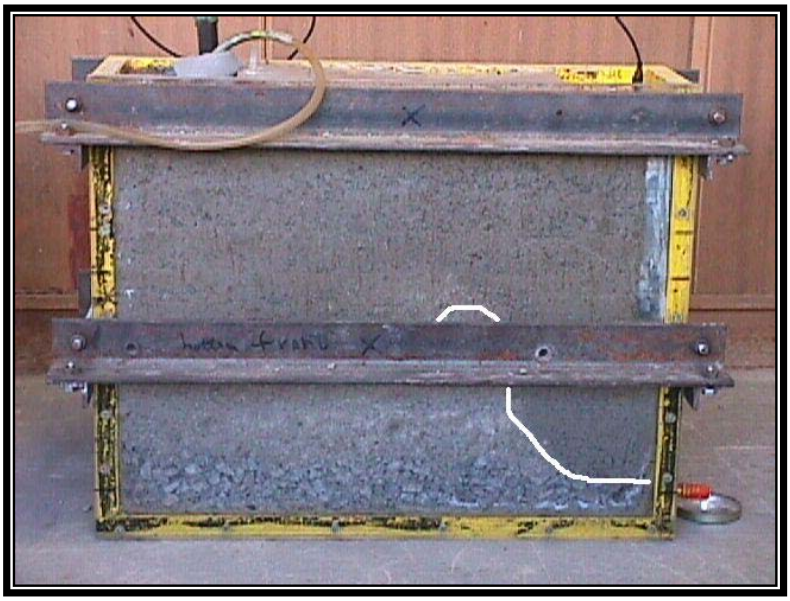


Figure 6.2c Wetting front for 200 mA test (Day 5, 6, 7)

Day 8



Day 9



Day 10

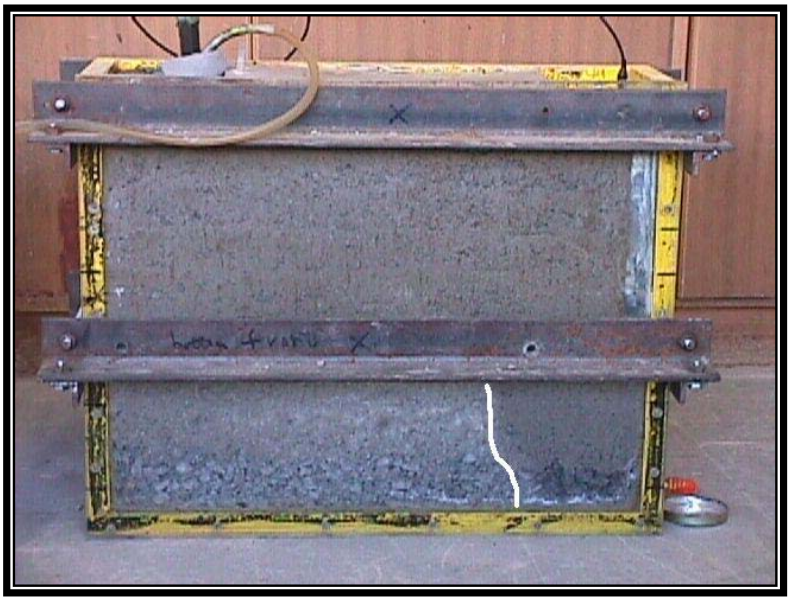
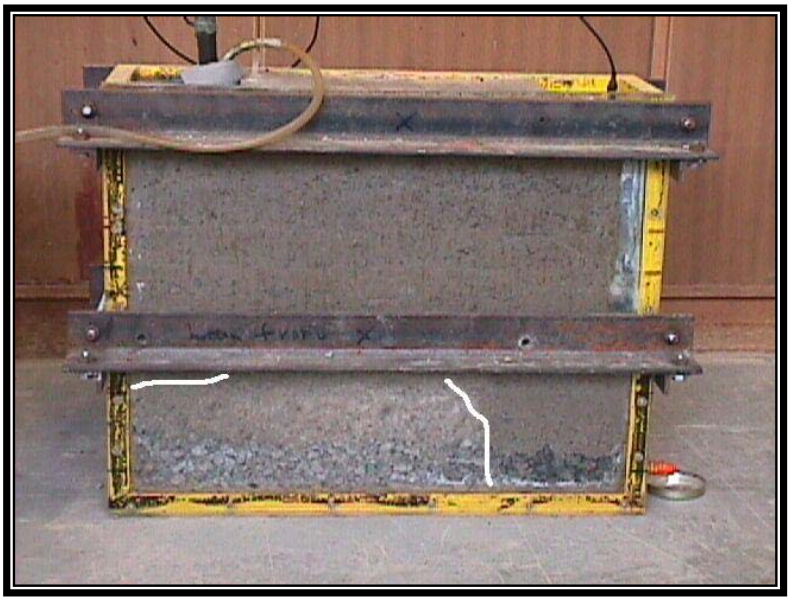
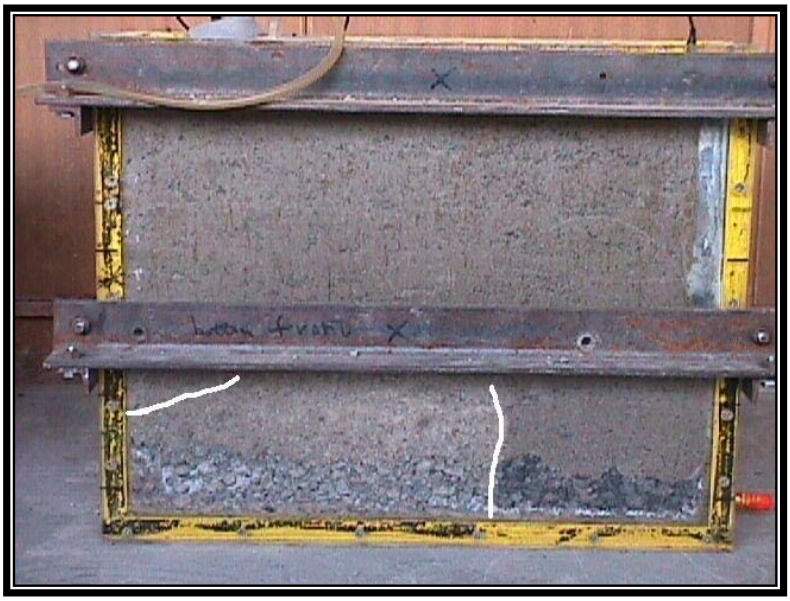


Figure 6.2d Wetting front for 200 mA test (Day 8, 9, 10)

Day 11



Day 12



Day 14

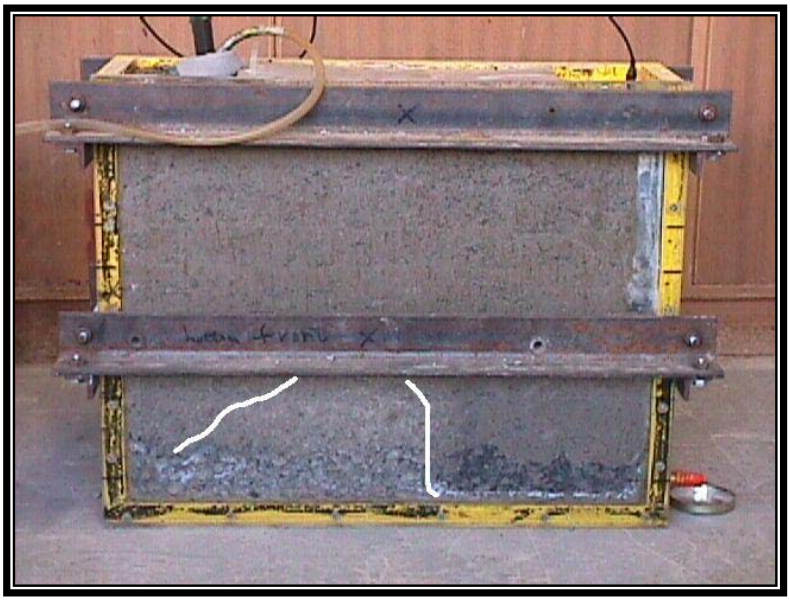


Figure 6.2e Wetting front for 200 mA test (Day 11, 12, 14)

Day 15

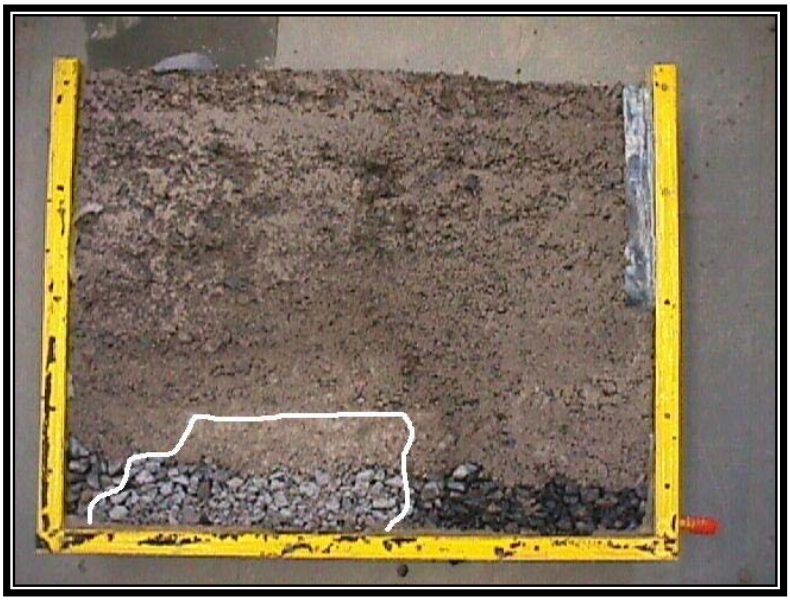


Figure 6.2f Wetting front for 200 mA test (Day 15)

Looking at Figure 6.2b it can be seen that the water builds up next to and below the cathode. This wetting front is formed from the initial moisture content in the test soil. If the water which accumulates in the cathode reservoir is not removed quickly enough, it will move downwards by force of gravity as can be seen in Figure 6.2f.

6.2.3 Soil moisture blocks

The gypsum moisture water blocks were first calibrated before they were used in any of the tests. The calibration of the soil moisture blocks can be seen in Figure 6.3.

It can be seen that the range in readings from about 3% moisture to 15% moisture is between 80 and 100. This range is too small for accurate measurements of moisture infiltration. The soil moisture blocks were only used in the first few tests, as the readings were not an effective manner of measuring the infiltration of moisture. It was then decided to perform identical tests at different time spans at 3, 5, 7, 10 and 15 days. The removal of moisture content soil samples, taken at the 9 areas described in Figure 4.9, were then used to determine the moisture infiltration.

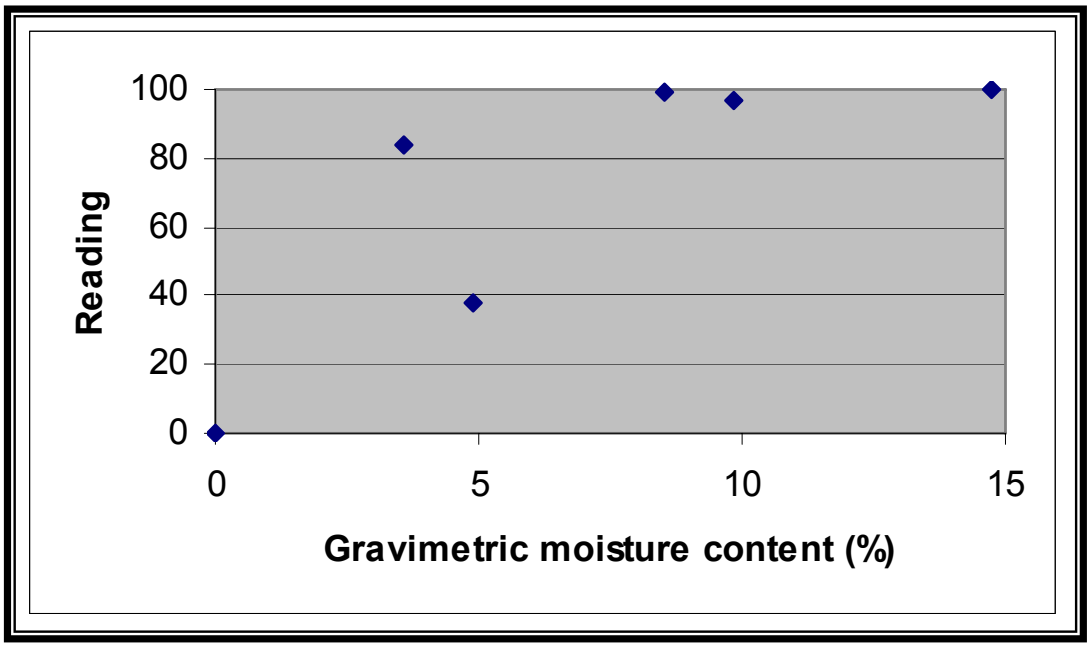


Figure 6.3 Calibration of soil moisture blocks

6.3 EFFECT OF THE ELECTRIC CURRENT

The final water contents at the 9 areas were plotted against the current intensities of 0 mA, 70 mA, 150 mA and 200 mA, for the 8% initial moisture content and 3 days tests. This is displayed graphically in Figure 6.4.

Looking at the figure it can be concluded that moisture infiltrates faster with more intense currents, and without an electric current the infiltrations tends to decrease with time. The areas 1, 4, 7 have a higher reading than the other areas, because these areas are very close to the anode where the water entered the soil. These three areas tend to get wet, even when no electric current is applied. The area under the road, area 2, shows a constant increase of moisture content to above 13%. Areas 5 and 8 show a small increase in moisture content. Areas 3, 6, 9 remain similar to the initial moisture content, indicating that the water has not yet infiltrated these areas. It can be seen that electro-osmosis is not effective at small currents and short time periods.

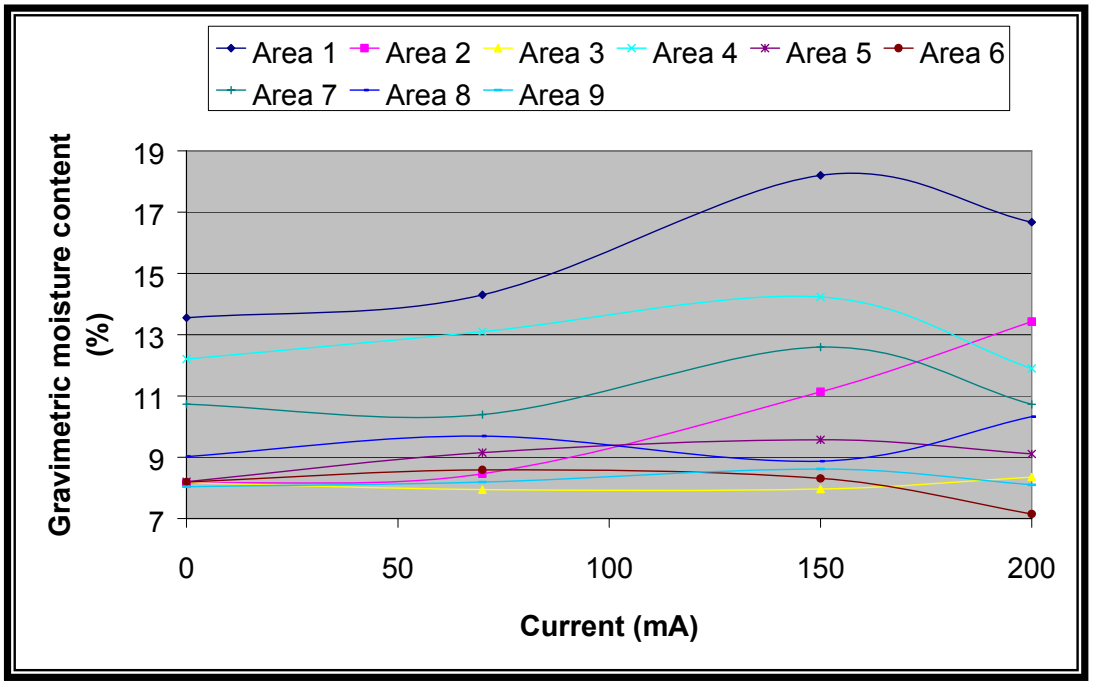


Figure 6.4 Effects of electric current on infiltration, 3 day test

Analysing the soil moisture block readings, in Appendix C, it can be seen that the blocks at the 1, 4, 7 areas tended to rise quicker to 100 at a higher current, than at lower currents. This agrees with the above mentioned graph. It was therefore decided to perform all the following tests at 200 mA, the maximum allowable current intensity from the power source. Tests were also performed at 0 mA to give us a comparison. The water in the cathode reservoir also increased as the current was increased. It can therefore be concluded that an increase in current intensity in the two-dimensional tests, increases the rate of infiltration. This was also the case in the one-dimensional tests.

6.4 MOISTURE INFILTRATION

Only the graphs from tests; 30% fines, 8% moisture content, 0 mA; 30% fines, 6% moisture content, 200 mA; 20% fines, 8% moisture content, 200 mA are shown in Figures 6.5, 6.7 and 6.8 respectively to aid in the discussion. The individual graphs are presented in Appendix C.

6.4.1 The 30% fines, 8% moisture content, 0 mA tests

The results of these tests are displayed graphically in Figure 6.5. Looking at the figure, the tests indicate that areas 1, 4, 7 have a higher reading than the other areas, because these areas are very close to the anode where the water is introduced into the soil. These three areas tend to get wet, even when no electric current is applied.

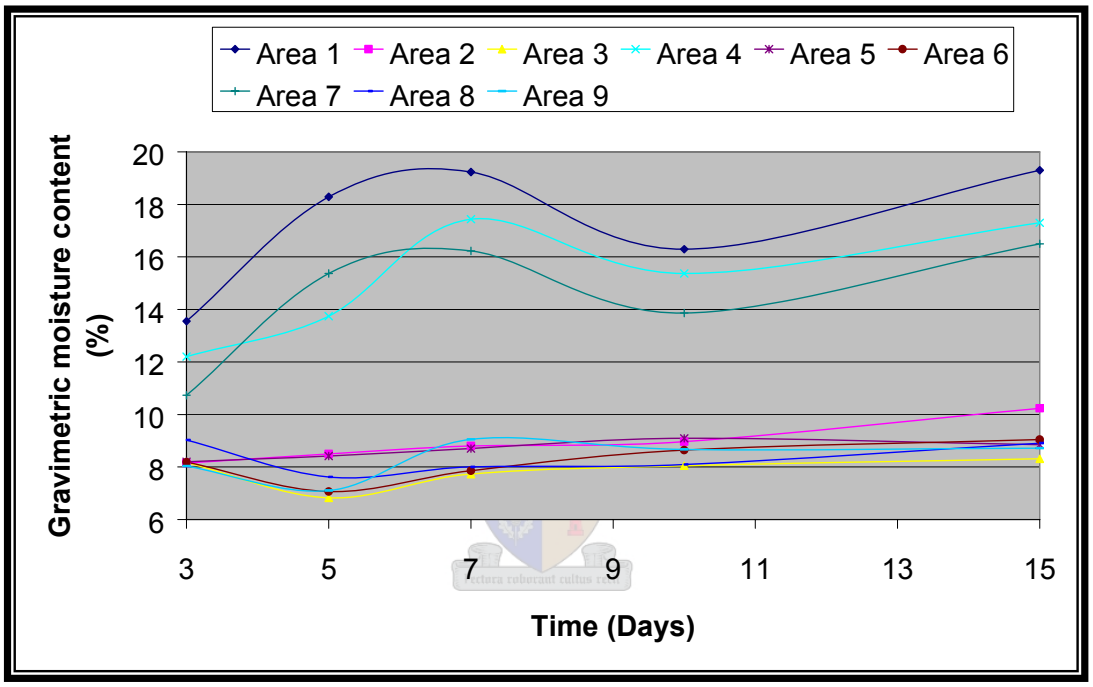


Figure 6.5 Moisture infiltration of 30% fines, 8% moisture content, 0 mA

There is little horizontal infiltration, but a gradual increase in moisture content occurs with time. The moisture content of the other areas remain similar to the initial moisture content, indicating that the water has not yet infiltrated these areas. Therefore, if no current is applied, areas 2, 3, 5, 6, 8, 9 do not get infiltrated. The soil moisture block readings can be seen in Figure 6.6.

The soil moisture readings showed that areas 1, 4, 7 rose to a 100 after 2 hours. Area 2 changed dramatically between 48 to 59 hours. Generally, the rest

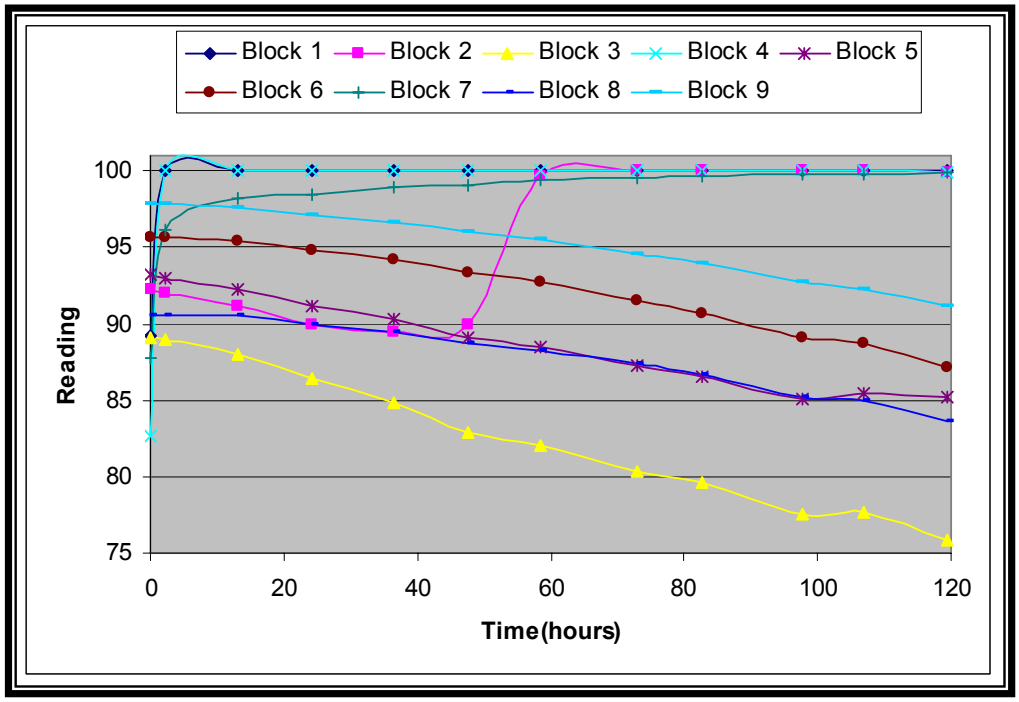


Figure 6.6 Soil moisture block readings of 30% fines, 8% moisture content, 0 mA

of the areas showed a decrease in readings as time went on. This could be due to the fans drying out the ground. The laboratory fans were left on during testing to expel the chloride gas produced, from the laboratory. It could also be due to the soil moisture blocks being not accurate and suitable for the tests. In general, the soil moisture blocks were not an effective means in determining the moisture content at the different areas.

6.4.2 The 30% fines, 8% moisture content, 200 mA tests

The water contents of the tests from day 3 to day 10 did not differ much from one another. These tests indicated that a minimum of 15 days was required to increase the moisture content at the cathode side, areas 3, 6, 9. Areas 2 and 3 of these tests with 200 mA were slightly wetter that the above test with 0 mA. Therefore slight wetting had occurred. The water in the cathode reservoir increased uniformly, from 263.2 grams after 3 days, to 334.5 grams after 5 days, to 725.4 grams after 7 days, to 852.3 grams after 10 days and to 1278.4 grams after 15 days.

6.4.3 The 30% fines, 6% moisture content, 0 mA tests

The tests indicated that areas 1, 4, 7 have a higher moisture content than the other areas, because these areas were very close to the anode. These three areas tended to get wet, even when no electric current is applied. It can be seen that water has infiltrated into areas 2, 5, 8, because there was an increase in moisture content. The moisture content of areas 3, 6, 9 remained similar to the initial moisture content, indicating that the water had not yet infiltrated these areas. Therefore if no current was applied, areas 3, 6, 9 do not get infiltrated.

Area 2 experienced a large increase in moisture content, this could be due to the insufficient compaction of the top layer. Difficulty was experienced in compacting the last layer into the boxes. Capillary action at the 6% moisture content was clearly greater than at the 8% moisture content, as could be expected.

6.4.4 The 30% fines, 6% moisture content, 200 mA tests

The results of these tests are displayed graphically in Figure 6.7. Looking at the figure, the tests indicated that all the areas had an increase in moisture content.

Horizontal infiltration did take place. Soil moisture blocks were used in the 10 day test and not the 7 and 15 day tests. The moisture content was therefore, on average, slightly higher in the 10 day test than in the 15 day test. This was because fine material was compacted around the soil moisture blocks. In other words, more fine material was present in the drying samples, which in turn meant a higher moisture content.

Water was collected in the reservoirs from the 10 and 15 day tests. The water in the reservoir increased uniformly, from 152.3 grams to 327.7 grams, with time. The water in the cathode reservoir increased uniformly, from 0 grams after 7 days, to 152.3 grams after 10 days and to 327.7 grams after 15 days.

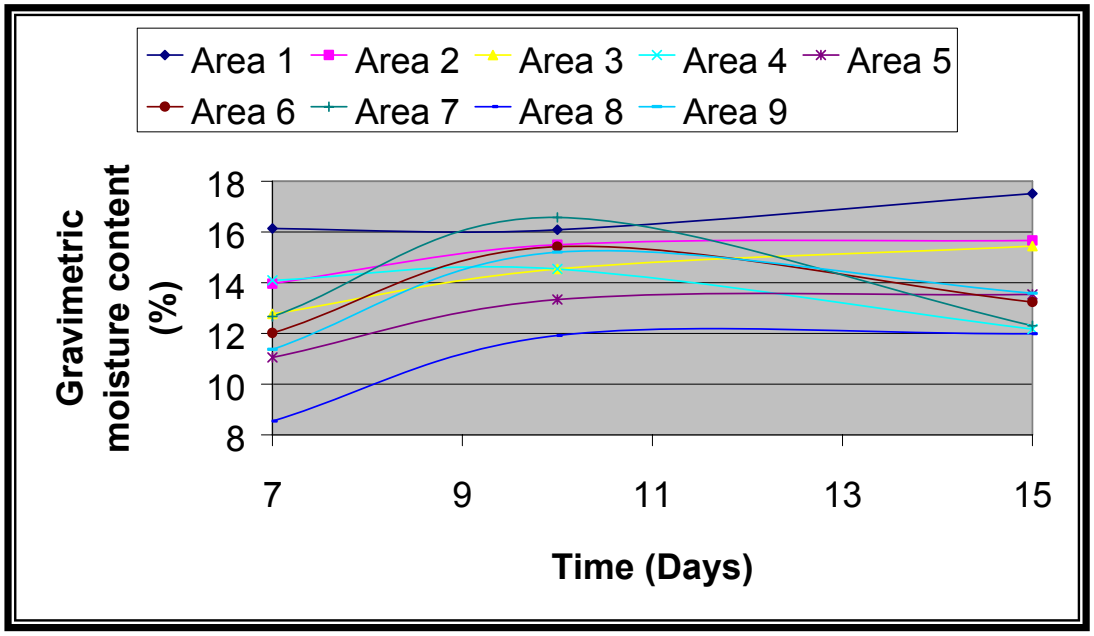


Figure 6.7 Moisture infiltration of 30% fines, 6% moisture content, 200 mA

6.4.5 The 20% fines, 8% moisture content, 0 mA tests

The tests indicated that areas 1, 4, 7 had a slight increase of moisture content. These three areas tended to get wet, even when no electric current was applied. The moisture content of the other areas remained similar to the initial moisture content, indicating that the water had not yet infiltrated these areas. Therefore if no current was applied, areas 2, 3, 5, 6, 8, 9 do not get infiltrated. Horizontal infiltration did not take place.

This could be due to the capillary action, or matric potential, being too small at this moisture content. The 8% initial moisture content was close to the optimum moisture content, therefore it would have very little capillary action. The decrease of fines to 20%, will also serve to reduce matric potential, which is the driving force for infiltration. Some of the moisture content values dropped to below the initial moisture content. The 15 day test also experienced a decrease in moisture content. This was most probably due to the fans drying out the soil.

6.4.6 The 20% fines, 8% moisture content, 200 mA tests

The results of these tests are displayed graphically in Figure 6.8. Looking at the figure, the tests indicated that all the areas had no increase in moisture content. Nearly all the moisture content values decreased to below the initial moisture content. The current seemed to have a drying effect on the soil. The drying effect could be caused by excessive electro-osmosis drawing the moisture out of the sample. Heating was caused by the current due to the high resistance created by the lower fines, 20% fines. It seemed as though electro-osmosis was not effective in 20% fines.

The high voltages experienced, were also caused when the anode compartment had run out of water as in tests number 23 and 24. This occurred, because during the process of electro-osmosis, tiny bubbles were given off from the carbon rod in the anode compartment. These bubbles occasionally entered the tube of the constant level reservoirs and formed an air lock. This, in turn, prevented water from entering the anode compartment. If no solution was present in the anode, the current would start to heat the soil sample.

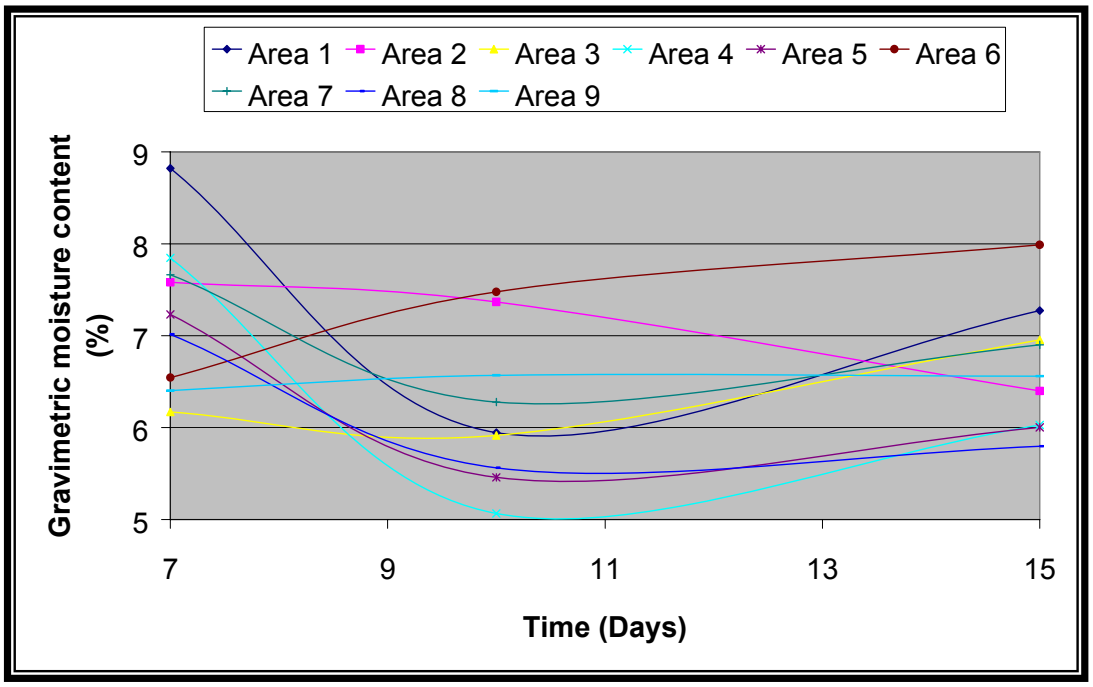


Figure 6.8 Moisture infiltration of 20% fines, 8% moisture content, 200 mA

The water in the cathode reservoir increased from 820.8 grams after 7 days, to 1065.2 grams after 10 days and to 1343.2 grams after 15 days.

6.4.7 The 20% fines, 6% moisture content, 0 mA tests

Most of the water; like in the 30% fines, 6% moisture content, 0 mA test; tended to move downwards by gravity into the 1, 4, 7 areas. There was an increase in moisture content on average by about 3% in the 2, 3, 5 areas. Areas 6, 8, 9 had a slight increase in moisture content. Therefore, a small amount of horizontal infiltration had taken place. This occurred in the 6% initial moisture content, because the drier material encouraged capillary action. Water did not collect in the cathode reservoir.

6.4.8 The 20% fines, 6% moisture content, 200 mA tests

The tests indicated that all the areas had an increase in moisture content. Time did not make a difference and the moisture content increase was rather small, from 6% to 8%. Horizontal infiltration did take place. The increase was not as much as in the 30% fines, 6% moisture content, 200 mA tests. The water in the cathode reservoir increased from 489.0 grams after 7 days and to 1120.2 grams after 10 days. The 15 day test had only 303.9 grams of effluent in the cathode reservoir. The anode compartment ran out of water and test number 30 could therefore be considered a failure. The high voltages experienced in the 15 day test, were also the result of the anode compartment being out of water for part of the test.

A solution to this problem would be to build a bigger model with a bigger anode compartment. The bubbles would then go into the air and not into the constant level reservoir tube, provided that the tube is in the one side of the anode and the carbon rod on the other side.

6.4.9 Conclusion

The 20% fines, 8% moisture content, 200 mA tests had a drying effect on the soil. This drying effect was also experienced, by De Wet (1995), on one-dimensional tests done at moisture contents of 9.6% and above. A zone of moisture decrease was experienced immediately ahead of the wetting front. A higher initial moisture content had led to a lower final moisture content. At lower contents this drying zone was not experienced, De Wet (1995). The drying action was probably caused in part by heat driven moisture transport and changes in the soil chemistry.

The 30% fines, 8% moisture content, 200 mA tests showed a slight increase in moisture content and in the 20% fines, 6% moisture content, 200 mA tests the increase was higher. The 30% fines, 6% moisture content, 200 mA tests showed the highest increase. Each area, from 1 to 9, has a graph drawn showing increase in moisture content at a specific area for a specific mixture. The individual graphs are presented in Appendix C. The graph of area 2 is shown in Figure 6.9, because it is the area under the road, to aid in the discussion.

Looking at the figure it can be concluded that electro-osmosis seemed to be more effective to accelerate moisture infiltration into 30% fines, rather than 20% fines. Electro-osmosis was more effective at lower moisture contents, namely the 6% moisture content. Therefore, electro-osmosis was most effective in the 30% fines, 6% moisture content, 200 mA tests and least effective in the 20% fines, 8% moisture content, 200 mA tests, as can be seen in the Figure 6.9.

Electro-osmosis was not effective at small current intensities and short time spans. The higher the current intensity, the better the infiltration of moisture into the sample. There was a constant inflow of water into the cathode reservoir. More water is collected in the cathode reservoir, on average, in the tests with lower fines percentages and higher initial moisture contents. This can be explained by the ratio of water to fines being at its highest at this combination. At low fines water was merely driven through, or out of the soil, rather than

increasing moisture anywhere. This also served as a point that electro-osmosis took place at a lower fines percentage. The total amount of fluid that arrived at the cathode ends of samples increased in proportion with the electric current intensity.

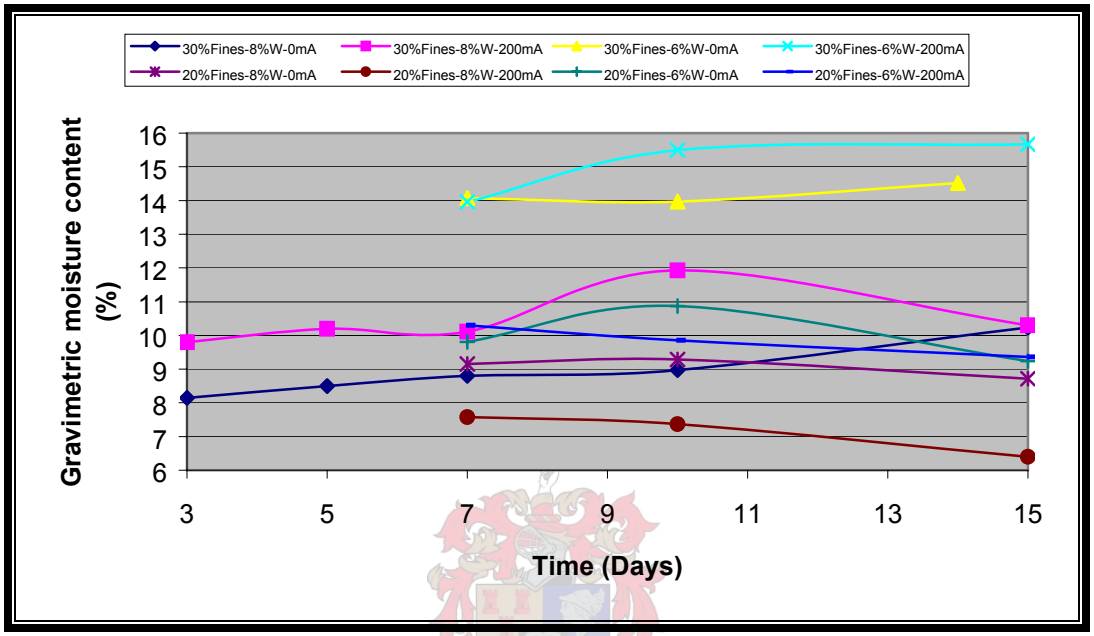


Figure 6.9 Moisture infiltration at area 2

6.5 ENERGY CONSUMPTION

Energy demands were greatly influenced by both moisture content and current intensity. The values of the total energy consumption for the individual tests are presented in Appendix C and in Table 6.2. It can be concluded from these values that energy consumption increased with an increase in current intensity, and an increase in time. The least total energy consumption occurred in the 30% fines, 8% initial moisture content test.

The 20% fines, 6% initial moisture content, 200 mA, 15 day test had a total energy consumption of 6 601.552 Wh. This was abnormally high, because of high voltages experienced when the anode compartment had run out of water.

This 15 day test can therefore be considered a failure as discussed in Section 6.4.8.

Table 6.2 Energy consumption for individual tests

Test no.	Fines (%)	Gravimetric moisture content (%)	Aimed moisture content (%)	Electric current (mA)	Treatment period (days)	Energy consumption (Wh)	Reservoir (g)	Unit rate (Wh/g)
6	30	8.95	8.00	70	3	101.061	0.0	-
7	30	8.95	8.00	150	3	381.611	67.2	5.7
8	30	8.95	8.00	200	3	669.320	263.2	2.5
9	30	8.03	8.00	200	5	878.891	334.5	2.6
10	30	8.04	8.00	200	7	1520.982	725.4	2.1
11	30	7.73	8.00	200	10	1896.012	852.3	2.2
12	30	8.83	8.00	200	15	3360.669	1278.4	2.6
16	30	5.46	6.00	200	7	2207.151	0.0	-
17	30	6.53	6.00	200	10	2402.672	152.3	15.8
18	30	5.46	6.00	200	15	4614.446	327.7	14.1
22	20	7.32	8.00	200	7	1476.485	820.8	1.8
23	20	8.46	8.00	200	10	3289.620	1065.2	3.1
24	20	8.13	8.00	200	15	5490.132	1343.2	4.1
28	20	6.31	6.00	200	7	1784.311	489.0	3.6
29	20	5.88	6.00	200	10	2071.046	1120.2	1.8
30	20	5.52	6.00	200	15	6601.552	303.9	21.7

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The 30% fines, 8% initial moisture content, 200 mA tests have a constant unit rate of about 2.5 Wh/g. The 30% fines, 6% initial moisture content, 200 mA tests have a constant unit rate of about 15 Wh/g. The 20% fines, 8% initial moisture content, 200 mA tests have a constant unit rate of about 3 Wh/g.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 INTRODUCTION

The objectives of the one-dimensional tests were stated in Chapter 5 as:

1. To determine the infiltration velocity of moisture into samples with various fines contents, electric currents and initial moisture contents in unsaturated compacted soil.
2. To determine the effects of different intensity currents applied to the sample at different fines contents.
3. To perform one-dimensional tests, to determine how much fines is required to allow for the process of electro-osmosis to occur in G5 material.

The objectives of the two-dimensional tests were stated in Chapter 6 as:

1. To perform two-dimensional tests and to develop a two-dimensional experimental apparatus which permits an investigation into the electro-osmotic acceleration of infiltration into the subgrade of pavements.
2. To evaluate the viability of the electro-osmotic acceleration of infiltration into the subgrade of pavements.

In Chapter 5 and 6 the experimental results were described. In this chapter the results are discussed and the necessary conclusions drawn. Recommendations, based on the data collected during the test period, are made for future research and development.

7.2 CONCLUSIONS OF THE ONE-DIMENSIONAL TESTS

From the experimental results of the research performed, the following conclusions were drawn:

1. The natural infiltration of moisture decreased with increased fines content. The decrease of fines to 20%, will also serve to reduce matric potential, which was the driving force for infiltration.

2. Without the presence of an electric current the infiltrations tended to cease. The infiltration process can be accelerated with the application of an electric current.

3. An electric current caused the moisture to infiltrate into the material at a constant velocity.

4. An increase in current intensity increased the rate of infiltration.

5. The amount of fines present in the soil has a significant effect on the electro-osmotic capabilities of the material.

6. At low fines content, less than 20% fines, electro-osmosis did not work. Below 20% fines the water no longer infiltrated, but it merely flowed through the sample bringing Darcy's Law into effect. The water no longer infiltrated into the soil sample, it simply flowed through the large voids. Even the electric current was affected, as it no longer travelled through the clay fines to initiate ion movement. The voids were filled with water. At 30% fines, the application of electro-osmosis seemed to have a telling effect on the velocity of moisture infiltration. Electro-osmosis increased the velocity of moisture infiltration drastically.

7. Capillary action at the 6% moisture content was clearly greater than at the 8% moisture content, as could be expected. This occurs because the 8% initial moisture content was closer to the optimum moisture content.

It can be concluded that electro-osmosis can only be effective when a sufficient amout of fines is present in the soil. This could be attributed to the fact that in order to be effective, electro-osmosis needs to induce the movement of ions within the soil. The more fines there are, the more ions are present. At low fines contents there may also be discontinuity in the clay, preventing electro-osmosis, because fines tend to concentrate at the contacts of the larger particles. This provided a good basis to perform two-dimensional tests. Two-dimensional tests should therefore be performed at 20% fines and above.

7.3 CONCLUSIONS OF THE TWO-DIMENSIONAL TESTS

From the experimental results of the research performed, the following conclusions were drawn:

1. Without the presence of an electric current the infiltrations tended to move downwards due to gravity. This would lead to the outer edges of the road being more saturated with water than the middle part, when water is applied to the shoulder areas.

2. Horizontal infiltration into a two-dimensional soil model may be improved and the rate of the infiltration increased by electro-osmosis.

3. An increase in current intensity increases the rate of infiltration.

4. With an adequate amount of fines added to the cruched hornfels, the infiltration process can be accelerated with the application of an electric current. Without an electrical current the infiltration tends to stagnate.

5. Electro-osmosis was most effective to accelerate horizontal infiltration in the 30% fines, 6% moisture content, 200 mA mixtures and, least effective in the 20% fines, 8% moisture content, 200 mA mixtures.

6. The total amount of fluid that arrived at the cathode ends of samples increased in proportion to the electric current intensity. On average, more water is collected in the cathode reservoir in the tests with lower fines percentages and higher initial moisture contents. At low fines, water was merely driven through, or out of the soil, rather than increasing moisture anywhere.

7. Energy consumption increased with an increase in current intensity, and an increase in time.

8. It was concluded that the soil moisture blocks were not an effective manner of measuring the infiltration of moisture. The soil moisture blocks were only used in the first few tests, because the operative range of the soil moisture blocks was too small.

It can be concluded that the electro-osmotic acceleration of infiltration into the subgrade of pavements would be possible, provided that the correct percentage of fines is present and the in situ moisture content is relatively low.

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7.4 RECOMMENDATIONS FOR FUTURE RESEARCH AND DEVELOPMENT

It can be expected that further development would have to be done before the electro-osmotic acceleration of infiltration into the subgrade of pavements could be put into practical use.

Topics and aspects of processes that require further attention:

1. Further study should first be undertaken in the form of a larger road model, to prevent an air lock from forming in the tube of the constant level reservoir, as discussed in Section 6.4.8. Utilising this data, it would also be possible to determine a more accurate correlation between speed of infiltration, fines content and electric current applied.

2. Larger current intensities should be used in future, to speed up the infiltration process. This was not possible with the present power sources.

3. It would also be very beneficial if a method of application could be devised, where electro-osmosis could be used out in the field to facilitate rapid infiltration of moisture into a road subgrade. This should be attempted to point out practical problems that may arise from such an operation and to establish the degree of success of the process in less controlled conditions.

4. The engineering properties of the material, after it has been subjected to electro-osmosis, should be determined to establish any side effects which may be detrimental to the behaviour of a soil structure. Material changing from plastic to brittle, decreases in compressibility and shear strength and other modifications may negatively influence the structure.

5. The problem about the cause of the drying phenomenon ahead of the wetting front has to be solved. Changes in the system chemistry, such as pH, could cause this problem. Heat driven moisture movement may contribute to the drying as well.

6. The coupled-flow infiltration phenomenon should be treated mathematically more correctly by using a differential equation. A finite difference technique should be employed to obtain the theoretical solution.

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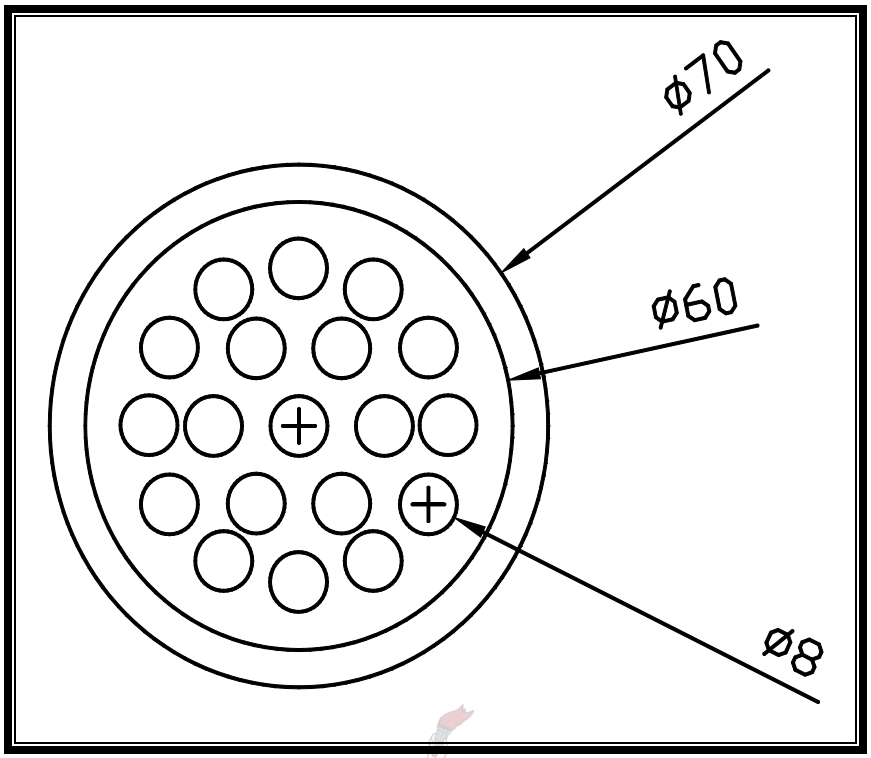
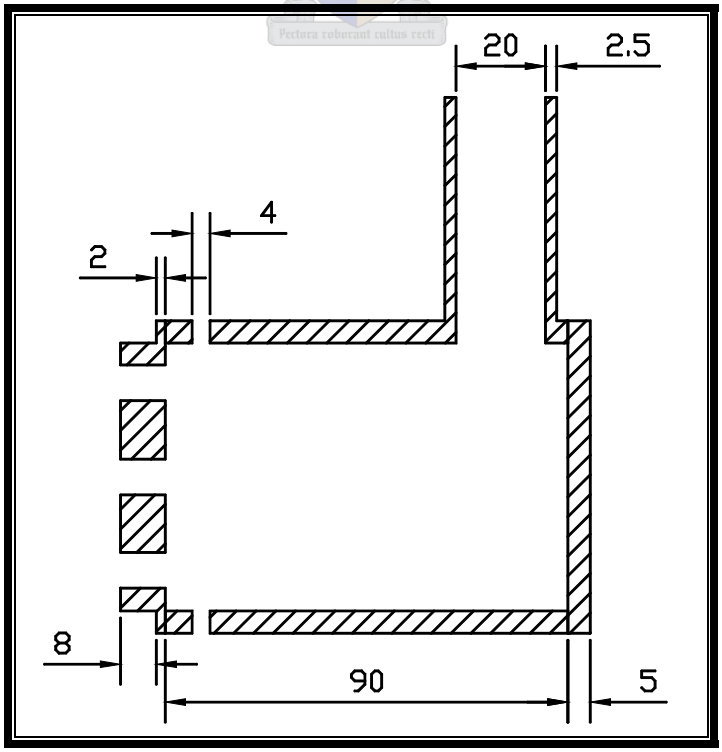
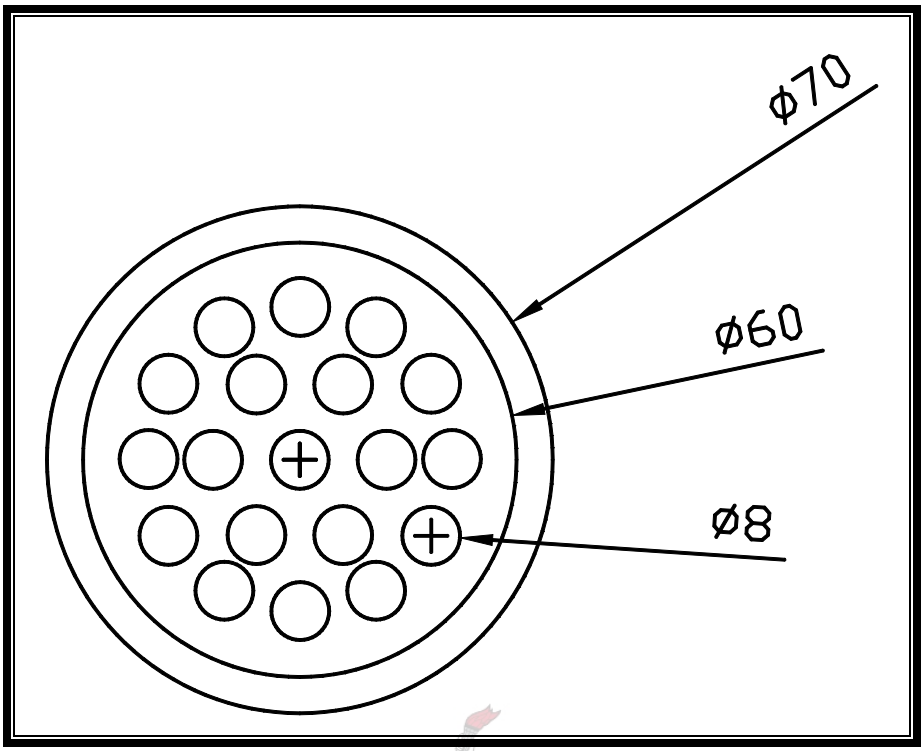
Appendix A TECHNICAL DRAWINGS



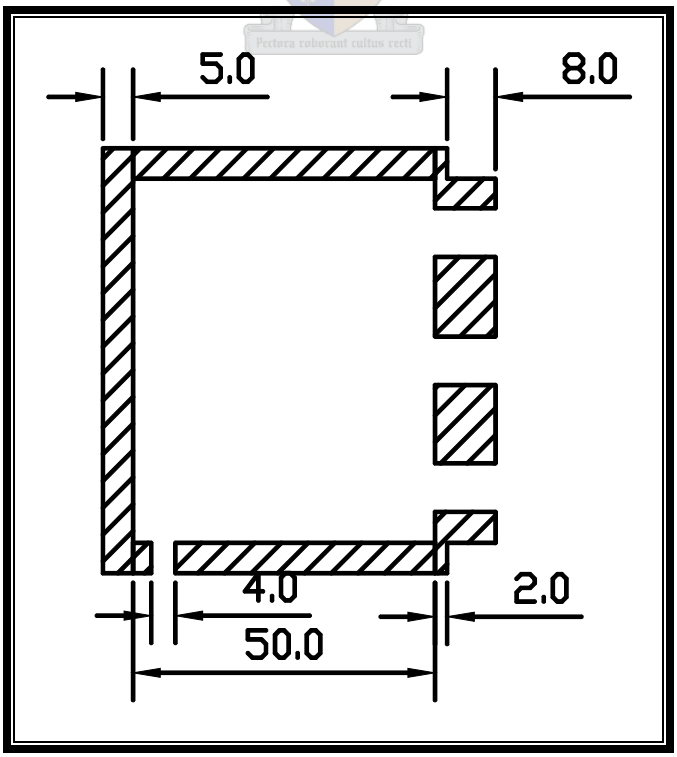
Anode compartment, cross section (One-dimensional test)



Anode compartment, long section (One-dimensional test)



Cathode compartment, cross section (One-dimensional test)



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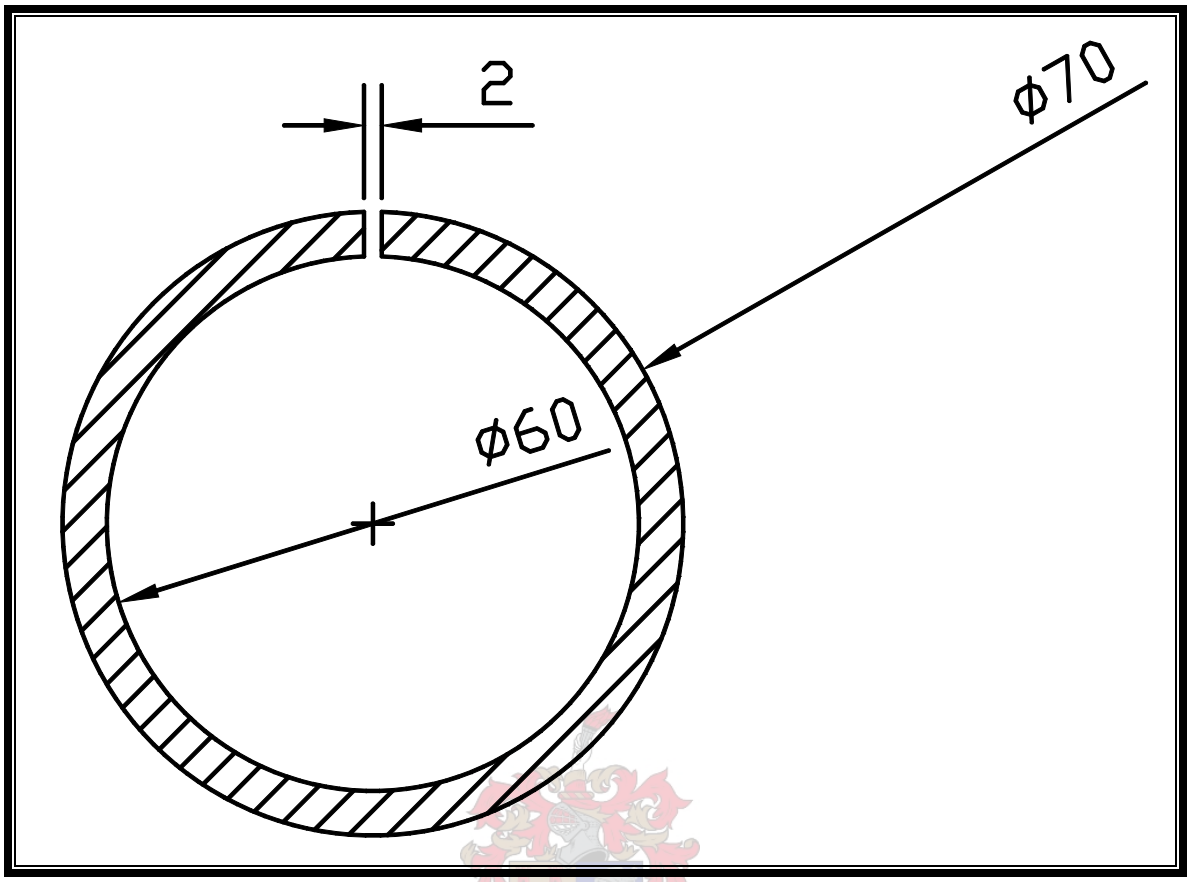

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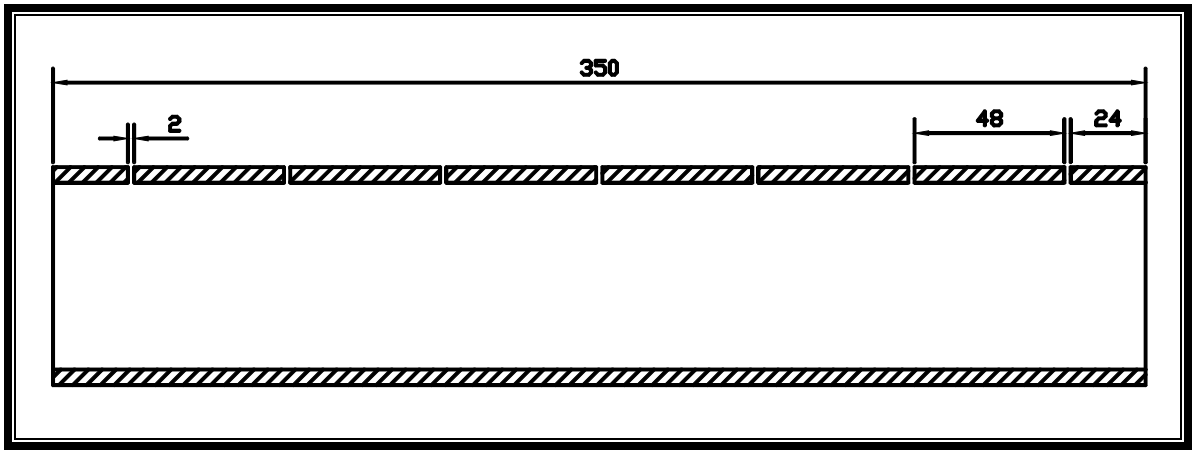

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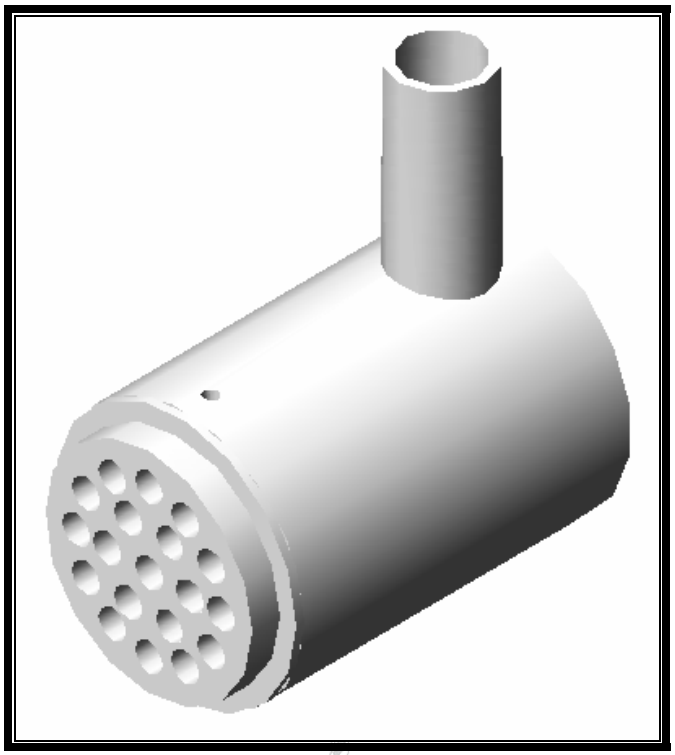
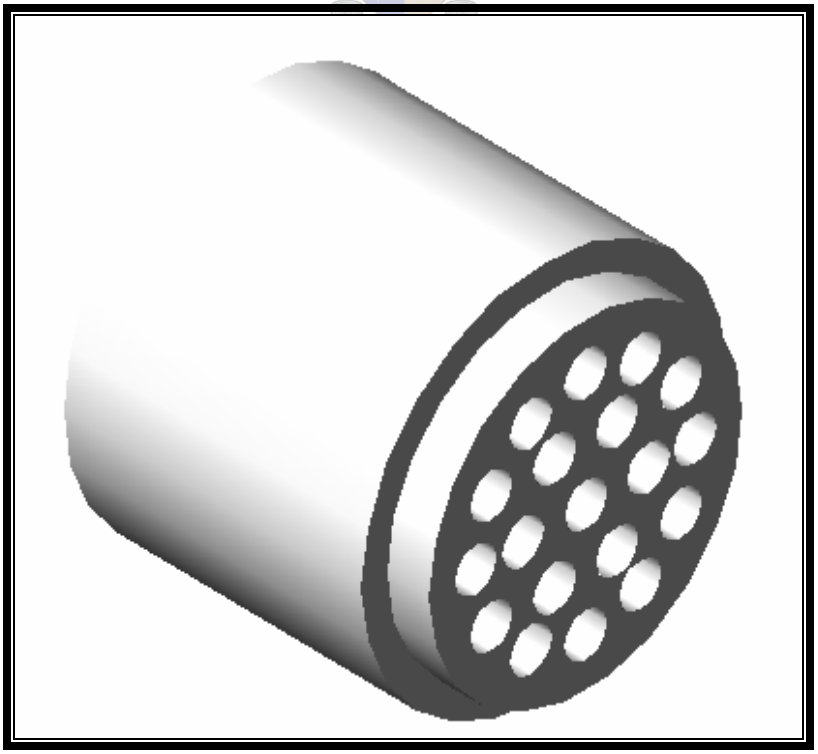


3-Dimensional anode compartment (One-dimensional test)



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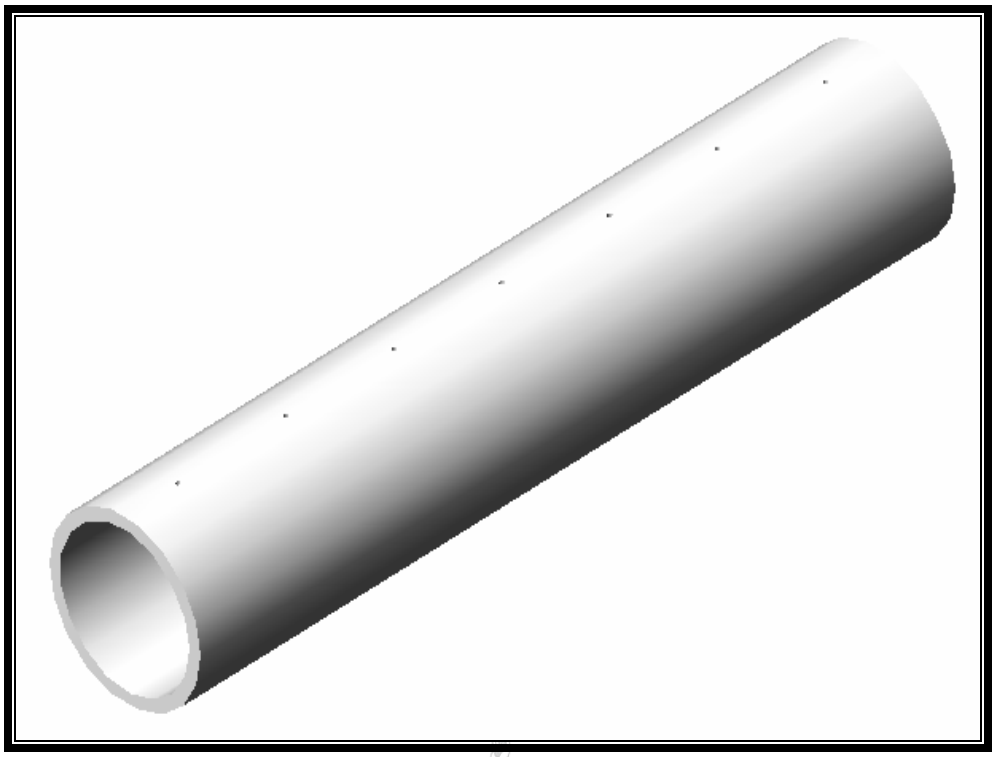

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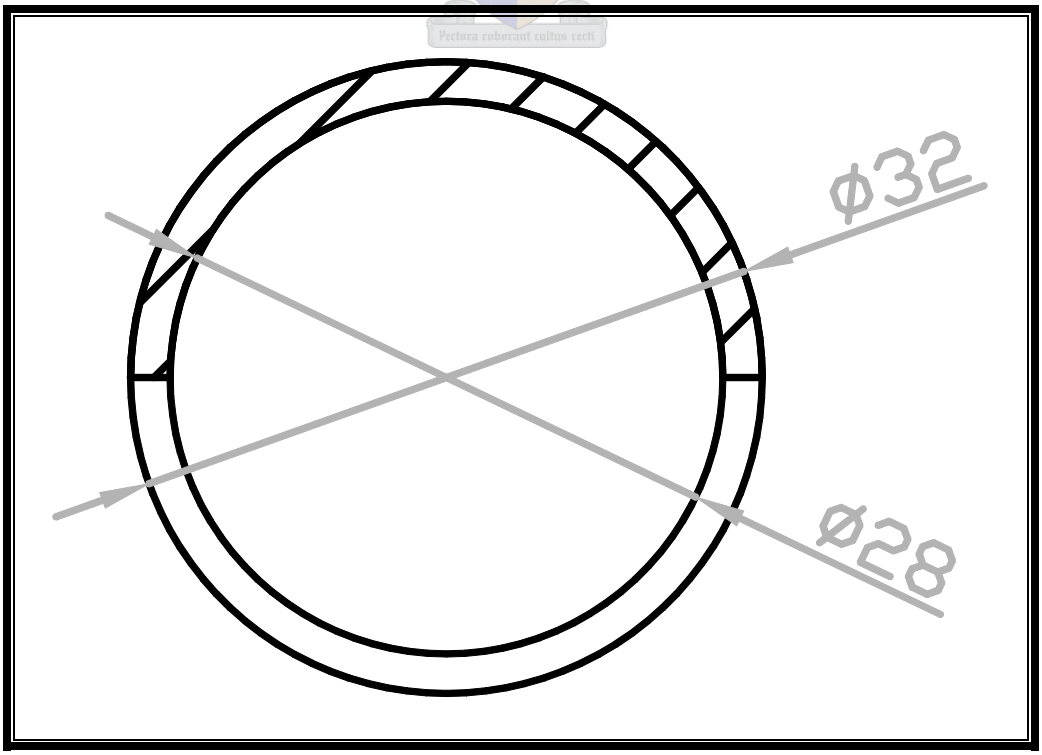

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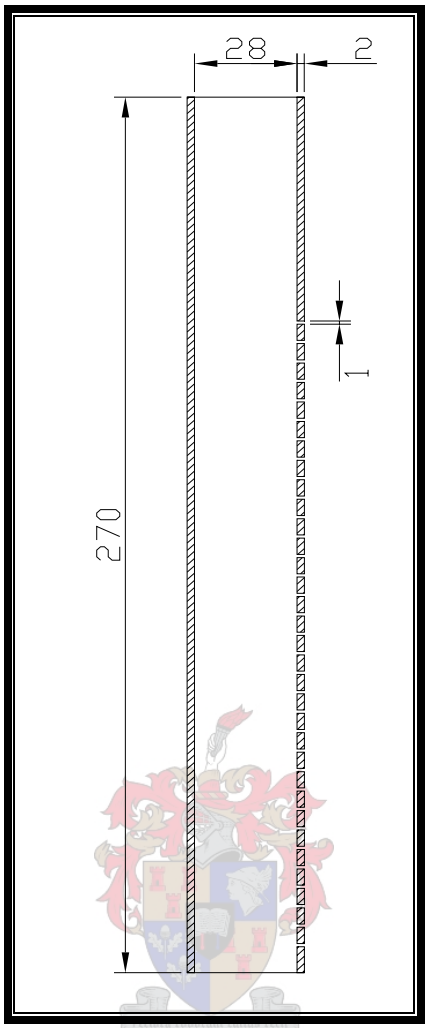
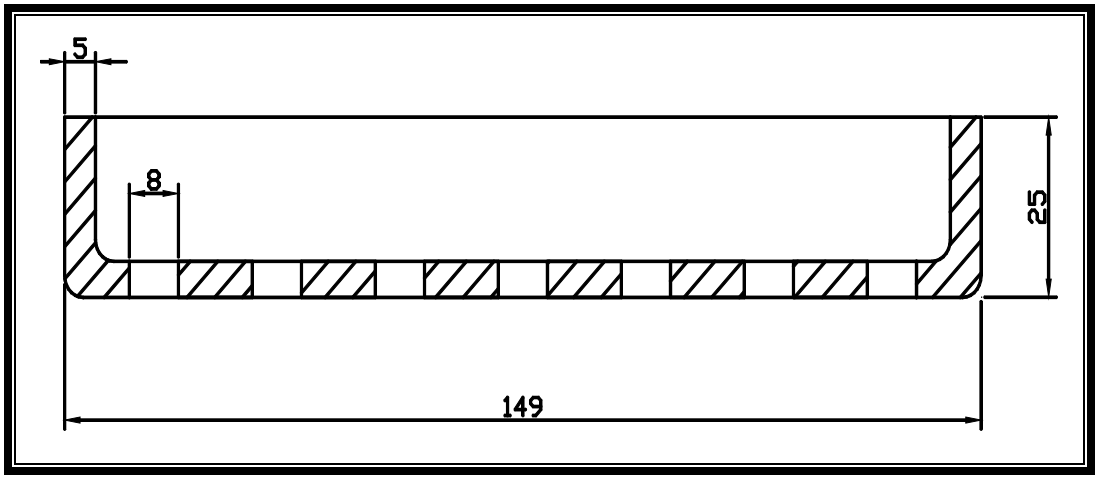


Anode compartment, long section (Two-dimensional test)



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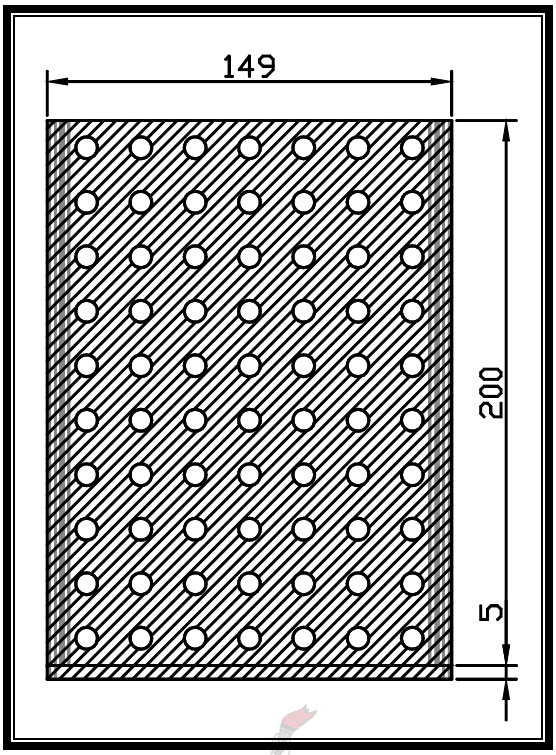
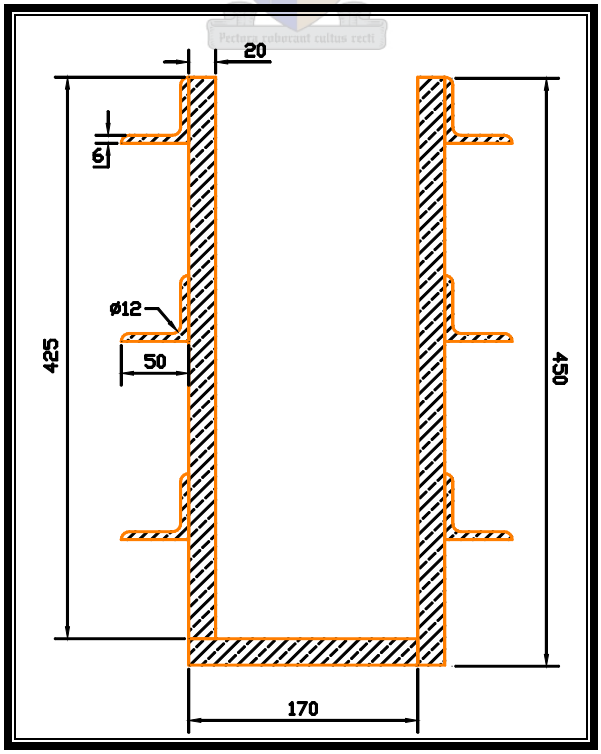
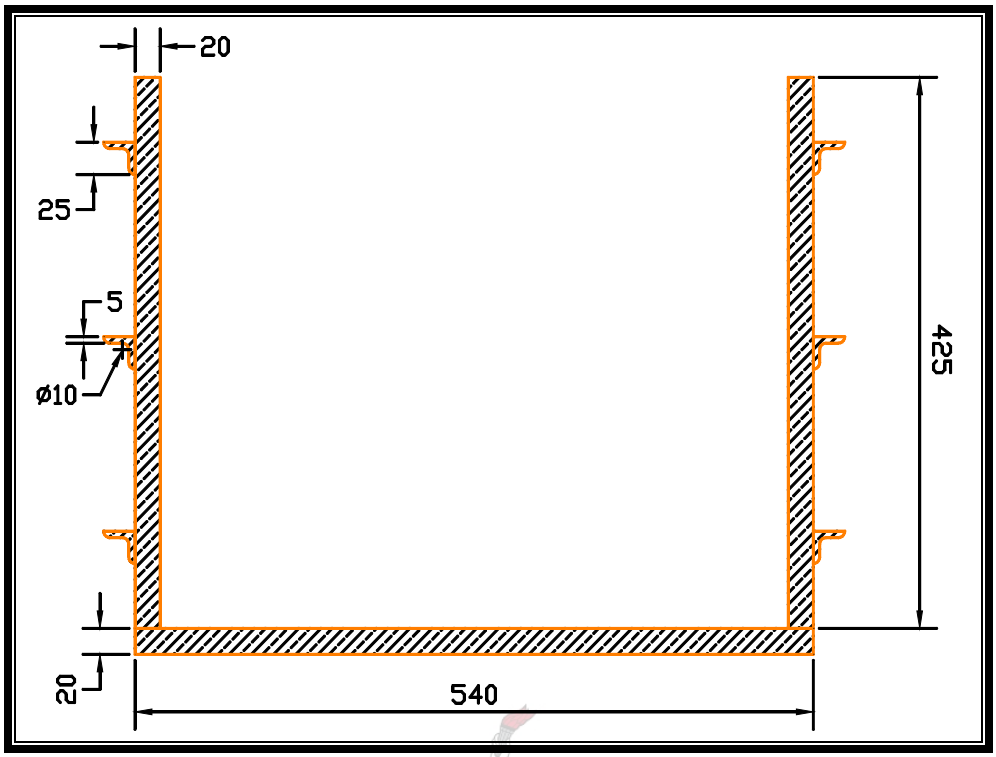


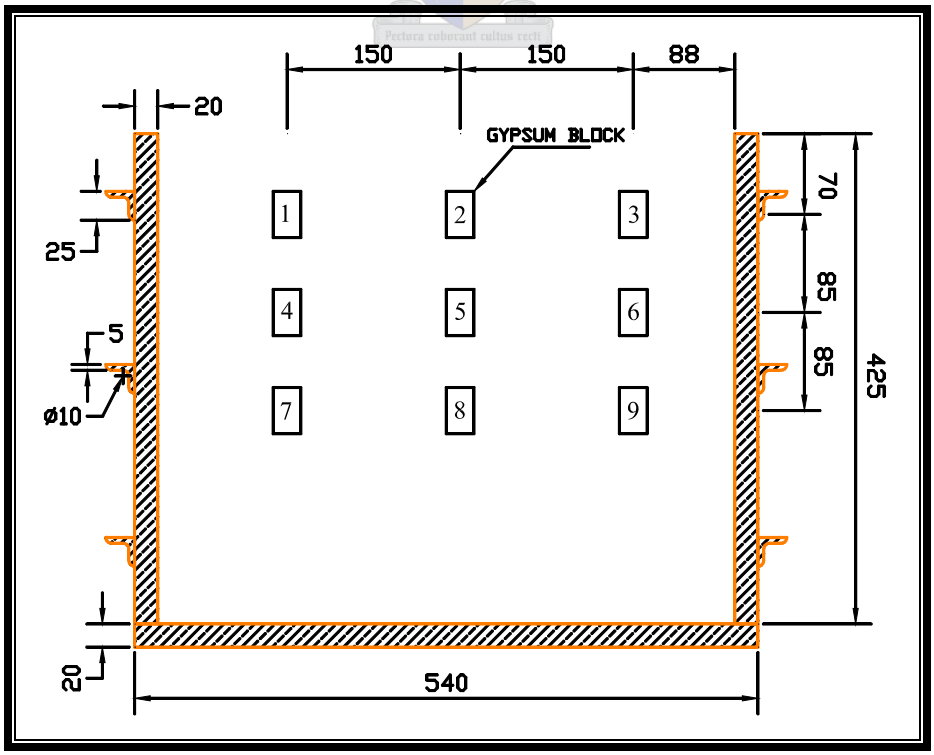
Cathode compartment, long section (Two-dimensional test)



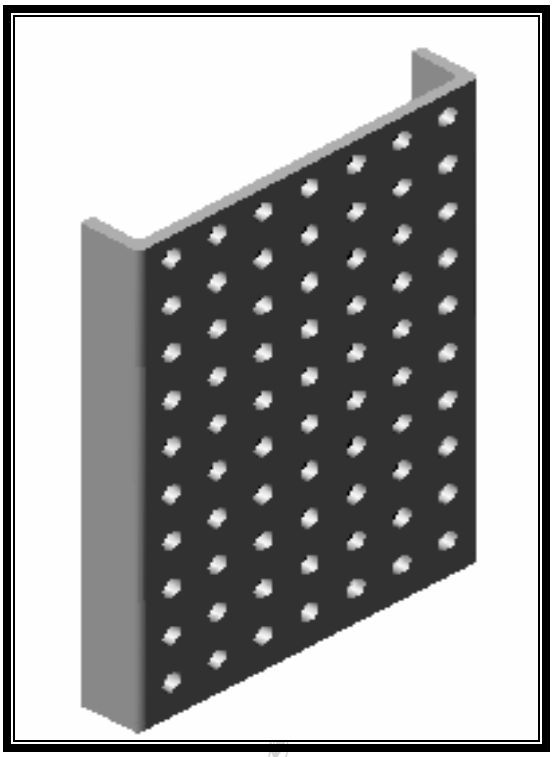
Wooden box with steel clamps, cross section (Two-dimensional test)



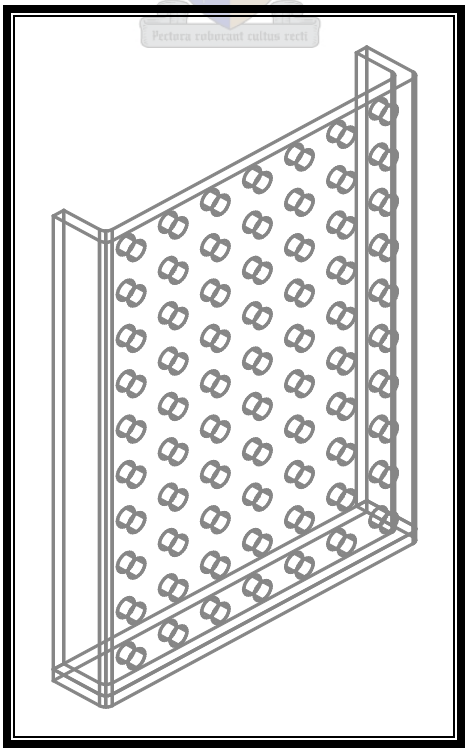
Wooden box with steel clamps, long section (Two-dimensional test)



Wooden box showing soil moisture blocks, long section (Two-dimensional test)



3-Dimensional cathode compartment (Two-dimensional test)



3-Dimensional cathode compartment (Two-dimensional test)

Appendix B RESULTS FROM ONE-DIMENSIONAL TESTS

Pectora roborant cultus recti

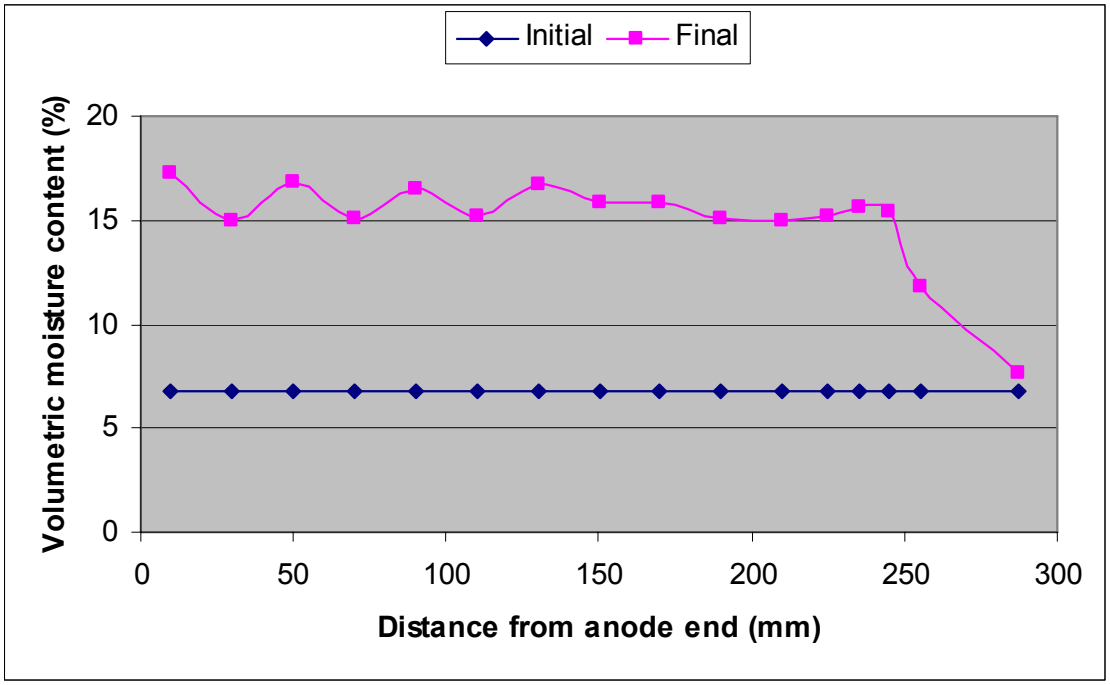
Test no. 1	
Initial moisture:	3.05% by weight
	6.80% by volume

Electric current:	0 mA
Fines:	0%
Treatment period:	22.1 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	20	10	7.75	17.26	2.8	7.1	4.3
2	20	30	6.70	14.93	3.8	8.3	4.5
3	20	50	7.54	16.79	2.9	7.2	4.3
4	20	70	6.79	15.13	2.6	5.7	3.1
5	20	90	7.43	16.55	3.2	7.9	4.7
6	20	110	6.82	15.20	2.9	6.4	3.5
7	20	130	7.50	16.70	2.9	7.1	4.2
8	20	150	7.11	15.85	3.1	7.2	4.1
9	20	170	7.13	15.87	2.9	6.8	3.9
10	20	190	6.80	15.14	2.8	6.3	3.5
11	20	210	6.74	15.01	2.3	5.0	2.7
12	10	225	6.83	15.20	1.9	4.3	2.4
13	10	235	7.04	15.68	1.7	3.9	2.2
14	10	245	6.91	15.39	2.8	6.4	3.6
15	10	255	5.31	11.83	3.7	6.4	2.7
16	55	287.5	3.43	7.63	14.7	16.5	1.8

Wetting front:	
Time (min)	Length (mm)
59	56
125	74
300	104
572	140
1323	230

Constant (x^2/t):	40
Incremental velocity (mm/min):	0.120



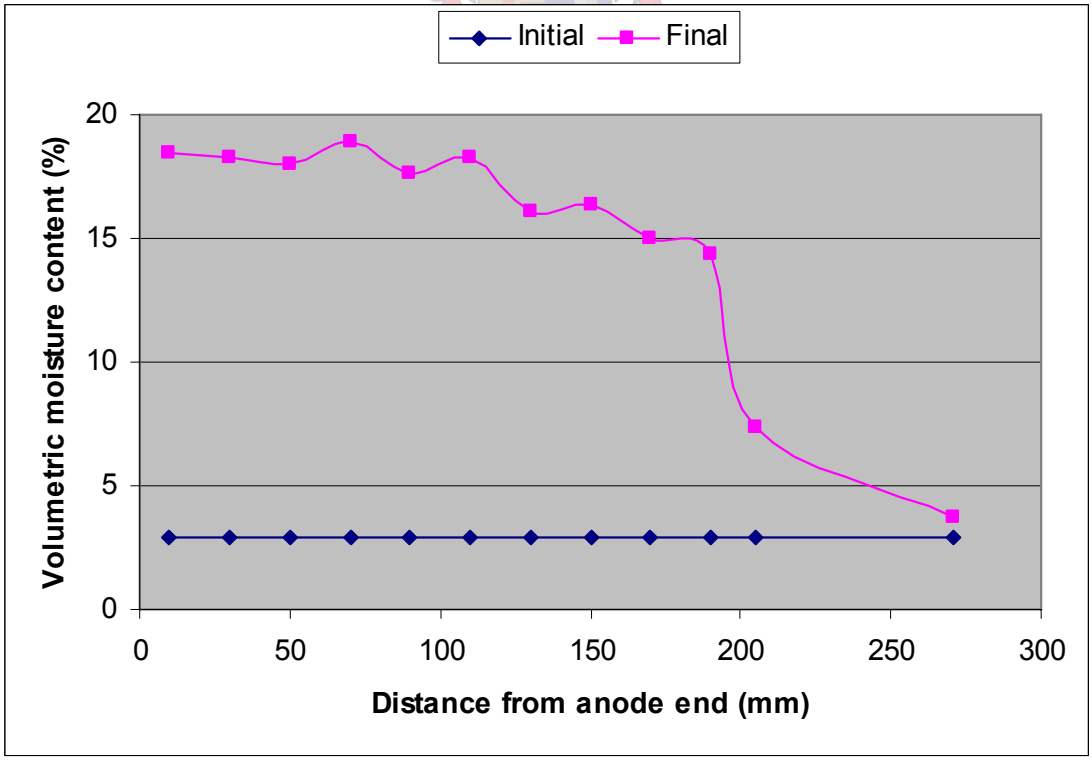
Test no. 2	
Initial moisture:	1.37% by weight
	2.89% by volume

Electric current:	0 mA
Fines:	2%
Treatment period:	10.2 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	20	10	8.74	18.44	1.4	9.0	7.6
2	20	30	8.64	18.24	1.5	9.4	7.9
3	20	50	8.53	18.01	1.9	12.0	10.1
4	20	70	8.94	18.88	1.9	12.2	10.3
5	20	90	8.34	17.60	1.7	10.6	8.9
6	20	110	8.65	18.25	1.5	9.4	7.9
7	20	130	7.64	16.13	1.6	9.2	7.6
8	20	150	7.77	16.39	1.6	9.0	7.4
9	20	170	7.13	15.04	1.8	9.4	7.6
10	20	190	6.79	14.32	1.1	5.3	4.2
11	10	205	3.48	7.36	1.8	4.6	2.8
12	122	271	1.75	3.70	7.8	10.0	2.2

Wetting front:	
Time (min)	Length (mm)
62	61
143	93
610	200

Constant (x^2/t):	65
Incremental velocity (mm/min):	0.229



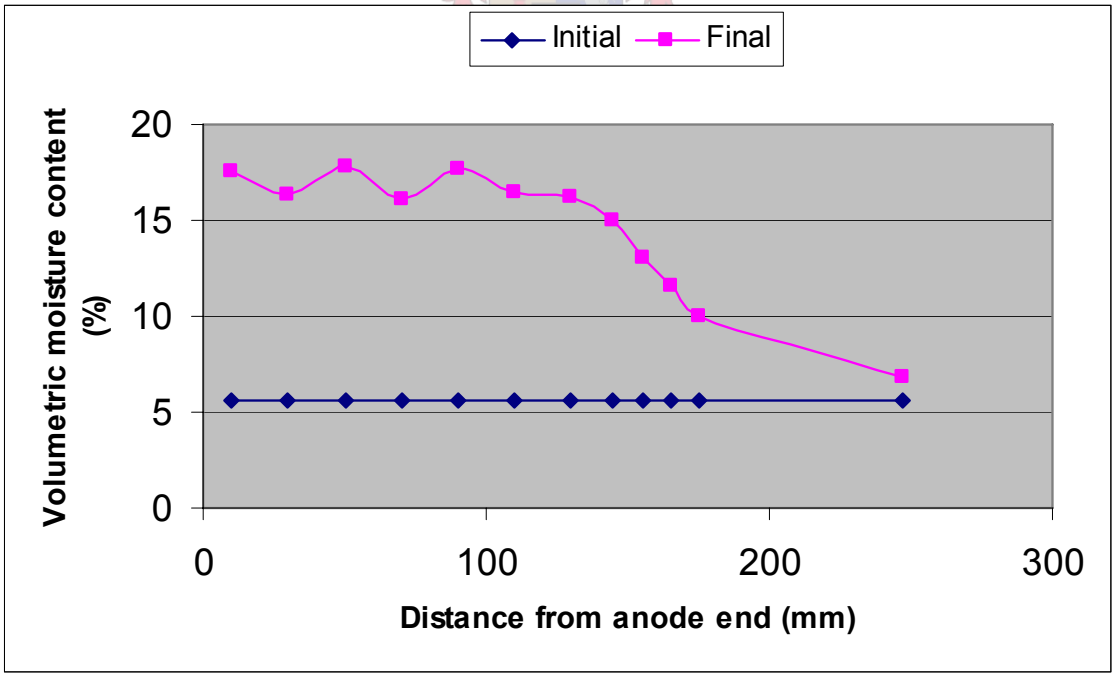
Test no. 3	
Initial moisture:	2.55% by weight
	5.63% by volume

Electric current:	0 mA
Fines:	4%
Treatment period:	4.9 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	20	10	7.95	17.53	2.5	7.9	5.4
2	20	30	7.40	16.33	2.8	8.1	5.3
3	20	50	8.05	17.75	2.1	6.5	4.4
4	20	70	7.32	16.15	2.6	7.5	4.9
5	20	90	8.00	17.63	2.5	7.7	5.2
6	20	110	7.47	16.47	2.4	6.9	4.6
7	20	130	7.36	16.23	2.3	6.6	4.3
8	10	145	6.78	14.96	1.9	5.0	3.1
9	10	155	5.94	13.09	2.0	4.6	2.6
10	10	165	5.25	11.58	2.0	4.1	2.1
11	10	175	4.52	9.98	2.1	3.8	1.7
12	135	247.5	3.09	6.82	22.7	27.5	4.8

Wetting front:	
Time (min)	Length (mm)
59	73
125	104
292	155

Constant (x^2/t):	82
Incremental velocity (mm/min):	0.305



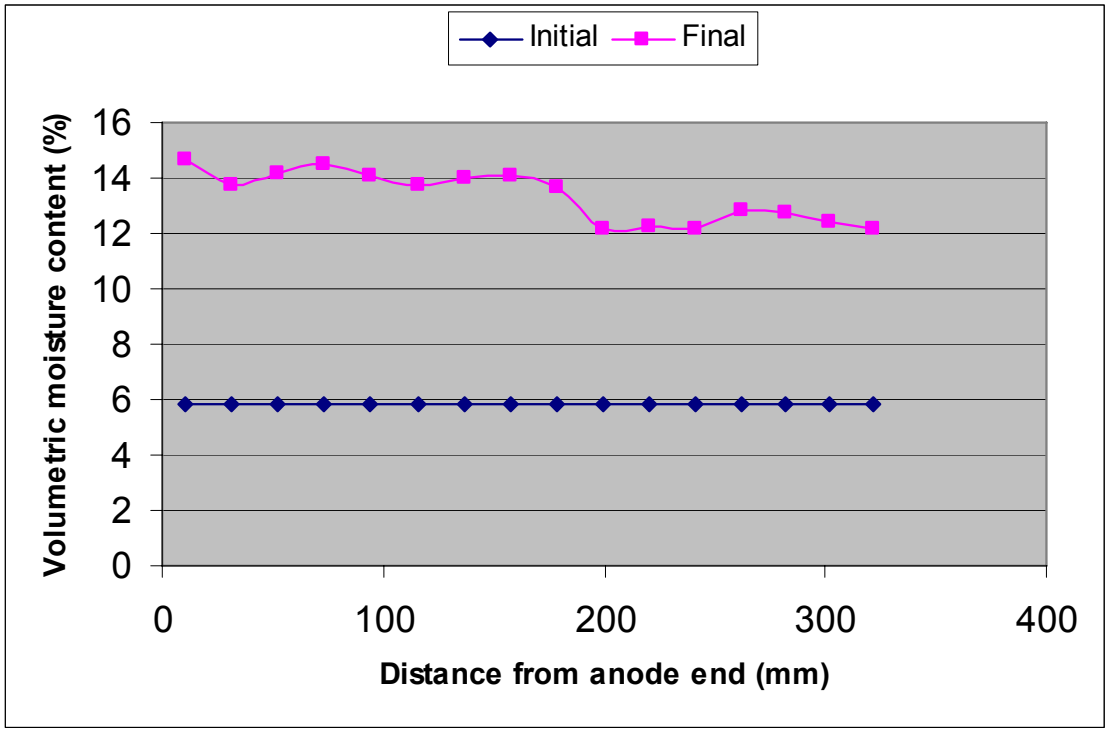
Test no. 4	
Initial moisture:	3.39% by weight
	5.86% by volume

Electric current:	15 mA
Fines:	4%
Treatment period:	19.8 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	21	10.5	8.50	14.70	5.9	14.9	9.0
2	21	31.5	7.96	13.77	4.8	11.3	6.5
3	21	52.5	8.19	14.16	3.5	8.5	5.0
4	21	73.5	8.41	14.54	3.4	8.4	5.0
5	21	94.5	8.14	14.07	3.4	8.2	4.8
6	21	115.5	7.96	13.77	3.7	8.6	4.9
7	21	136.5	8.08	13.98	5.1	12.1	7.0
8	21	157.5	8.16	14.12	3.8	9.2	5.4
9	21	178.5	7.90	13.66	3.3	7.7	4.4
10	21	199.5	7.01	12.13	4.3	8.9	4.6
11	21	220.5	7.07	12.22	3.7	7.7	4.0
12	21	241.5	7.02	12.13	5.4	11.1	5.7
13	20	262	7.42	12.83	3.3	7.3	4.0
14	20	282	7.38	12.76	3.6	7.9	4.3
15	20	302	7.17	12.40	5.3	11.3	6.0
16	20	322	7.04	12.18	4.3	9.0	4.7
						Reservoir	38.2

Wetting front:	
Time (min)	Length (mm)
15	61
4813	260

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.427



Volt readings (V):						
Time (hours):	0.6	8.0	16.6			
Interval (mm): 0-15	7.21	8.20	6.79			
15-65	10.70	13.81	11.75			
65-115	*	*	50.70			
115-165	*	*	*			
165-215	42.50	21.10	25.20			
215-265	74.30	34.30	46.10			
265-315	54.30	43.30	27.50			
315-332	3.35	0.09	0.12			
Current (mA):						

Pectora roborant cultus recti

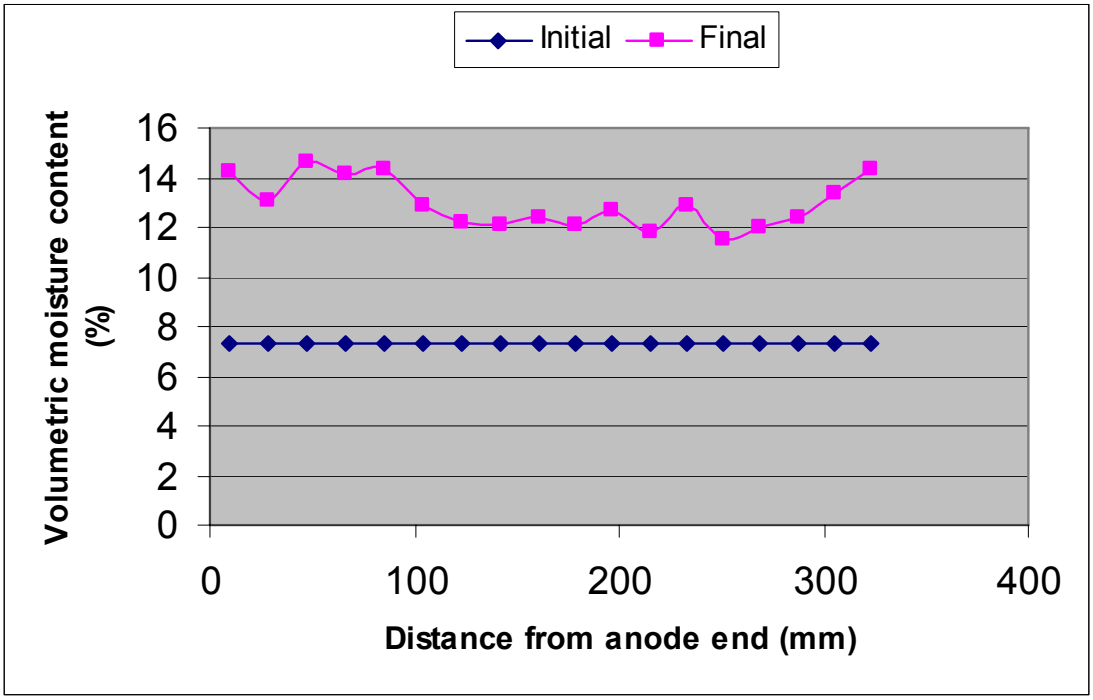
Test no. 5	
Initial moisture:	3.39% by weight
	7.36% by volume

Electric current:	25 mA
Fines:	4%
Treatment period:	30.3 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	19	9.5	6.55	14.22	3.7	7.2	3.5
2	19	28.5	6.02	13.08	2.8	5.1	2.2
3	19	47.5	6.76	14.68	3.8	7.6	3.8
4	19	66.5	6.49	14.11	3.0	5.7	2.7
5	19	85.5	6.59	14.33	3.1	6.0	2.9
6	19	104.5	5.94	12.90	3.2	5.6	2.4
7	19	123.5	5.61	12.19	3.7	6.2	2.5
8	19	142.5	5.56	12.07	2.7	4.4	1.7
9	18	161	5.72	12.43	3.9	6.7	2.7
10	18	179	5.56	12.08	3.3	5.4	2.1
11	18	197	5.83	12.67	3.6	6.3	2.6
12	18	215	5.45	11.84	3.5	5.7	2.1
13	18	233	5.93	12.88	3.5	6.1	2.6
14	18	251	5.30	11.52	3.6	5.6	2.0
15	18	269	5.52	11.99	3.7	6.1	2.4
16	18	287	5.72	12.42	4.7	7.9	3.2
17	18	305	6.15	13.37	5.9	10.7	4.8
18	18	323	6.60	14.34	6.4	12.6	6.1
						Reservoir	32.2

Wetting front:	
Time (min)	Length (mm)
15	25
482	187

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.347



Volt readings (V):						
Time (hours):	0.6	8.0	16.6	30.3		
Interval (mm): 0-15	2.34	9.50	8.78	7.06		
15-65	30.70	22.20	26.00	24.60		
65-115	47.10	21.70	42.10	46.30		
115-165	80.40	71.20	84.40	95.20		
165-215	69.60	81.10	71.10	69.40		
215-265	57.20	77.90	70.50	51.90		
265-315	37.50	46.60	33.70	39.30		
315-332	13.30	11.90	6.58	8.41		
Current (mA):						

Pectora roborant cultus recti

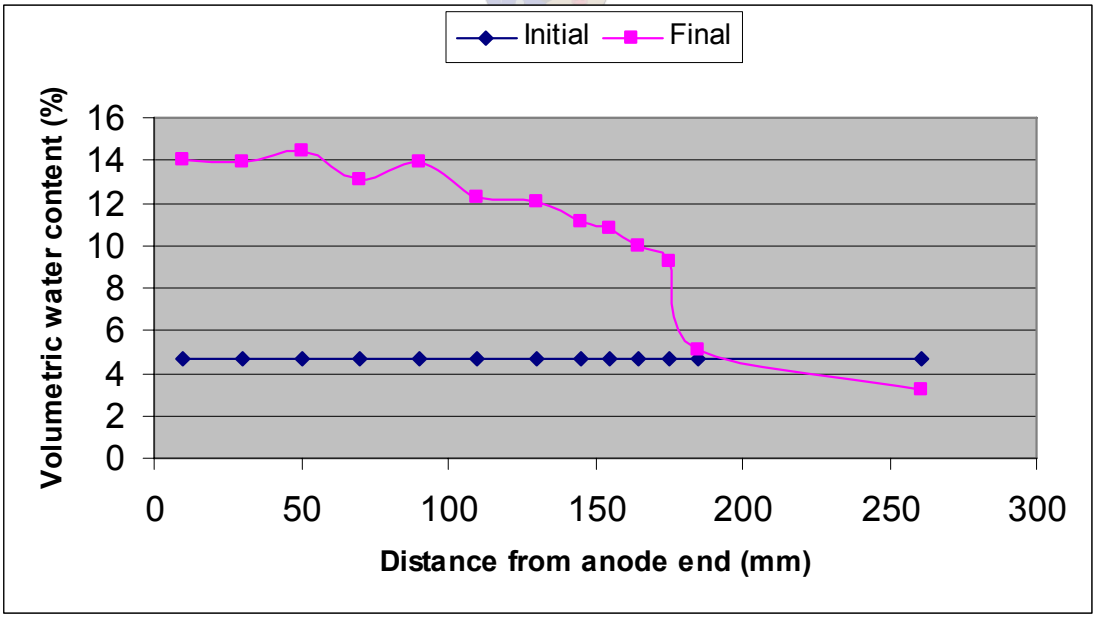
Test no. 6	
Initial moisture:	3.03% by weight
	4.72% by volume

Electric current:	0 mA
Fines:	6%
Treatment period:	27.7 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	20	10	9.00	14.03	2.9	8.5	5.7
2	20	30	8.90	13.87	3.3	9.7	6.4
3	20	50	9.29	14.48	3.0	9.3	6.3
4	20	70	8.41	13.11	3.5	9.6	6.1
5	20	90	8.92	13.91	3.0	8.8	5.8
6	20	110	7.85	12.23	2.3	5.9	3.6
7	20	130	7.73	12.05	2.3	5.9	3.6
8	10	145	7.12	11.09	1.6	3.7	2.1
9	10	155	6.92	10.78	2.2	5.1	2.9
10	10	165	6.40	9.97	2.4	5.1	2.7
11	10	175	5.91	9.21	2.9	5.6	2.7
12	10	185	3.28	5.11	2.9	3.1	0.2
13	142	261	2.07	3.23	23.1	15.8	-7.3

Wetting front:	
Time (min)	Length (mm)
25	65
141	146
221	167

Constant (x^2/t):	126
Incremental velocity (mm/min):	0.263



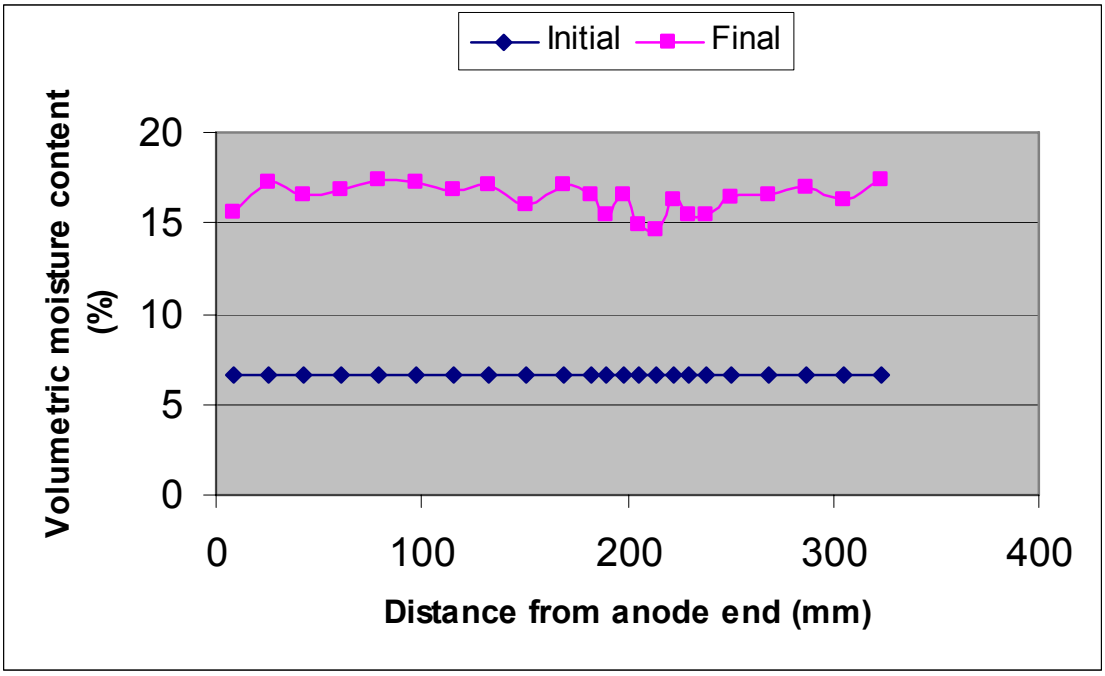
Test no. 7	
Initial moisture:	3.03% by weight
	6.58% by volume

Electric current:	15 mA
Fines:	6%
Treatment period:	18.7 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	17	8.5	7.16	15.56	2.6	6.1	3.5
2	17	25.5	7.92	17.21	3.1	8.0	4.9
3	18	43	7.60	16.51	3.7	9.4	5.7
4	18	61	7.76	16.87	3.0	7.6	4.6
5	18	79	7.98	17.34	2.8	7.3	4.5
6	18	97	7.94	17.24	4.1	10.8	6.7
7	18	115	7.73	16.80	2.3	5.8	3.5
8	18	133	7.89	17.14	3.4	8.8	5.4
9	18	151	7.38	16.04	2.3	5.7	3.4
10	18	169	7.85	17.05	3.1	8.1	5.0
11	8	182	7.63	16.58	1.4	3.6	2.2
12	8	190	7.13	15.49	1.7	3.9	2.2
13	8	198	7.61	16.54	2.0	5.1	3.1
14	8	206	6.84	14.86	1.7	3.8	2.1
15	8	214	6.74	14.65	2.2	4.8	2.6
16	8	222	7.46	16.21	1.6	4.0	2.4
17	8	230	7.12	15.47	1.8	4.2	2.4
18	8	238	7.11	15.45	2.6	6.2	3.6
19	18	251	7.57	16.45	1.7	4.3	2.6
20	18	269	7.62	16.55	2.3	5.8	3.5
21	18	287	7.78	16.90	1.9	4.9	3.0
22	18	305	7.51	16.31	3.8	9.4	5.6
23	18	323	7.97	17.32	4.0	10.5	6.5
						Reservoir	12.8

Wetting front:	
Time (min)	Length (mm)
11	30
482	135
850	190
1121	223

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.122



Volt readings (V):						
Time (hours):	0.6	8.0	16.6	18.7		
Interval (mm): 0-15	7.34	7.46	7.29	5.15		
15-65	23.30	17.26	20.20	29.00		
65-115	54.20	15.09	16.40	24.30		
115-165	41.30	36.70	16.60	31.50		
165-215	53.20	58.30	48.10	41.10		
215-265	51.90	64.50	83.90	31.40		
265-315	52.00	67.60	64.00	36.40		
315-332	11.80	11.10	6.61	3.00		
Current (mA):						

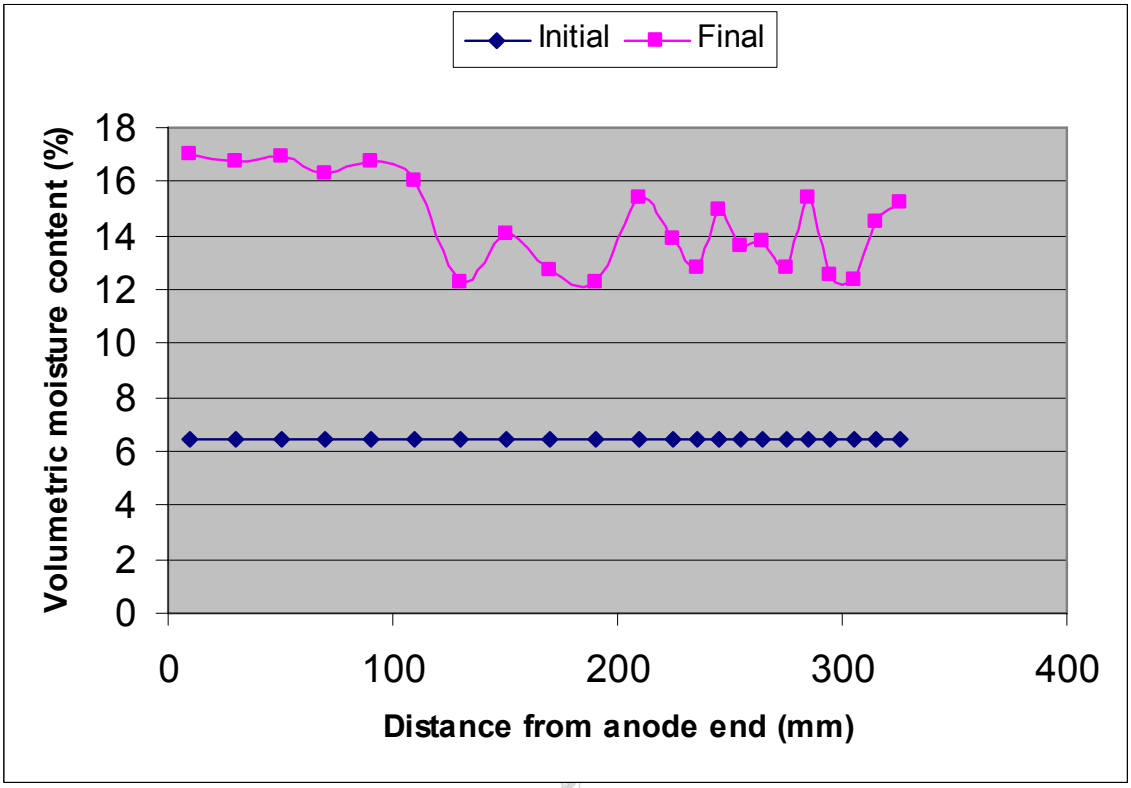
Test no. 8	
Initial moisture:	3.03% by weight
	6.44% by volume

Electric current:	25 mA
Fines:	6%
Treatment period:	31.5 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	20	10	8.02	17.04	2.8	7.4	4.6
2	20	30	7.88	16.75	2.6	6.7	4.1
3	20	50	7.98	16.96	3.3	8.8	5.5
4	20	70	7.67	16.30	3.8	9.6	5.8
5	20	90	7.89	16.76	1.9	5.0	3.1
6	20	110	7.53	16.01	3.3	8.1	4.9
7	20	130	5.76	12.24	2.6	5.0	2.4
8	20	150	6.61	14.05	2.6	5.6	3.0
9	20	170	5.97	12.68	2.3	4.6	2.3
10	20	190	5.78	12.28	2.2	4.2	2.0
11	20	210	7.27	15.45	2.1	5.0	2.9
12	10	225	6.55	13.92	1.7	3.7	2.0
13	10	235	6.04	12.84	1.5	2.9	1.4
14	10	245	7.03	14.95	1.9	4.4	2.5
15	10	255	6.39	13.59	1.8	3.8	2.0
16	10	265	6.47	13.76	1.8	3.7	2.0
17	10	275	6.00	12.76	1.5	2.9	1.4
18	10	285	7.23	15.37	2.5	6.0	3.5
19	10	295	5.91	12.57	2.8	5.5	2.7
20	10	305	5.82	12.37	3.4	6.6	3.2
21	10	315	6.84	14.55	4.4	10.0	5.6
22	12	326	7.17	15.25	5.1	12.1	7.0
						Reservoir	32.2

Wetting front:	
Time (min)	Length (mm)
56	105
325	143
1058	235

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.126



Volt readings (V):						
Time (hours):	1.0	6.4	17.6	31.5		
Interval (mm): 0-15	6.11	6.87	9.13	5.50		
15-65	7.57	13.12	25.40	28.30		
65-115	42.10	24.80	58.10	66.20		
115-165	56.60	34.60	29.90	43.40		
165-215	62.10	85.80	63.70	76.70		
215-265	63.40	80.20	69.70	60.30		
265-315	62.10	88.10	84.60	58.20		
315-332	13.30	1.07	4.75	4.10		
Current (mA):						

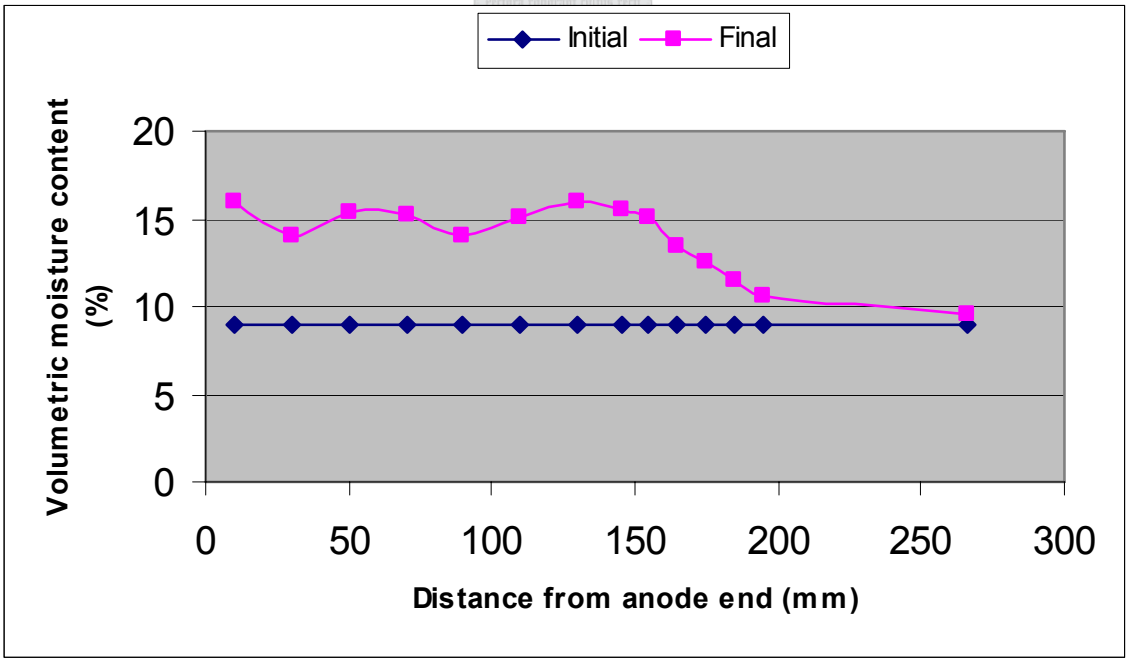
Test no. 9	
Initial moisture:	3.82% by weight
	8.89% by volume

Electric current:	0 mA
Fines:	8%
Treatment period:	31.5 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	20	10	6.88	16.00	3.5	6.3	2.8
2	20	30	6.05	14.08	3.5	5.6	2.1
3	20	50	6.61	15.37	3.5	6.0	2.5
4	20	70	6.56	15.25	3.8	6.5	2.7
5	20	90	6.03	14.03	4.7	7.4	2.7
6	20	110	6.45	15.01	4.7	7.9	3.2
7	20	130	6.88	16.01	4.0	7.2	3.2
8	10	145	6.67	15.52	3.8	6.7	2.9
9	10	155	6.50	15.11	2.7	4.6	1.9
10	10	165	5.81	13.50	3.5	5.3	1.8
11	10	175	5.37	12.49	3.6	5.0	1.4
12	10	185	4.91	11.42	2.8	3.6	0.8
13	10	195	4.59	10.67	3.2	3.9	0.7
14	132	266	4.09	9.51	31.4	33.6	2.2

Wetting front:	
Time (min)	Length (mm)
58	74
124	93
331	144
451	171

Constant (x^2/t):	65
Incremental velocity (mm/min):	0.225



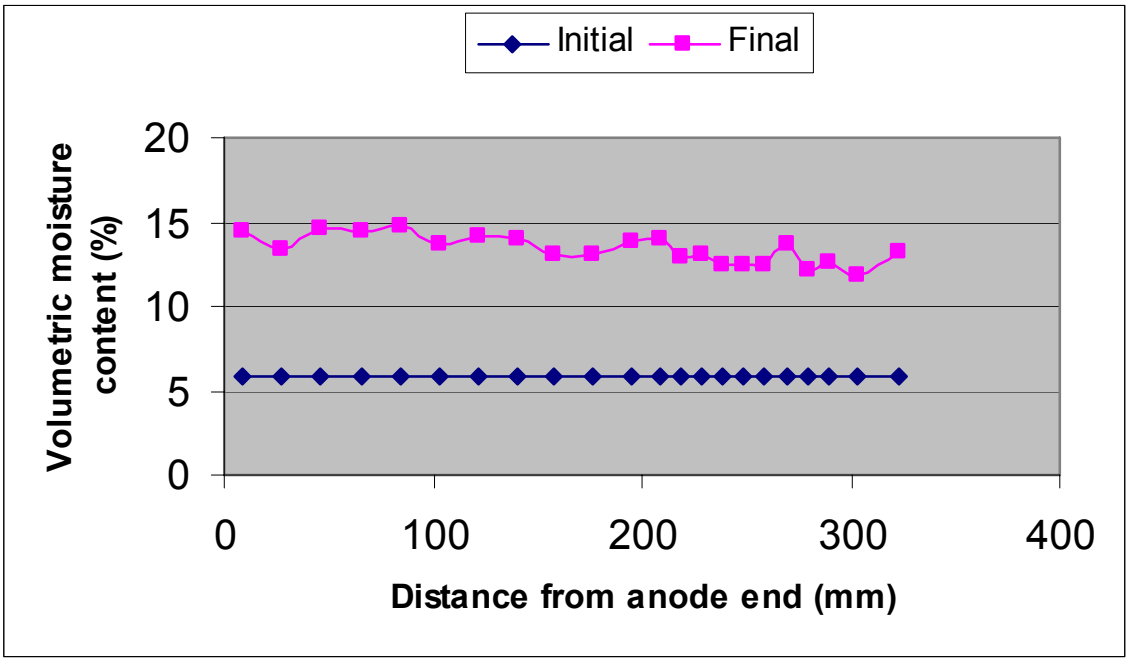
Test no. 10	
Initial moisture:	3.45% by weight
	5.79% by volume

Electric current:	15 mA
Fines:	8%
Treatment period:	34.7 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	18	9	8.64	14.47	2.8	6.9	4.1
2	19	27.5	7.96	13.33	4.0	9.3	5.3
3	19	46.5	8.74	14.65	3.2	8.2	5.0
4	19	65.5	8.60	14.42	3.9	9.8	5.9
5	19	84.5	8.80	14.74	3.5	9.0	5.5
6	19	103.5	8.16	13.67	3.8	8.9	5.1
7	18	122	8.43	14.13	2.7	6.5	3.8
8	18	140	8.35	14.00	2.8	6.8	4.0
9	18	158	7.84	13.13	3.1	7.0	3.9
10	19	176.5	7.79	13.05	3.5	7.9	4.4
11	18	195	8.28	13.87	3.3	7.9	4.6
12	10	209	8.35	13.98	2.2	5.4	3.2
13	10	219	7.69	12.89	2.2	4.9	2.7
14	10	229	7.83	13.11	2.6	5.8	3.2
15	10	239	7.42	12.43	2.6	5.6	3.0
16	10	249	7.40	12.39	2.2	4.8	2.6
17	10	259	7.47	12.51	2.4	5.1	2.7
18	10	269	8.22	13.77	2.0	4.7	2.7
19	10	279	7.28	12.21	2.1	4.4	2.3
20	10	289	7.57	12.68	2.1	4.6	2.5
21	19	303.5	7.10	11.90	4.3	8.9	4.6
22	19	322.5	7.87	13.18	5.1	11.7	6.6
						Reservoir	43.1

Wetting front:	
Time (min)	Length (mm)
79	79
625	194
829	232

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.186



Volt readings (V):						
Time (hours):	10.5	23.5	34.7			
Interval (mm): 0-15	8.68	8.85	7.50			
15-65	13.78	12.16	10.50			
65-115	23.20	25.00	25.80			
115-165	34.70	44.70	50.30			
165-215	35.90	38.10	41.20			
215-265	70.00	38.80	47.90			
265-315	59.50	31.70	37.20			
315-332	6.89	4.60	4.50			
Current (mA):						

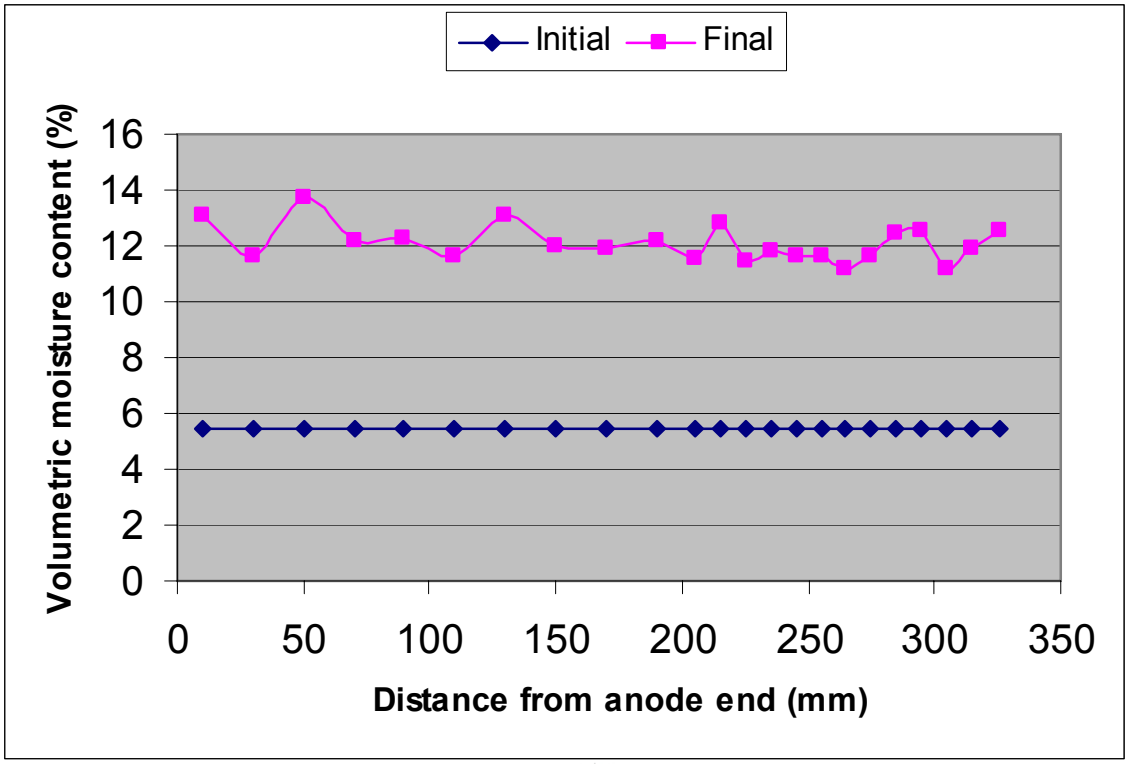
Test no. 11	
Initial moisture:	3.45% by weight
	5.49% by volume

Electric current:	25 mA
Fines:	8%
Treatment period:	13.2 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	20	10	8.23	13.07	3.8	9.1	5.3
2	20	30	7.30	11.59	3.7	7.8	4.1
3	20	50	8.64	13.73	4.2	10.5	6.3
4	20	70	7.69	12.21	3.9	8.7	4.8
5	20	90	7.75	12.32	4.0	8.9	4.9
6	20	110	7.34	11.66	2.9	6.2	3.3
7	20	130	8.22	13.05	3.4	8.2	4.8
8	20	150	7.56	12.01	2.6	5.7	3.1
9	20	170	7.48	11.89	3.5	7.7	4.1
10	20	190	7.69	12.22	3.3	7.3	4.0
11	10	205	7.29	11.58	2.3	4.9	2.6
12	10	215	8.05	12.79	1.6	3.8	2.2
13	10	225	7.22	11.47	2.0	4.1	2.1
14	10	235	7.44	11.82	1.9	4.1	2.2
15	10	245	7.32	11.63	1.9	4.1	2.2
16	10	255	7.32	11.63	3.4	7.1	3.7
17	10	265	7.03	11.17	2.0	4.0	2.0
18	10	275	7.31	11.62	1.9	4.0	2.1
19	10	285	7.82	12.43	1.6	3.7	2.1
20	10	295	7.92	12.58	1.8	4.1	2.3
21	10	305	7.03	11.17	2.0	4.0	2.0
22	10	315	7.48	11.88	2.4	5.2	2.8
23	12	326	7.91	12.57	3.6	8.3	4.7
						Reservoir	20.7

Wetting front:	
Time (min)	Length (mm)
50	81
772	218

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.190



Volt readings (V):						
Time (hours):	0.3	3.2	12.8			
Interval (mm): 0-15	20.20		27.70			
15-65	*		*			
65-115	47.80		37.20			
115-165	57.50		44.30			
165-215	68.00		58.60			
215-265	81.80		70.30			
265-315	49.10		41.00			
315-332	18.51		18.80			
Current (mA):	13.5	25.0				

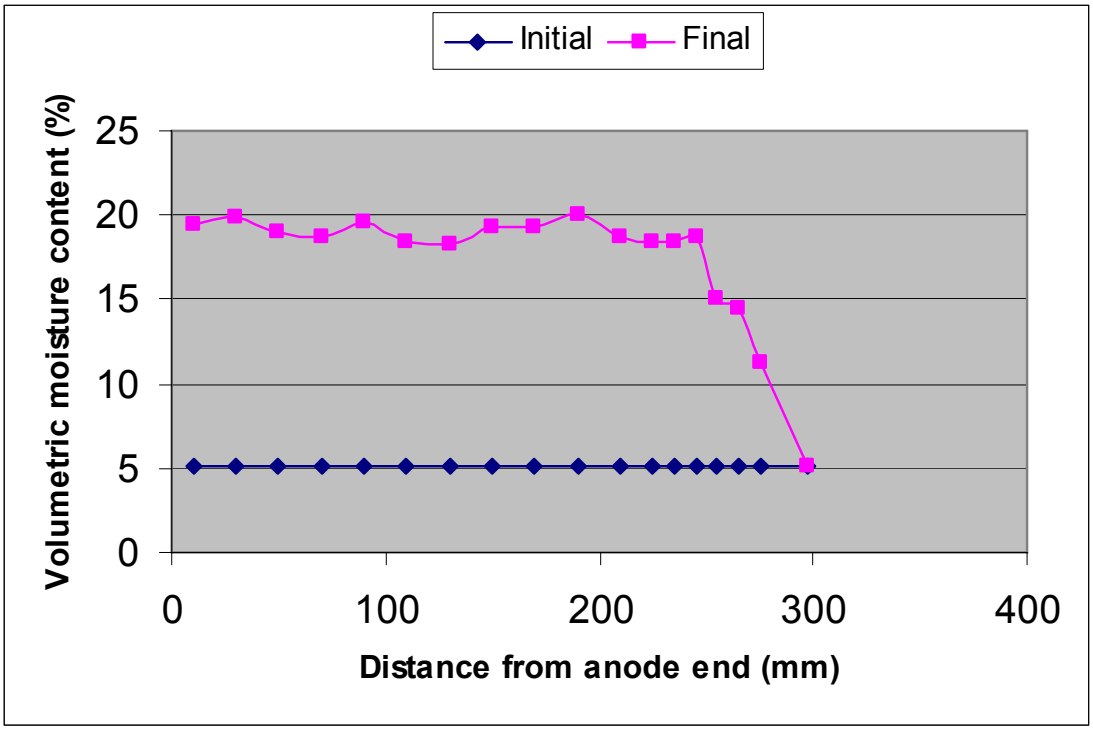
Test no. 12	
Initial moisture:	2.45% by weight
	5.15% by volume

Electric current:	0 mA
Fines:	10%
Treatment period:	12.2 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	20	10	9.27	19.45	2.3	8.7	6.4
2	20	30	9.50	19.93	2.6	10.2	7.6
3	20	50	9.09	19.08	2.2	8.0	5.8
4	20	70	8.95	18.78	1.8	6.4	4.6
5	20	90	9.31	19.54	2.8	10.8	8.0
6	20	110	8.74	18.35	1.8	6.4	4.6
7	20	130	8.70	18.26	2.5	8.7	6.2
8	20	150	9.18	19.26	2.1	7.7	5.6
9	20	170	9.18	19.26	2.5	9.4	6.9
10	20	190	9.55	20.04	2.3	9.1	6.8
11	20	210	8.95	18.78	3.2	11.6	8.4
12	10	225	8.81	18.49	1.6	5.7	4.1
13	10	235	8.79	18.45	1.5	5.4	3.9
14	10	245	8.91	18.70	2.3	8.2	5.9
15	10	255	7.17	15.06	1.6	4.8	3.2
16	10	265	6.91	14.50	2.2	6.3	4.1
17	10	275	5.34	11.21	1.8	3.9	2.1
18	35	297.5	2.42	5.07	6.8	6.7	-0.1

Wetting front:	
Time (min)	Length (mm)
109	81
730	219

Constant (x^2/t):	66
Incremental velocity (mm/min):	0.222



Test no. 13	
Initial moisture:	3.06% by weight
	6.70% by volume

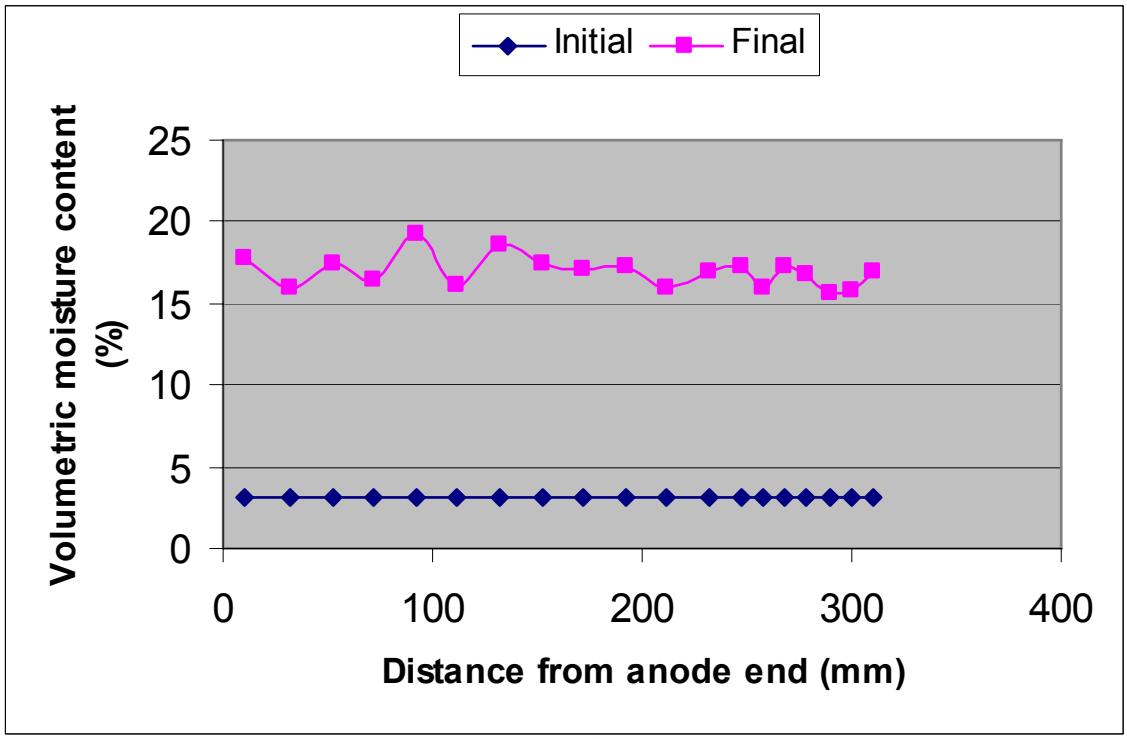
Electric current:	15 mA
Fines:	10%
Treatment period:	47.7 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	21	10.5	8.08	17.72	3.8	10.0	6.2
2	21	31.5	7.26	15.91	3.1	7.3	4.2
3	20	52	7.92	17.36	2.8	7.3	4.5
4	20	72	7.51	16.47	3.0	7.3	4.3
5	20	92	8.74	19.18	3.6	10.3	6.7
6	20	112	7.37	16.17	3.5	8.5	5.0
7	20	132	8.45	18.54	3.2	8.9	5.7
8	20	152	7.98	17.51	3.1	8.2	5.1
9	20	172	7.81	17.12	2.7	6.9	4.2
10	20	192	7.86	17.23	3.1	8.0	4.9
11	20	212	7.29	15.99	3.3	7.8	4.5
12	20	232	7.69	16.87	3.1	7.7	4.6
13	11	247.5	7.84	17.19	3.2	8.2	5.0
14	10	258	7.25	15.90	2.3	5.4	3.1
15	10	268	7.87	17.25	2.4	6.3	3.9
16	11	278.5	7.64	16.75	3.0	7.6	4.6
17	11	289.5	7.13	15.63	2.8	6.5	3.7
18	10	300	7.18	15.74	2.5	5.9	3.4
19	10	310	7.76	17.02	2.4	6.0	3.6
						Reservoir	8.2

Wetting front:	
Time (min)	Length (mm)
431	95
675	128
1394	213

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.118

Pectora roborant cultus recti



Volt readings (V):						
Time (hours):	0.4	7.2	13.1	23.2	31.2	47.6
Interval (mm): 0-6	5.03	5.58	5.22	4.67	4.64	4.30
6-56	37.40	13.40	14.79	17.58	22.90	37.80
56-106	68.40	27.30	24.20	25.00	24.10	30.80
106-156	48.90	42.60	31.10	24.40	24.10	25.20
156-206	52.10	50.10	61.10	32.70	29.00	33.30
206-256	69.30	62.10	80.90	82.30	38.90	33.30
256-306	60.80	57.60	55.90	55.60	42.20	26.50
306-315	7.71	3.30	2.78	0.92	0.71	0.75
Current (mA):	14.75	15.21	15.20	15.46	16.35	15.25

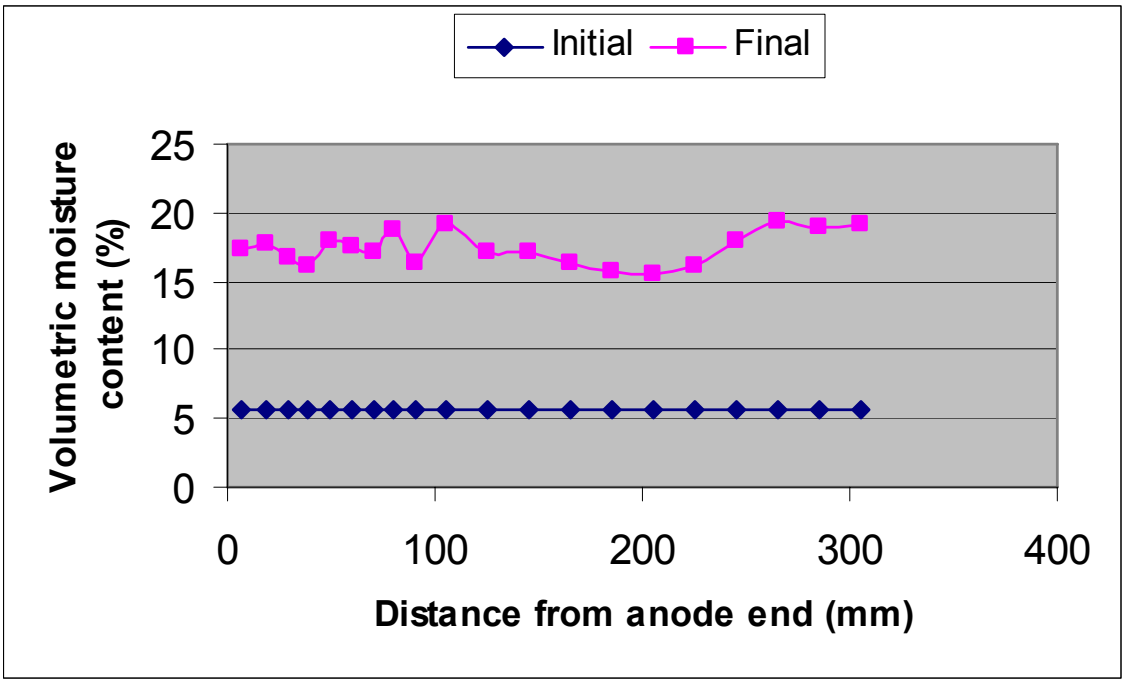
Test no. 14	
Initial moisture:	2.64% by weight
	5.72% by volume

Electric current:	25 mA
Fines:	10%
Treatment period:	46.9 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	13	6.5	8.00	17.32	2.7	8.2	5.5
2	11	18.5	8.22	17.80	2.4	7.5	5.1
3	10	29	7.77	16.82	2.4	7.0	4.6
4	10	39	7.50	16.23	1.9	5.3	3.4
5	10	49	8.32	18.01	1.7	5.3	3.6
6	11	59.5	8.13	17.60	2.5	7.7	5.2
7	10	70	7.89	17.09	2.5	7.5	5.0
8	10	80	8.70	18.84	1.8	5.8	4.0
9	10	90	7.56	16.37	2.1	5.9	3.8
10	20	105	8.82	19.08	3.1	10.5	7.4
11	20	125	7.91	17.13	2.3	6.9	4.6
12	20	145	7.89	17.08	2.6	7.9	5.3
13	20	165	7.50	16.24	2.1	6.1	4.0
14	20	185	7.27	15.74	3.4	9.3	5.9
15	20	205	7.19	15.56	1.7	4.6	2.9
16	20	225	7.49	16.22	3.2	9.2	6.0
17	20	245	8.26	17.88	2.3	7.1	4.8
18	20	265	8.93	19.33	3.0	10.1	7.1
19	20	285	8.77	18.99	2.7	8.8	6.2
20	20	305	8.85	19.16	2.1	7.1	5.0
						Reservoir	30.4

Wetting front:	
Time (min)	Length (mm)
427	95
671	141
1394	235

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.130



Volt readings (V):						
Time (hours):	0.4	7.1	13.0	23.2	31.2	46.8
Interval (mm): 0-6	5.36	6.18	5.26	4.98	7.05	4.57
6-56	23.00	15.60	21.20	33.60	48.80	74.30
56-106	77.90	30.00	42.20	54.30	43.10	42.80
106-156	55.80	67.50	30.00	44.40	37.90	42.30
156-206	59.00	71.70	73.40	58.30	51.40	57.50
206-256	62.60	82.20	102.80	74.20	50.60	63.50
256-306	51.10	64.70	64.60	70.60	27.80	55.20
306-315	11.80	5.30	2.27	1.19	1.06	1.67
Current (mA):	14.68	20.10	19.40	24.60	30.50	23.30

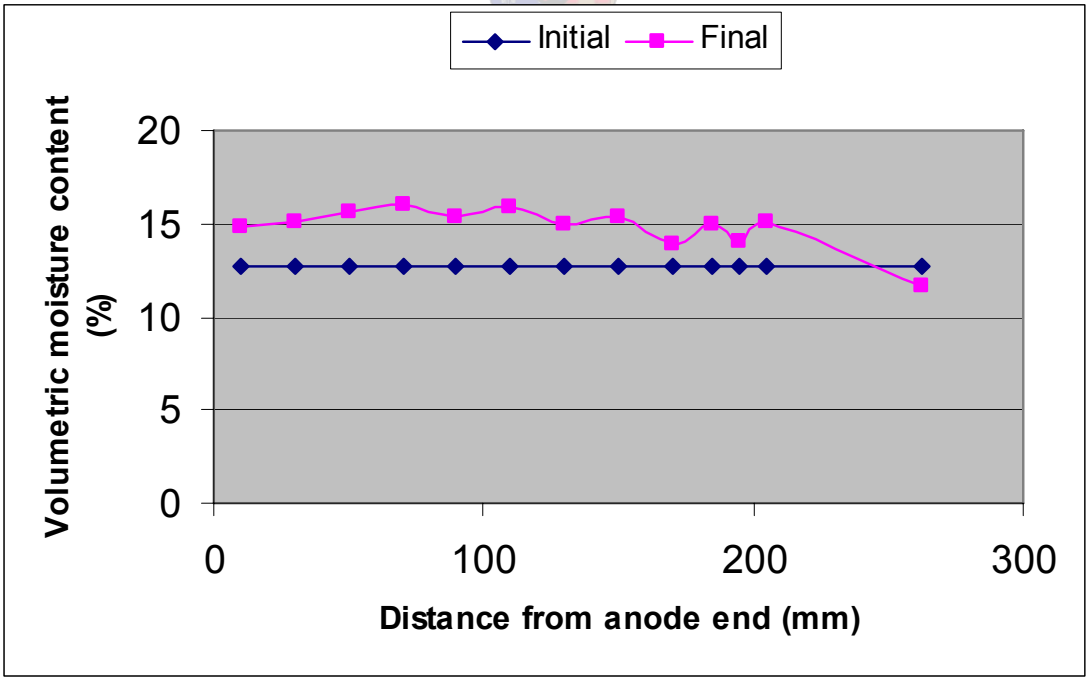
Test no. 15	
Initial moisture:	5.60% by weight
	12.68% by volume

Electric current:	0 mA
Fines:	10%
Treatment period:	8.5 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	20	10	6.54	14.81	5.8	6.8	1.0
2	20	30	6.66	15.09	6.6	7.8	1.2
3	20	50	6.91	15.65	5.4	6.7	1.3
4	20	70	7.07	16.01	7.3	9.2	1.9
5	20	90	6.77	15.34	5.4	6.5	1.1
6	20	110	7.01	15.87	6.7	8.3	1.7
7	20	130	6.60	14.96	4.3	5.1	0.8
8	20	150	6.81	15.42	5.3	6.5	1.2
9	20	170	6.14	13.91	5.4	5.9	0.5
10	10	185	6.62	14.99	4.4	5.2	0.8
11	10	195	6.20	14.05	3.7	4.1	0.4
12	10	205	6.67	15.12	4.7	5.6	0.9
13	105	262.5	5.12	11.61	41.5	38.0	-3.5

Wetting front:	
Time (min)	Length (mm)
63	106
271	160
512	196

Constant (x^2/t):	75
Incremental velocity (mm/min):	0.149



Test no. 16	
Initial moisture:	4.26% by weight
	9.33% by volume

Electric current:	15 mA
Fines:	10%
Treatment period:	34.2 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	315	157.5	7.40	16.21	79.8	138.6	58.8
						Reservoir	27.3

Wetting front:	
Time (min)	Length (mm)
56	105
325	143
1058	230

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.119

Volt readings (V):						
Time (hours):	0.0	8.9	23.1			
Interval (mm): 0-6						
6-56						
56-106						
106-156						
156-206						
206-256						
256-306						
306-315						
Current (mA):	15.04	16.26	16.32			

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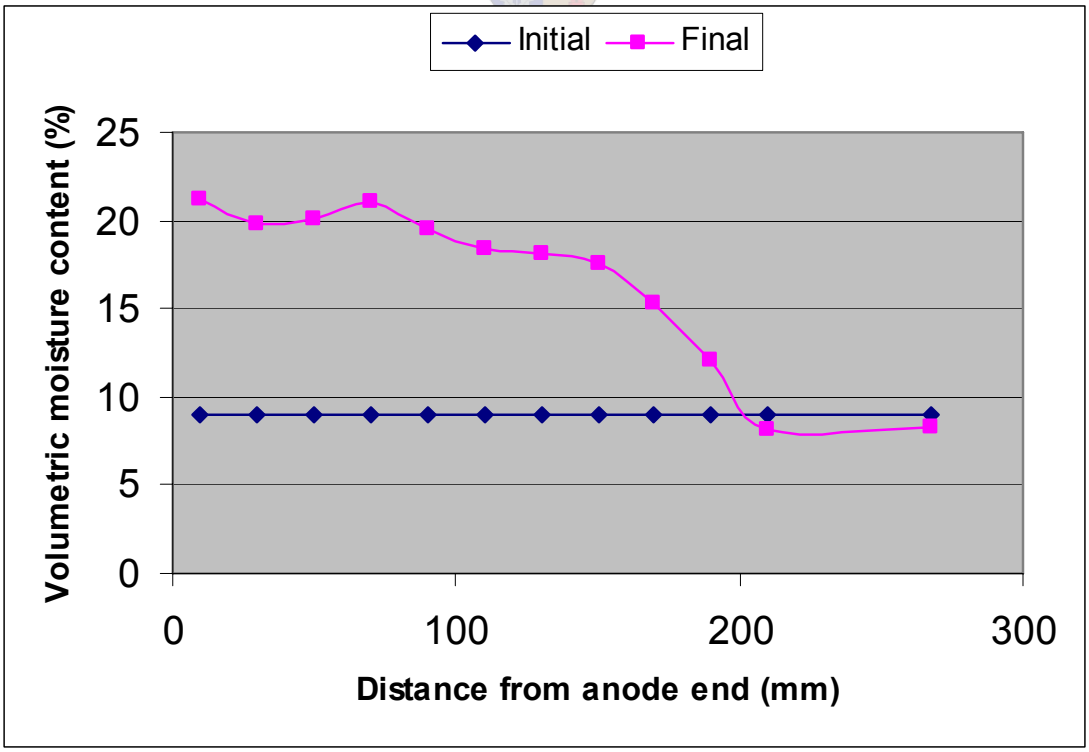
Test no. 17	
Initial moisture:	4.20% by weight
	9.03% by volume

Electric current:	0 mA
Fines:	15%
Treatment period:	8.3 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	20	10	9.82	21.14	5.4	12.6	7.2
2	20	30	9.22	19.85	4.5	9.8	5.4
3	20	50	9.35	20.13	6.5	14.4	7.9
4	20	70	9.79	21.07	6.2	14.4	8.2
5	20	90	9.10	19.58	6.3	13.6	7.3
6	20	110	8.55	18.39	5.5	11.1	5.6
7	20	130	8.40	18.09	5.5	10.9	5.5
8	20	150	8.17	17.60	6.0	11.6	5.6
9	20	170	7.08	15.24	4.0	6.7	2.7
10	20	190	5.63	12.11	6.2	8.3	2.1
11	20	210	3.80	8.18	5.9	5.3	-0.6
12	95	267.5	3.83	8.24	14.7	13.4	-1.3

Wetting front:	
Time (min)	Length (mm)
46	81
109	113
221	150
375	193
495	224

Constant (x^2/t):	101
Incremental velocity (mm/min):	0.258



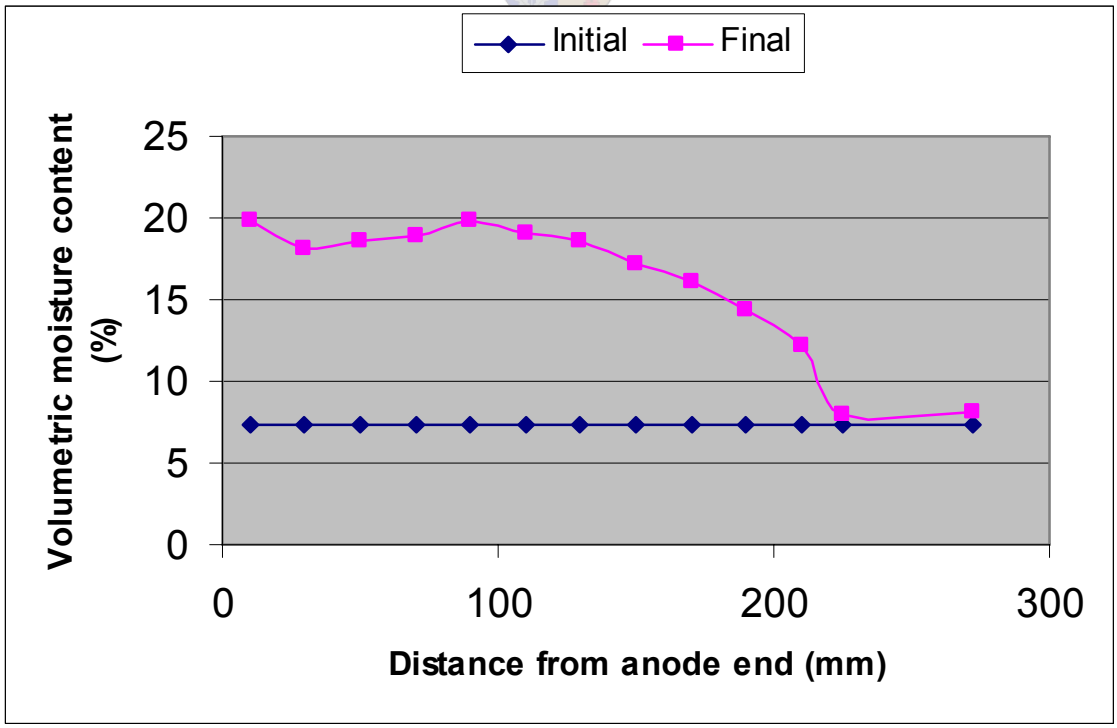
Test no. 18	
Initial moisture:	3.43% by weight
	7.39% by volume

Electric current:	0 mA
Fines:	20%
Treatment period:	9.3 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	20	10	9.23	19.89	4.2	11.4	7.1
2	20	30	8.37	18.05	4.7	11.4	6.7
3	20	50	8.62	18.59	3.7	9.2	5.5
4	20	70	8.73	18.83	4.2	10.7	6.5
5	20	90	9.22	19.88	5.3	14.3	9.0
6	20	110	8.86	19.09	4.8	12.5	7.7
7	20	130	8.61	18.57	4.8	12.0	7.2
8	20	150	7.94	17.12	3.8	8.8	5.0
9	20	170	7.47	16.10	4.1	8.9	4.8
10	20	190	6.65	14.34	4.6	8.9	4.3
11	20	210	5.67	12.22	4.3	7.1	2.8
12	10	225	3.66	7.89	2.4	2.6	0.2
13	85	272.5	3.77	8.13	12.0	13.2	1.2

Wetting front:	
Time (min)	Length (mm)
30	63
108	101
432	211
559	237

Constant (x^2/t):	101
Incremental velocity (mm/min):	0.205



Test no. 19	
Initial moisture:	2.19% by weight
	4.71% by volume

Electric current:	15 mA
Fines:	20%
Treatment period:	196.9 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	315	157.5	9.02	19.42	41.0	168.9	127.9
						Reservoir	21.0

Wetting front:	
Time (min)	Length (mm)
531	74
1405	122
2888	195

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.049

Volt readings (V):						
Time (hours):	1.3	8.9	23.4	48.1	73.3	95.7
Interval (mm): 0-6	3.78	4.82	5.12	5.89	4.93	6.15
6-56	38.20	6.73	8.98	17.62	36.40	55.80
56-106	53.40	42.70	10.01	15.45	13.50	13.80
106-156	53.40	60.40	49.20	16.52	16.01	13.30
156-206	51.10	59.90	72.00	20.20	21.90	18.50
206-256	91.40	99.80	108.50	157.10	36.90	26.40
256-306	49.20	59.30	75.90	103.20	44.10	26.70
306-315	4.71	5.00	3.74	2.32	1.54	0.72
Current (mA):	7.60	10.04	10.81	15.47	16.80	15.32

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Test no. 20	
Initial moisture:	2.03% by weight
	4.30% by volume

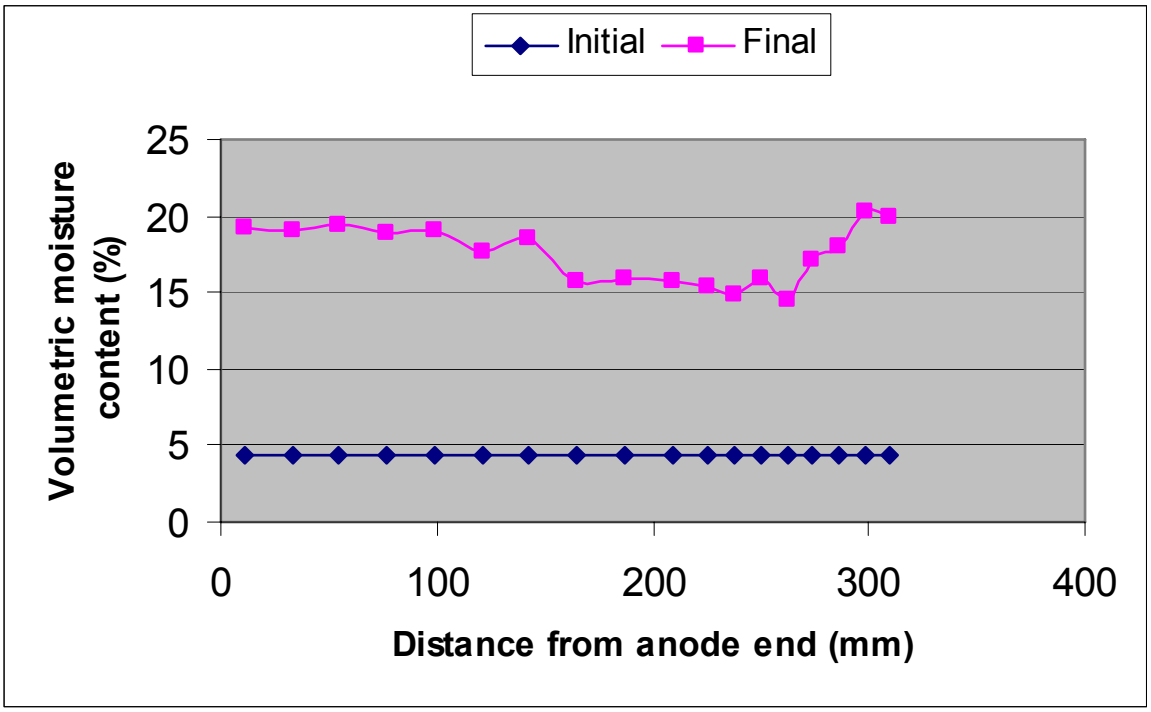
Electric current:	25 mA
Fines:	20%
Treatment period:	72.3 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	22	11	9.08	19.22	2.9	13.1	10.2
2	22	33	9.03	19.12	2.3	10.2	7.9
3	22	55	9.13	19.32	2.9	13.0	10.1
4	22	77	8.88	18.80	2.7	11.6	8.9
5	22	99	9.01	19.07	2.6	11.6	9.0
6	22	121	8.37	17.72	2.7	11.1	8.4
7	22	143	8.72	18.45	2.9	12.4	9.5
8	22	165	7.46	15.79	2.1	7.6	5.5
9	22	187	7.51	15.90	2.8	10.2	7.4
10	22	209	7.44	15.75	2.2	8.2	5.9
11	12	226	7.24	15.32	1.1	3.9	2.8
12	12	238	7.03	14.89	1.3	4.6	3.3
13	12	250	7.51	15.90	1.3	4.8	3.5
14	12	262	6.84	14.47	1.4	4.8	3.4
15	12	274	8.13	17.21	1.5	6.0	4.5
16	12	286	8.52	18.03	2.5	10.5	8.0
17	12	298	9.60	20.32	1.4	6.7	5.3
18	11	309.5	9.39	19.88	1.6	7.6	6.0
						Reservoir	8.2

Wetting front:	
Time (min)	Length (mm)
554	78
1540	133
2917	188

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.040

Pectora roborant cultus recti



Volt readings (V):						
Time (hours):	1.7	9.2	23.8	48.6	53.4	72.3
Interval (mm): 0-6	2.37	2.97	3.04	3.81	5.98	4.36
6-56	27.60	4.29	5.09	14.76	34.70	65.40
56-106	45.20	36.40	3.81	10.59	21.60	24.70
106-156	51.50	59.80	47.60	18.79	37.50	37.80
156-206	67.70	75.90	87.90	46.70	57.60	50.10
206-256	71.00	77.40	92.50	98.10	79.30	52.70
256-306	54.40	59.50	69.20	135.90	102.80	44.10
306-315	3.35	3.90	2.90	1.57	1.89	0.93
Current (mA):	4.72	5.74	6.21	14.34	28.50	25.20

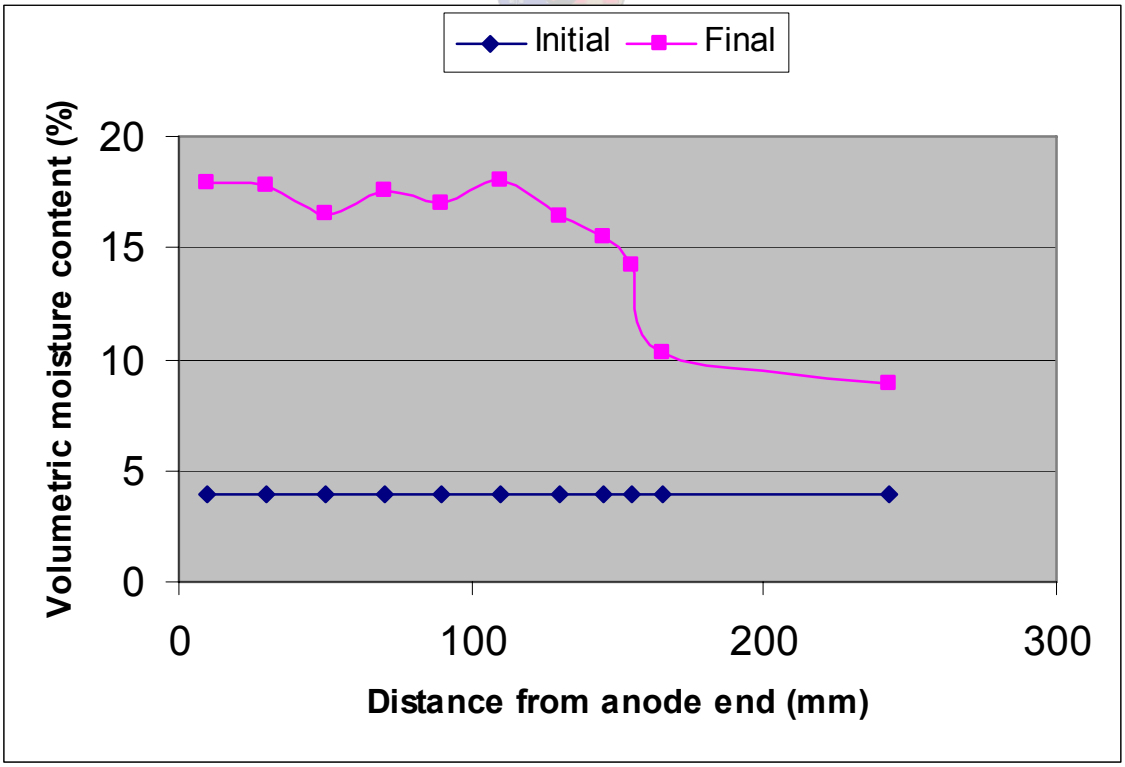
Test no. 21	
Initial moisture:	3.93% by weight
	8.81% by volume

Electric current:	0 mA
Fines:	20%
Treatment period:	23.1 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	20	10	7.98	17.88	6.5	13.2	6.7
2	20	30	7.93	17.77	4.6	9.2	4.6
3	20	50	7.37	16.52	4.4	8.3	3.9
4	20	70	7.82	17.52	3.8	7.6	3.8
5	20	90	7.58	16.99	5.1	9.8	4.7
6	20	110	8.03	18.00	4.1	8.4	4.3
7	20	130	7.35	16.47	4.7	8.7	4.1
8	10	145	6.92	15.51	2.8	4.9	2.1
9	10	155	6.35	14.22	4.1	6.6	2.5
10	10	165	4.61	10.34	4.7	5.5	0.8
11	145	242.5	3.97	8.90	28.6	28.9	0.3

Wetting front:	
Time (min)	Length (mm)
44	39
231	75
299	86
383	97
1386	162

Constant (x^2/t):	19
Incremental velocity (mm/min):	0.065



Test no. 22	
Initial moisture:	3.59% by weight
	7.79% by volume

Electric current:	15 mA
Fines:	20%
Treatment period:	47.8 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	315	157.5	8.62	18.68	63.5	152.4	88.9
						Reservoir	13.8

Wetting front:	
Time (min)	Length (mm)
46	44
231	102
306	119
391	138
460	153
1167	280

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.180

Volt readings (V):						
Time (hours):	0.0	0.7	3.9	7.3	19.5	42.5
Interval (mm): 0-6		4.04	3.95	3.57	3.15	
6-56		18.41	12.41	12.96	12.47	
56-106		29.90	11.72	9.67	10.71	
106-156		30.90	31.20	14.59	17.21	
156-206		41.70	41.60	43.30	23.70	
206-256		37.30	38.50	40.70	20.50	
256-306		35.50	34.10	35.70	28.50	
306-315		2.76	2.70	2.57	2.00	
Current (mA):	15.25	16.50	16.44	15.70	16.63	16.85

Test no. 23	
Initial moisture:	3.43% by weight
	7.50% by volume

Electric current:	25 mA
Fines:	20%
Treatment period:	66.3 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	315	157.5	7.77	17.00	64.1	145.3	81.2
						Reservoir	44.6

Wetting front:	
Time (min)	Length (mm)
53	54
230	93
293	106
377	121
1161	231

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.140

Volt readings (V):						
Time (hours):	0.0	0.7	3.8	7.3	19.4	42.5
Interval (mm): 0-6		9.69	8.34	7.46	6.10	
6-56		20.60	15.13	16.08	20.60	
56-106		57.70	34.90	31.50	35.30	
106-156		57.00	55.10	52.40	36.70	
156-206		36.20	33.50	34.90	28.00	
206-256		43.70	39.20	39.50	35.90	
256-306		48.70	49.10	51.10	43.40	
306-315		3.10	2.45	1.95	1.10	
Current (mA):	25.00	26.80	25.50	25.60	25.60	25.20

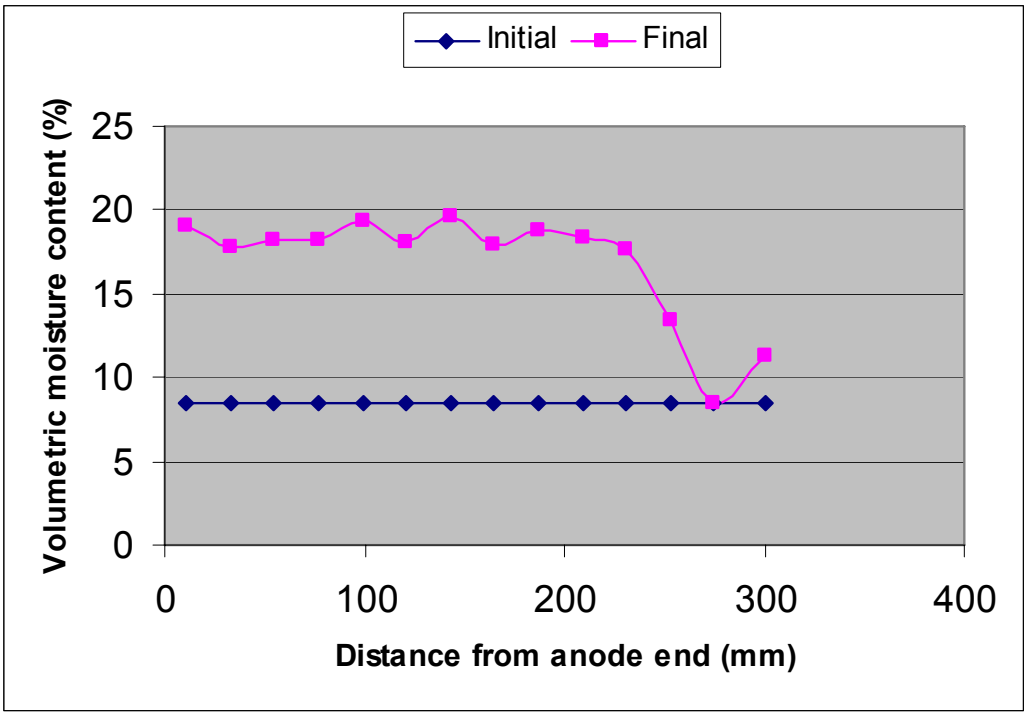
Test no. 24	
Initial moisture:	3.91% by weight
	8.49% by volume

Electric current:	0 mA
Fines:	25%
Treatment period:	23.4 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	22	11	8.79	19.07	4.9	11.1	6.2
2	22	33	8.20	17.79	5.6	11.7	6.1
3	22	55	8.39	18.21	3.9	8.4	4.5
4	22	77	8.42	18.27	5.8	12.5	6.7
5	22	99	8.95	19.42	4.5	10.3	5.8
6	22	121	8.34	18.10	6.0	12.7	6.7
7	22	143	9.07	19.68	5.1	11.9	6.8
8	22	165	8.26	17.93	4.6	9.8	5.2
9	22	187	8.68	18.84	5.6	12.5	6.9
10	22	209	8.48	18.40	4.0	8.7	4.7
11	22	231	8.12	17.62	4.7	9.7	5.0
12	22	253	6.16	13.36	5.0	7.8	2.8
13	22	275	3.91	8.48	5.6	5.6	0.0
14	29	300.5	5.22	11.33	6.2	8.3	2.1
						Outflow	2.1

Wetting front:	
Time (min)	Length (mm)
45	50
109	73
222	83
289	97
395	119
707	165
1402	244

Constant (x^2/t):	42
Incremental velocity (mm/min):	0.114



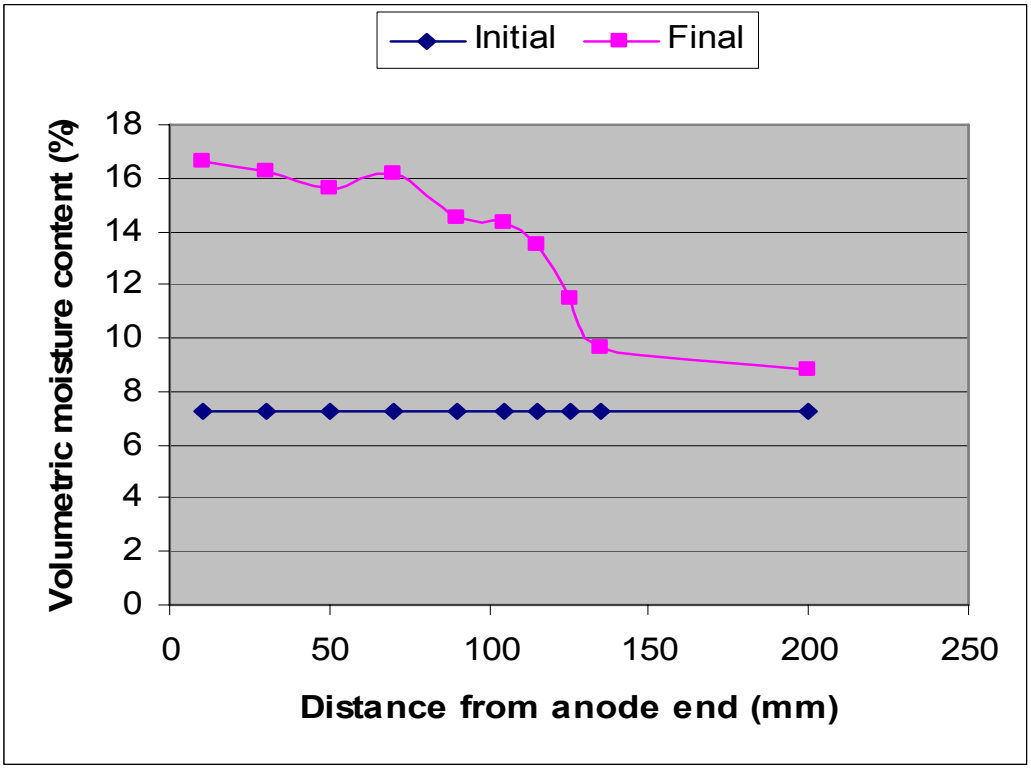
Test no. 25	
Initial moisture:	3.45% by weight
	7.28% by volume

Electric current:	0 mA
Fines:	30%
Treatment period:	73.6 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	20	10	7.90	16.67	3.2	7.3	4.1
2	20	30	7.72	16.29	4.6	10.2	5.6
3	20	50	7.39	15.59	3.3	7.0	3.7
4	20	70	7.66	16.16	4.4	9.7	5.3
5	20	90	6.90	14.56	2.9	5.7	2.9
6	10	105	6.79	14.33	3.7	7.3	3.6
7	10	115	6.41	13.52	2.6	4.8	2.2
8	10	125	5.46	11.51	2.0	3.1	1.1
9	10	135	4.56	9.63	2.7	3.6	0.9
10	120	200	4.17	8.80	20.9	25.3	4.4

Wetting front:	
Time (min)	Length (mm)
33	43
47	44
340	65
443	72
565	78
1171	89
1455	93
1965	99
2646	106
4106	121

Constant (x^2/t):	4
Incremental velocity (mm/min):	0.010



Test no. 26	
Initial moisture:	4.03% by weight
	8.80% by volume

Electric current:	15 mA
Fines:	30%
Treatment period:	92.1 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	315	157.5	8.40	18.37	74.7	156.0	81.3
						Reservoir	16.5

Wetting front:	
Time (min)	Length (mm)
26	34
103	51
168	60
410	83
450	86
627	97
1282	142
1635	168
1943	191
2670	245

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.074

Volt readings (V):						
Time (hours):	0.0	0.4	6.9	19.2	32.4	44.5
Interval (mm): 0-6		5.93	5.94	7.06	6.46	4.87
6-56		12.53	10.19	12.65	14.49	16.54
56-106		22.10	18.31	14.70	14.33	13.84
106-156		24.60	25.80	18.51	17.45	17.58
156-206		17.00	16.96	17.45	14.93	13.29
206-256		23.30	23.80	24.80	25.70	21.60
256-306		18.10	17.73	16.97	13.37	10.35
306-315		3.21	0.06	1.35	0.19	1.09
Current (mA):	15.69	16.41	16.90	16.60	16.90	16.79

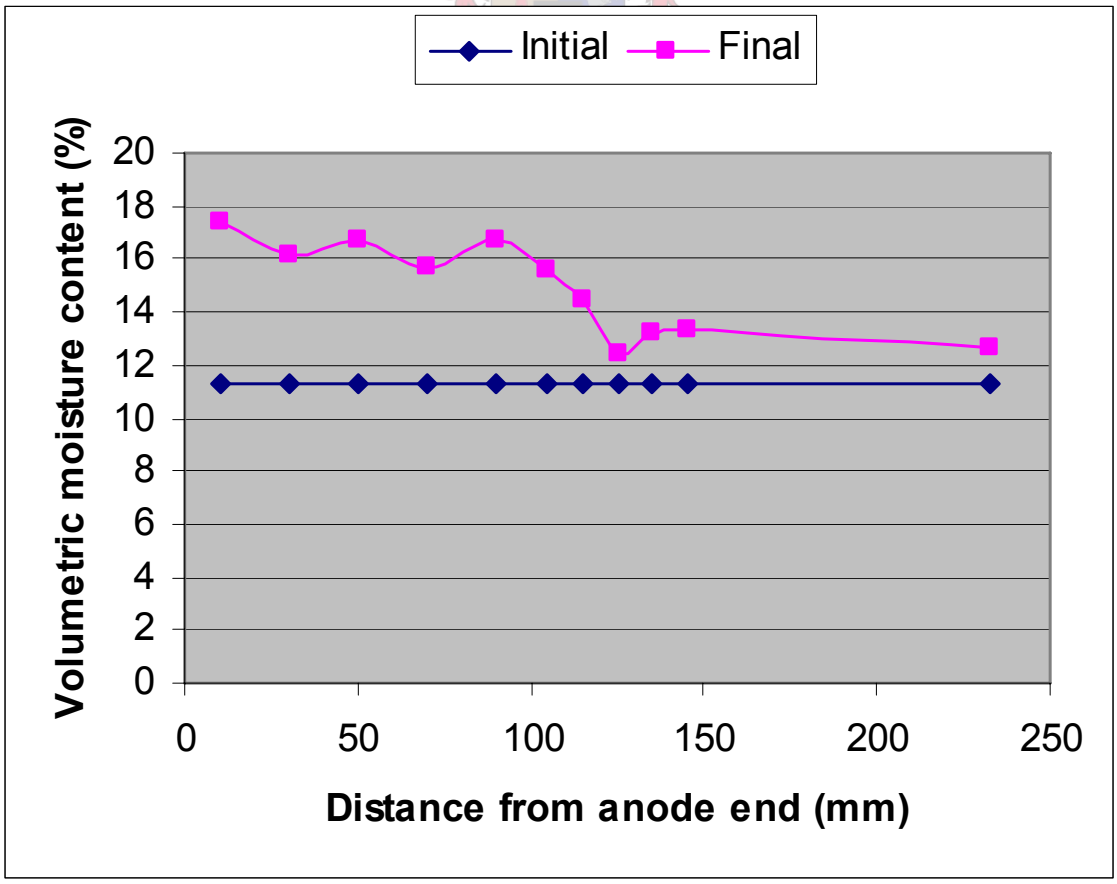
Test no. 27	
Initial moisture:	4.96% by weight
	11.33% by volume

Electric current:	0 mA
Fines:	30%
Treatment period:	110.3 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	20	10	7.60	17.38	4.7	7.2	2.5
2	20	30	7.06	16.15	4.9	7.0	2.1
3	20	50	7.30	16.69	7.1	10.4	3.3
4	20	70	6.86	15.68	5.3	7.4	2.1
5	20	90	7.33	16.77	4.5	6.6	2.1
6	10	105	6.82	15.60	3.4	4.7	1.3
7	10	115	6.32	14.46	7.6	9.7	2.1
8	10	125	5.43	12.41	3.9	4.3	0.4
9	10	135	5.78	13.21	3.6	4.2	0.6
10	10	145	5.83	13.33	3.9	4.6	0.7
11	165	232.5	5.54	12.67	45.5	50.9	5.4

Wetting front:	
Time (min)	Length (mm)
127	29
295	51
1603	88
4071	124

Constant (x^2/t):	4
Incremental velocity (mm/min):	0.015



Test no. 28	
Initial moisture:	4.96% by weight
	11.18% by volume

Electric current:	15 mA
Fines:	30%
Treatment period:	187.7 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	315	157.5	7.84	17.69	92.1	145.8	53.7
						Reservoir	1.0

Wetting front:	
Time (min)	Length (mm)
62	35
131	67
859	110
1176	129

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.060

Volt readings (V):						
Time (hours):	0.0	1.0	5.0	14.7	21.4	
Interval (mm): 0-6		5.76	6.32	4.28	4.45	
6-56		*	23.80	*	25.00	
56-106		*	*	*	*	
106-156		15.81	16.37	16.64	15.60	
156-206		14.83	15.05	15.28	14.63	
206-256		16.50	16.75	17.21	16.98	
256-306		13.39	13.93	13.65	13.33	
306-315		3.84	2.93	1.74	1.34	
Current (mA):	15.10	16.10	15.20	15.00	15.11	

Pectora roborant cultus recti

Test no. 29	
Initial moisture:	4.96% by weight
	11.37% by volume

Electric current:	25 mA
Fines:	30%
Treatment period:	158.9 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	315	157.5	7.44	17.08	95.8	143.9	48.1
						Reservoir	9.6

Wetting front:	
Time (min)	Length (mm)
58	77
130	79
295	82

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.018

Volt readings (V):						
Time (hours):	0.0	1.0	5.1	14.7		
Interval (mm): 0-6		6.04	6.67	4.89		
6-56		17.38	19.55	24.10		
56-106		*	44.20	*		
106-156		*	*	*		
156-206		*	45.40	*		
206-256		*	*	*		
256-306		19.32	20.00	23.40		
306-315		4.22	3.24	2.80		
Current (mA):	25.20	26.90	26.00	26.10		

Pectora roborant cultus recti

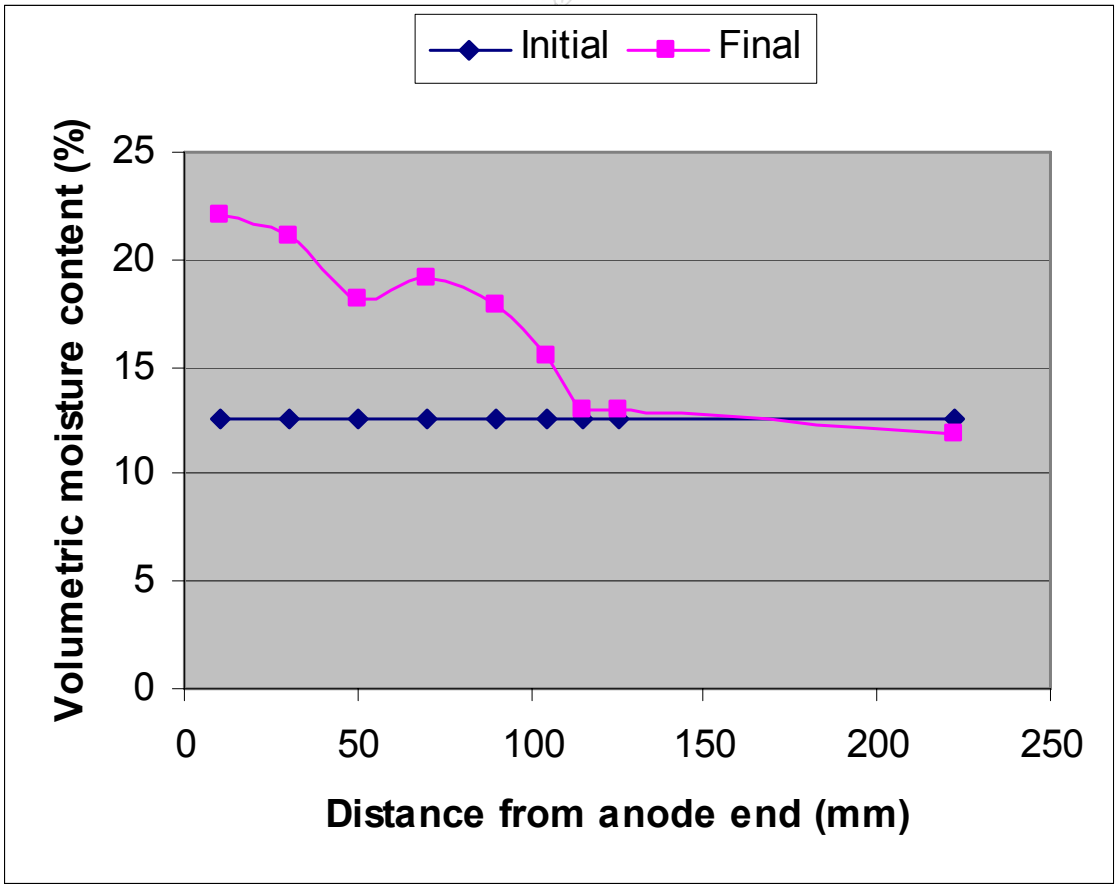
Test no. 30	
Initial moisture:	5.96% by weight
	12.59% by volume

Electric current:	0 mA
Fines:	40%
Treatment period:	124.9 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	20	10	10.42	22.01	5.0	8.7	3.7
2	20	30	10.00	21.12	6.9	11.6	4.7
3	20	50	8.59	18.13	5.5	7.9	2.4
4	20	70	9.09	19.20	4.7	7.2	2.5
5	20	90	8.44	17.83	5.4	7.7	2.3
6	10	105	7.35	15.52	2.3	2.8	0.5
7	10	115	6.17	13.02	4.1	4.2	0.1
8	10	125	6.17	13.03	5.2	5.3	0.2
9	185	222.5	5.60	11.82	66.2	62.2	-4.0

Wetting front:	
Time (min)	Length (mm)
50	24
3104.4	78.7

Constant (x^2/t):	2
Incremental velocity (mm/min):	0.018



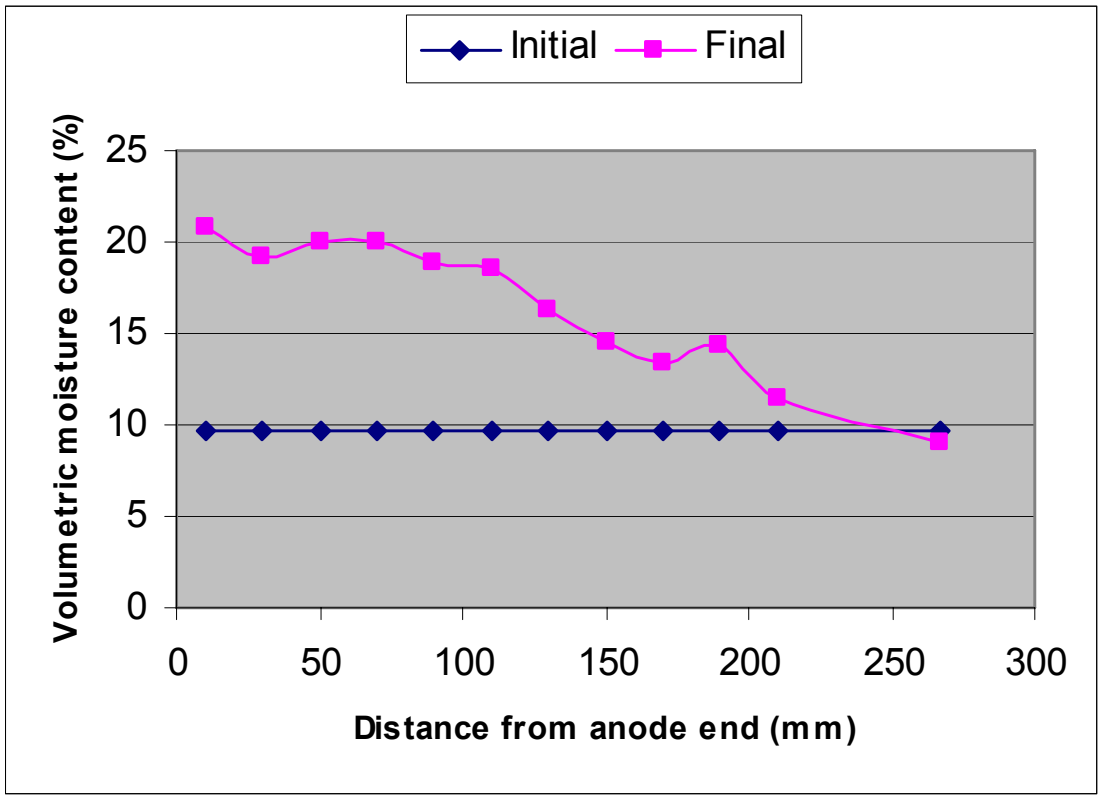
Test no. 31	
Initial moisture:	4.50% by weight
	9.72% by volume

Electric current:	0 mA
Fines:	50%
Treatment period:	172.3 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	20	10	9.60	20.74	5.9	12.6	6.7
2	20	30	8.87	19.16	5.8	11.3	5.6
3	20	50	9.24	19.96	5.2	10.7	5.5
4	20	70	9.25	19.99	3.6	7.5	3.9
5	20	90	8.73	18.86	5.3	10.2	5.0
6	20	110	8.60	18.58	2.9	5.6	2.7
7	20	130	7.55	16.31	6.1	10.3	4.2
8	20	150	6.75	14.58	3.9	5.8	1.9
9	20	170	6.23	13.46	3.0	4.1	1.1
10	20	190	6.68	14.43	4.7	7.0	2.3
11	20	210	5.30	11.45	2.8	3.3	0.5
12	95	267.5	4.18	9.03	31.7	29.5	-2.2

Wetting front:	
Time (min)	Length (mm)
85	27
137	33
240	46
379	55
1391	88
5037	140
8723	180

Constant (x^2/t):	4
Incremental velocity (mm/min):	0.011



Test no. 32	
Initial moisture:	4.50% by weight
	9.84% by volume

Electric current:	15 mA
Fines:	50%
Treatment period:	168.2 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	315	157.5	7.73	16.90	82.1	141.1	58.9
						Reservoir	3.9

Wetting front:	
Time (min)	Length (mm)
137	40
240	66
376	84
1397	131
3593	220

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.041

Volt readings (V):						
Time (hours):	0.0	35.9				
Interval (mm): 0-6						
6-56						
56-106						
106-156						
156-206						
206-256						
256-306						
306-315						
Current (mA):	15.10	15.92				

Pectora roborant cultus recti

Test no. 33	
Initial moisture:	4.50% by weight
	9.57% by volume

Electric current:	25 mA
Fines:	50%
Treatment period:	143.7 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	315	157.5	8.17	17.37	80.4	146.0	65.6
						Reservoir	13.9

Wetting front:	
Time (min)	Length (mm)
76	46
128	91
231	111
1383	169

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.050

Volt readings (V):						
Time (hours):	0.0	35.8				
Interval (mm): 0-6						
6-56						
56-106						
106-156						
156-206						
206-256						
256-306						
306-315						
Current (mA):	25.00	26.90				

Pectora roborant cultus recti

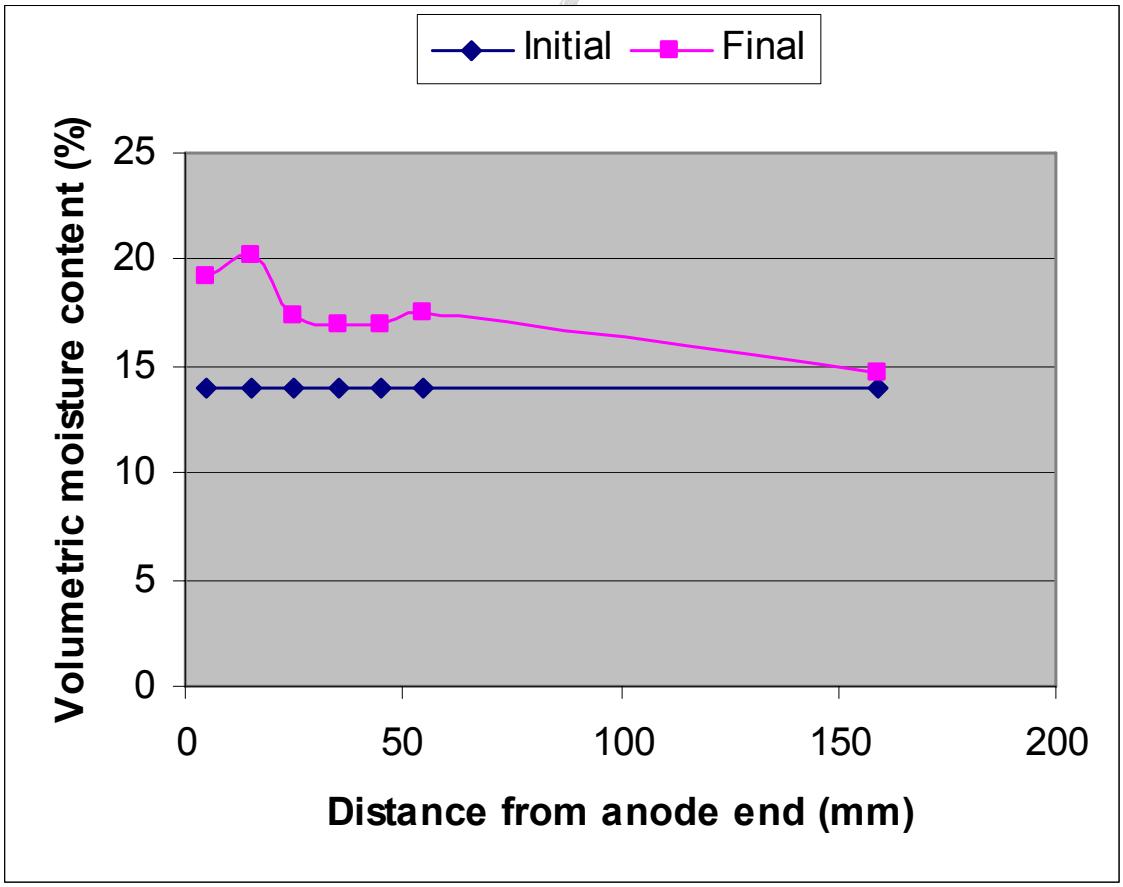
Test no. 34	
Initial moisture:	6.50% by weight
	13.96% by volume

Electric current:	0 mA
Fines:	50%
Treatment period:	235.6 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	10	5	8.96	19.24	3.6	5.0	1.4
2	10	15	9.41	20.20	4.8	7.0	2.2
3	10	25	8.10	17.39	3.9	4.9	1.0
4	10	35	7.88	16.92	7.0	8.5	1.5
5	10	45	7.86	16.88	4.0	4.8	0.8
6	10	55	8.14	17.48	4.2	5.3	1.1
7	199	159.5	6.81	14.63	67.4	70.6	3.2

Wetting front:	
Time (min)	Length (mm)
65	24
115	25
1363	51

Constant (x^2/t):	2
Incremental velocity (mm/min):	0.021



Test no. 35	
Initial moisture:	6.50% by weight
	14.27% by volume

Electric current:	15 mA
Fines:	50%
Treatment period:	116.1 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	315	157.5	7.68	16.86	116.6	137.8	21.2
						Reservoir	6.9

Wetting front:	
Time (min)	Length (mm)
62	41
113	42

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.020

Volt readings (V):						
Time (hours):	0.0	22.7	43.1			
Interval (mm): 0-6						
6-56						
56-106						
106-156						
156-206						
206-256						
256-306						
306-315						
Current (mA):	15.03	16.50	15.60			

Pectora roborant cultus recti

Test no. 36	
Initial moisture:	6.50% by weight
	14.08% by volume

Electric current:	25 mA
Fines:	50%
Treatment period:	380.0 hours

Section no.	Length (mm)	Centre (mm)	ω (%)	θ (%)	Water mass Initial (g)	Final (g)	Change (g)
1	315	157.5	9.43	20.42	118.0	171.1	53.1
						Reservoir	2.6

Wetting front:	
Time (min)	Length (mm)
68	54
117	65
1356	100
2584	154

Constant (x^2/t):	N/A
Incremental velocity (mm/min):	0.044

Volt readings (V):						
Time (hours):	0.0	22.7	43.1			
Interval (mm): 0-6						
6-56						
56-106						
106-156						
156-206						
206-256						
256-306						
306-315						
Current (mA):	25.20	27.10	25.20			

Pectora roborant cultus recti

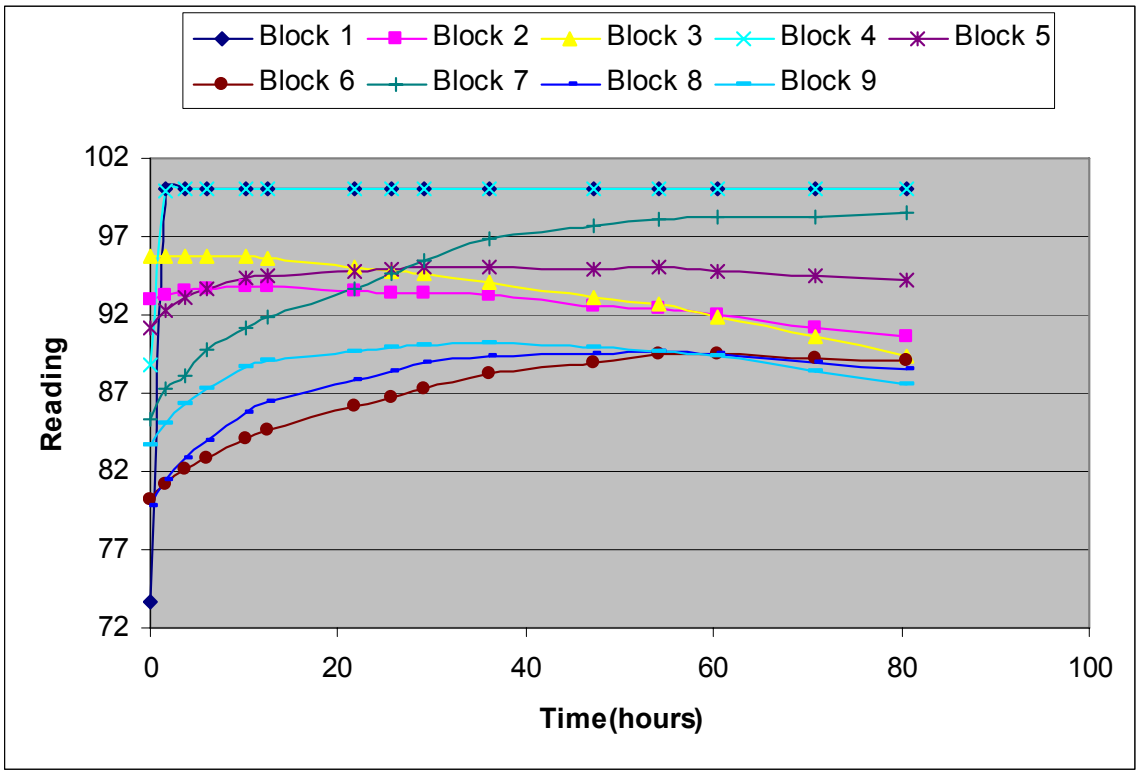
Appendix C RESULTS FROM TWO-DIMENSIONAL TESTS

Pectora roborant cultus recti

Test no. 1	
Aimed moisture:	8.00% by weight
True moisture:	8.76% by weight

Electric current:	0 mA
Fines:	30%
Treatment period:	3 days

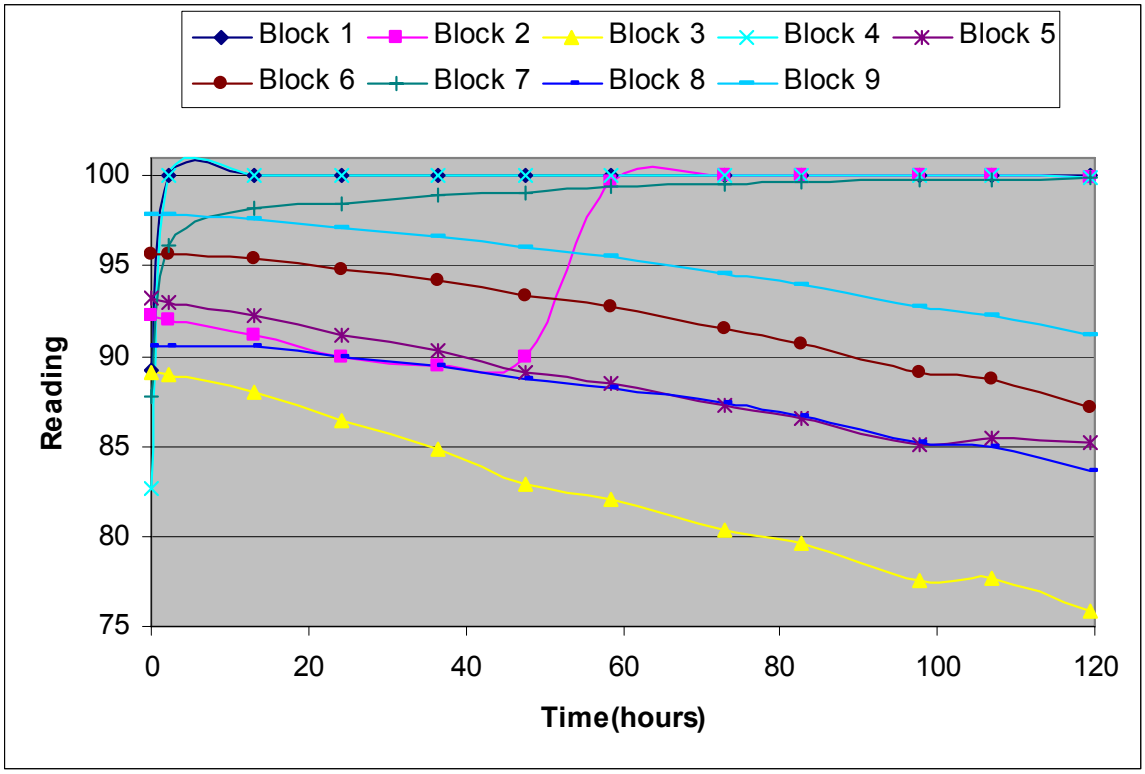
Area no.	ω (%)
1	13.55
2	8.15
3	8.17
4	12.21
5	8.20
6	8.19
7	10.73
8	9.02
9	8.03



Test no. 2	
Aimed moisture:	8.00% by weight
True moisture:	7.01% by weight

Electric current:	0 mA
Fines:	30%
Treatment period:	5 days

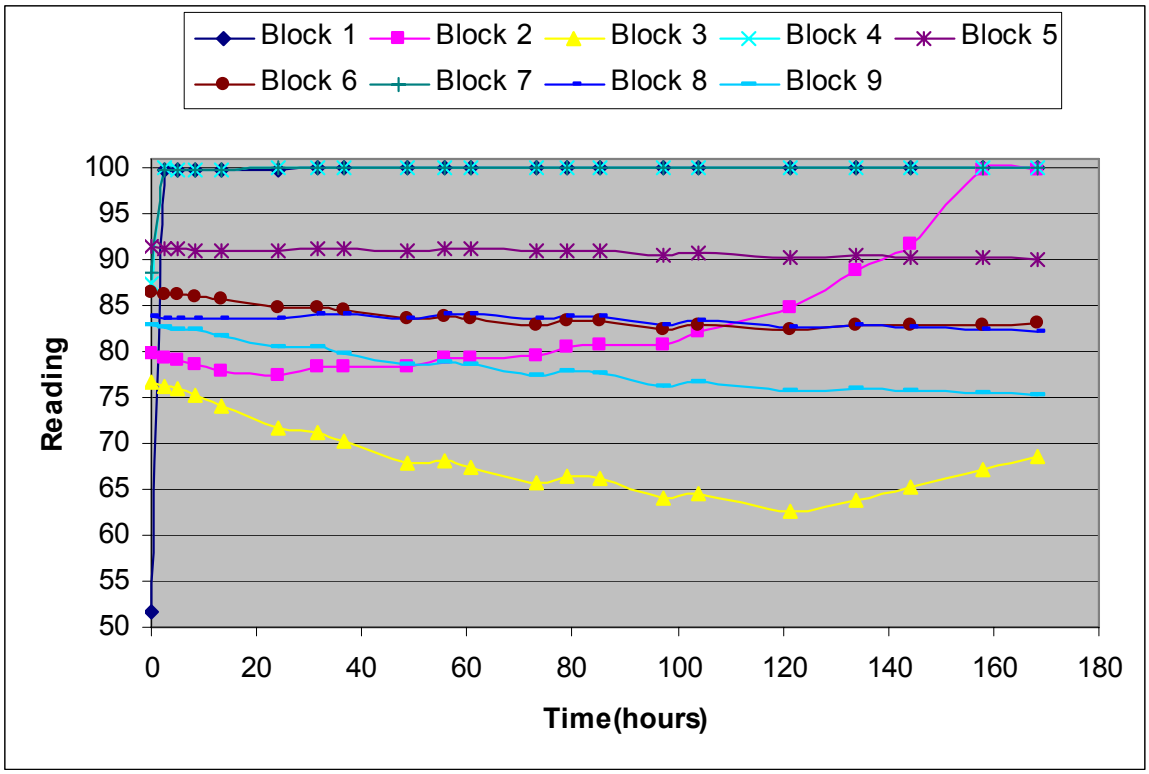
Area no.	ω (%)
1	18.29
2	8.50
3	6.83
4	13.75
5	8.42
6	7.06
7	15.37
8	7.62
9	7.11



Test no. 3	
Aimed moisture:	8.00% by weight
True moisture:	7.66% by weight

Electric current:	0 mA
Fines:	30%
Treatment period:	7 days

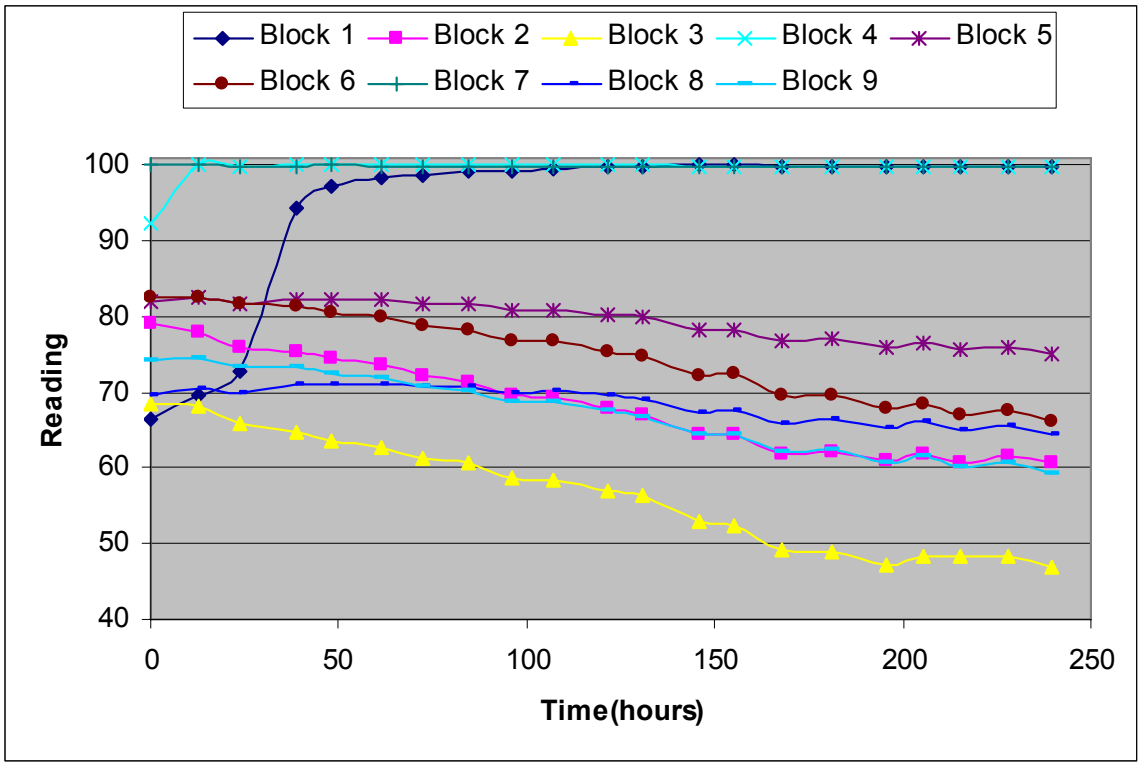
Area no.	ω (%)
1	19.23
2	8.80
3	7.73
4	17.44
5	8.70
6	7.86
7	16.23
8	8.00
9	9.05



Test no. 4	
Aimed moisture:	8.00% by weight
True moisture:	8.34% by weight

Electric current:	0 mA
Fines:	30%
Treatment period:	10 days

Area no.	ω (%)
1	16.29
2	8.97
3	8.05
4	15.37
5	9.10
6	8.64
7	13.86
8	8.09
9	8.67



Test no. 5	
Aimed moisture:	8.00% by weight
True moisture:	8.51% by weight

Electric current:	0 mA
Fines:	30%
Treatment period:	15 days

Area no.	**ω (%)**
1	19.30
2	10.24
3	8.31
4	17.30
5	8.85
6	9.04
7	16.50
8	8.90
9	8.71

Pectora roborant cultus recti

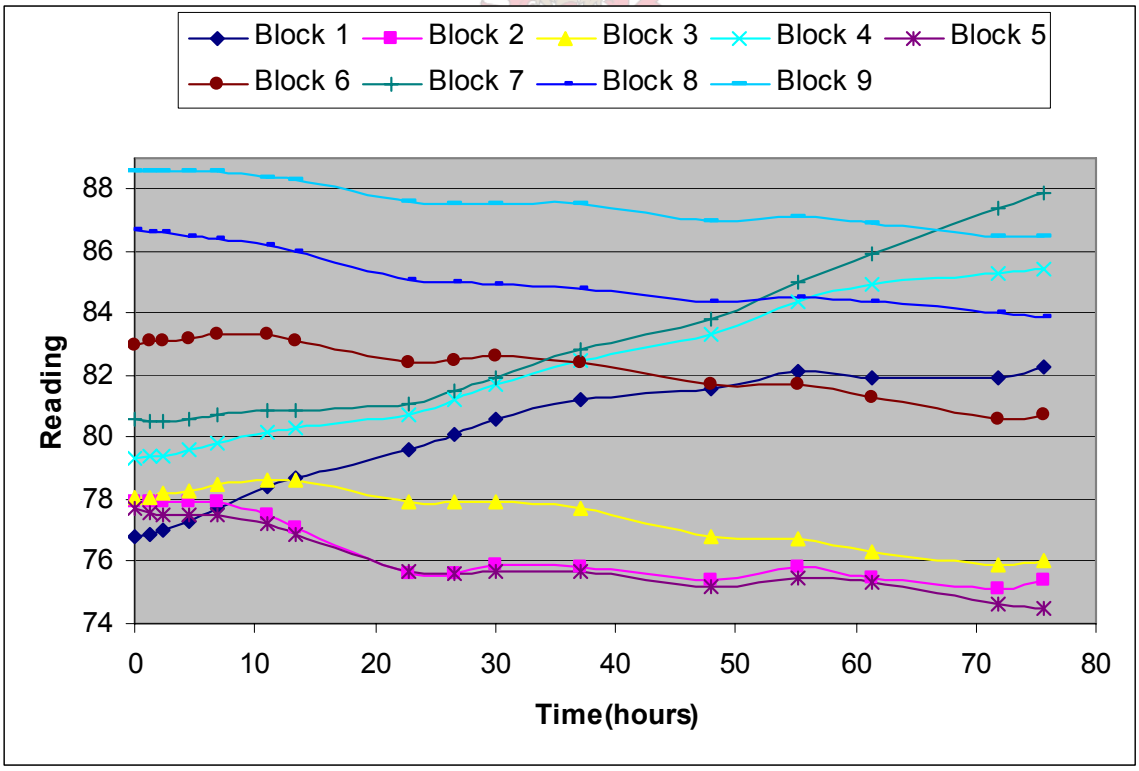
Test no. 6	
Aimed moisture:	8.00% by weight
True moisture:	8.95% by weight

Electric current:	70 mA
Fines:	30%
Treatment period:	3 days

Area no.	ω (%)
1	14.30
2	8.46
3	7.95
4	13.10
5	9.15
6	8.59
7	10.39
8	9.69
9	8.19

Time (days)	Reservoir (g)
3.1	0.0
	0.0

Time (hours)	Current (mA)	Volts (V)	Total energy consumption (Wh)
0.00	70	23	
2.42	70	19	
4.55	70	18	
6.83	70	17	
11.05	70	15	
13.37	70	17	
22.85	70	18	29.020
26.67	70	18	
30.05	70	22	
37.08	70	21	
47.92	70	20	35.532
55.12	70	18	
61.30	70	20	
71.80	70	20	
75.73	70	17	36.509
			101.061



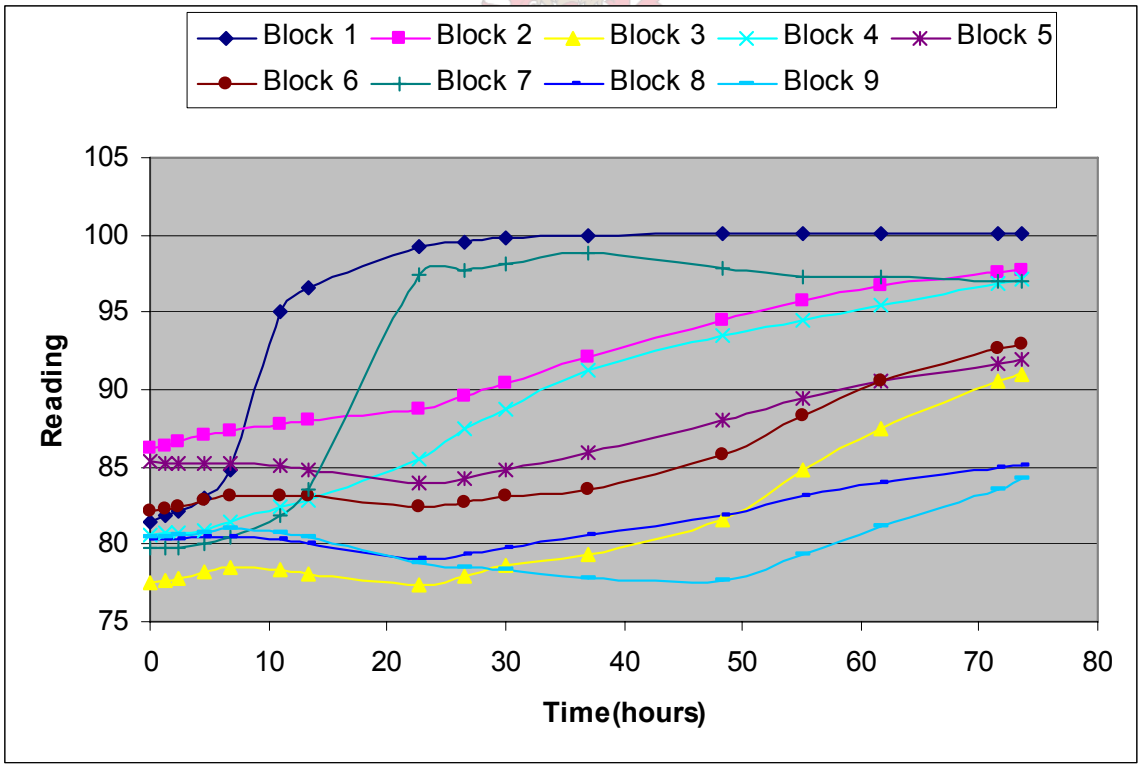
Test no. 7	
Aimed moisture:	8.00% by weight
True moisture:	8.95% by weight

Electric current:	150 mA
Fines:	30%
Treatment period:	3 days

Area no.	ω (%)
1	18.20
2	11.14
3	7.96
4	14.23
5	9.57
6	8.31
7	12.60
8	8.87
9	8.61

Time (days)	Reservoir (g)
2.1	24.9
3.0	42.3
	67.2

Time (hours)	Current (mA)	Volts (V)	Total energy consumption (Wh)
0.00	150	50	
2.40	150	41	
4.52	150	39	
6.72	150	35	
11.05	150	35	
13.37	150	34	
22.72	150	35	130.945
26.58	150	35	
29.98	150	35	
37.07	150	33	
48.35	150	33	130.730
55.03	150	32	
61.63	150	31	
71.67	150	32	
73.53	150	32	119.936
			381.611



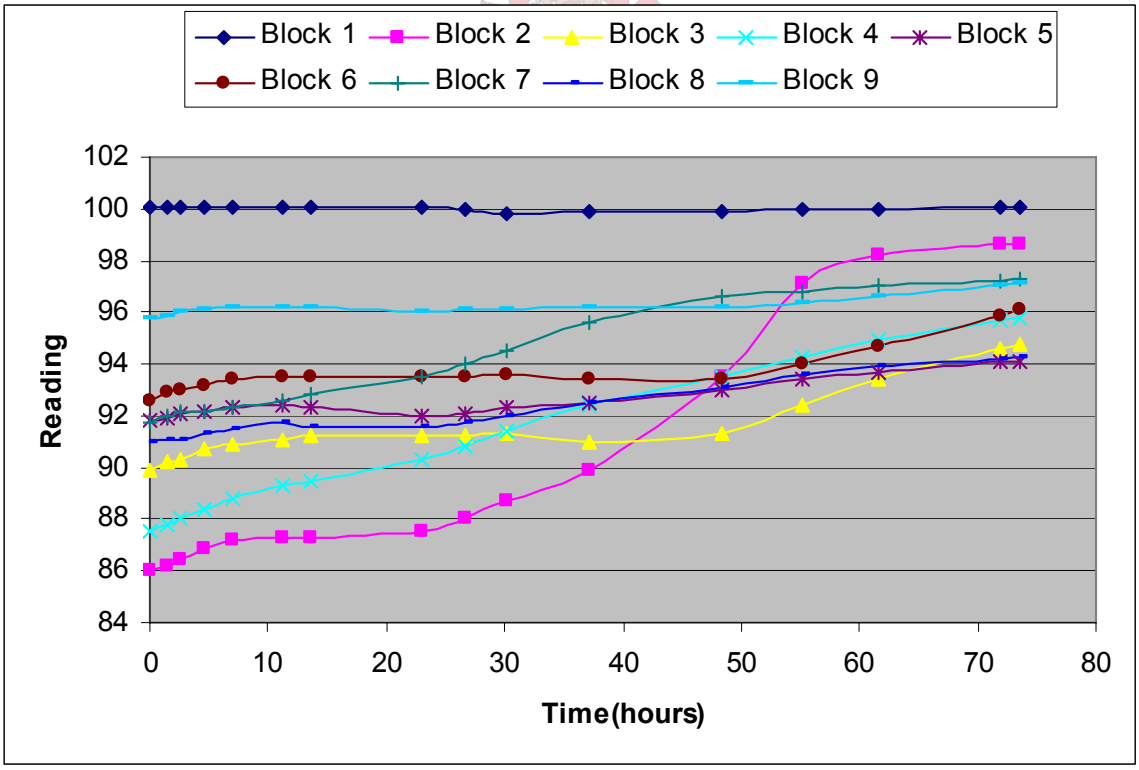
Test no. 8	
Aimed moisture:	8.00% by weight
True moisture:	8.95% by weight

Electric current:	200 mA
Fines:	30%
Treatment period:	3 days

Area no.	ω (%)
1	18.20
2	11.14
3	7.96
4	14.23
5	9.57
6	8.31
7	12.60
8	8.87
9	8.61

Time (days)	Reservoir (g)
1.6	79.1
2.1	64.3
3.0	119.8
	263.2

Time (hours)	Current (mA)	Volts (V)	Total energy consumption (Wh)
0.00	200	63	
2.55	200	51	
4.68	200	45	
6.97	200	41	
11.22	200	40	
13.53	200	41	
22.90	200	42	211.334
26.73	200	45	
30.12	200	43	
37.20	200	42	
48.37	200	45	222.833
55.17	200	46	
61.67	200	47	
71.85	200	47	
73.52	200	47	235.153
			669.320



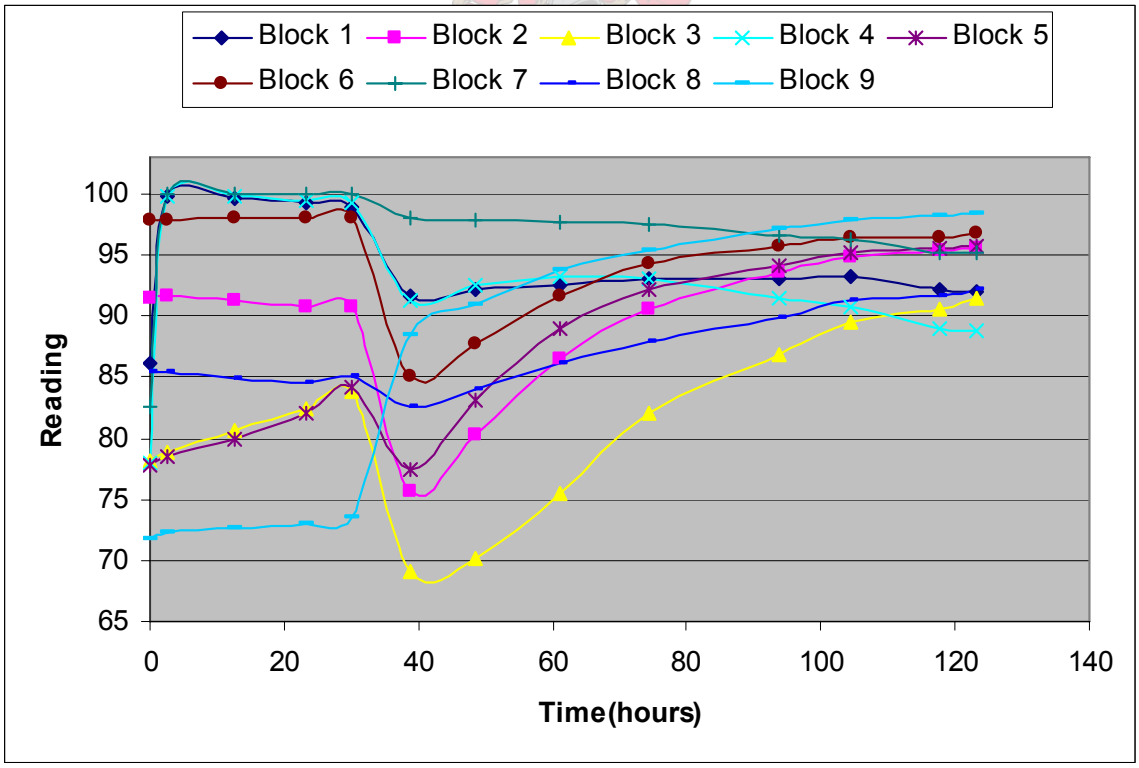
Test no. 9	
Aimed moisture:	8.00% by weight
True moisture:	8.03% by weight

Electric current:	200 mA
Fines:	30%
Treatment period:	5 days

Area no.	ω (%)
1	12.90
2	10.20
3	7.23
4	10.80
5	7.77
6	7.43
7	10.30
8	7.87
9	7.71

Time (days)	Reservoir (g)
1.0	23.7
2.0	80.1
3.1	87.1
3.9	58.3
5.1	85.3
	334.5

Time (hours)	Current (mA)	Volts (V)	Total energy consumption (Wh)
0.00	200	33	
12.60	200	25	
23.13	200	24	126.462
30.02	200	25	
38.88	200	35	
48.63	200	35	161.500
61.22	200	36	
74.52	200	38	191.5366667
93.68	200	40	
104.48	200	40	239.7333333
117.63	200	42	
123.27	200	43	159.6583333
			878.891



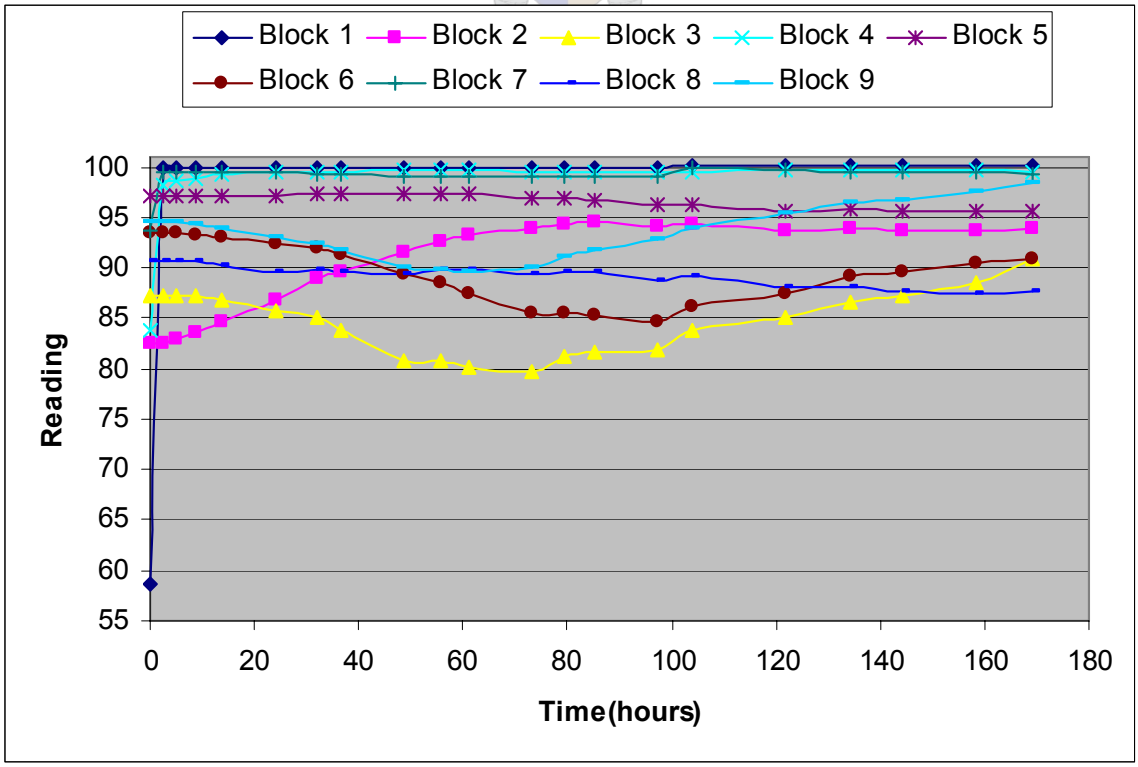
Test no. 10	
Aimed moisture:	8.00% by weight
True moisture:	8.04% by weight

Electric current:	200 mA
Fines:	30%
Treatment period:	7 days

Area no.	ω (%)
1	13.78
2	10.11
3	8.47
4	11.25
5	8.95
6	8.51
7	10.90
8	7.57
9	8.67

Time (days)	Reservoir (g)
1.0	45.7
2.0	114.1
3.0	121.2
4.1	118.0
5.1	112.6
6.0	105.7
7.0	108.1
	725.4

Time (hours)	Current (mA)	Volts (V)	Total energy consumption (Wh)
0.00	200	42	
2.62	200	39	
5.03	200	33	
8.53	200	33	
13.82	200	34	
24.32	200	38	177.512
32.08	200	39	
36.68	200	40	
48.83	200	41	196.133
55.83	200	41	
61.12	200	41	
73.23	200	43	203.333
79.32	200	43	
85.27	200	44	
97.13	200	48	215.100
104.05	200	46	
121.65	200	49	232.908
134.1	200	50	
144.4	200	51	229.775
158.3	200	52	
169.1	200	56	266.220
			1520.982



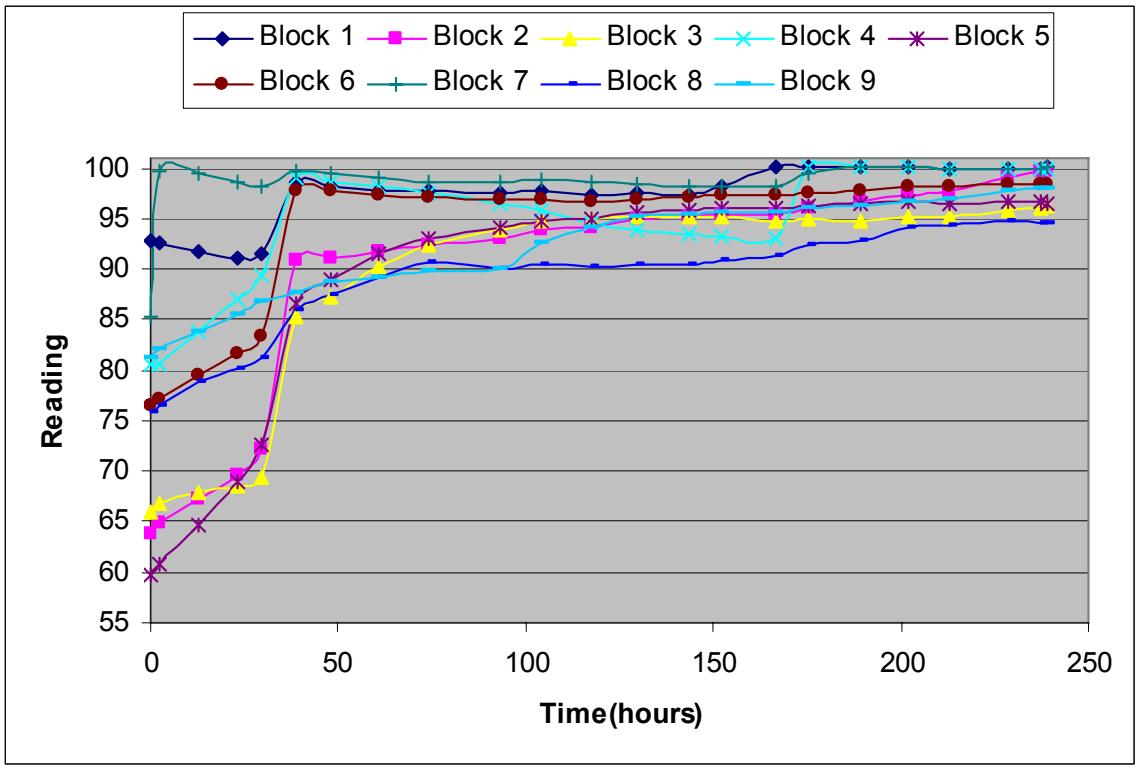
Test no. 11	
Aimed moisture:	8.00% by weight
True moisture:	7.73% by weight

Electric current:	200 mA
Fines:	30%
Treatment period:	10 days

Area no.	ω (%)
1	14.66
2	11.93
3	7.05
4	12.40
5	8.60
6	7.53
7	11.62
8	7.58
9	8.85

Time (days)	Reservoir (g)
2.0	86.5
3.1	137.6
3.9	84.3
5.4	138.5
6.3	90.1
7.3	91.3
7.9	60.1
8.9	82.8
10.0	81.1
	852.3

Time (hours)	Current (mA)	Volts (V)	Total energy consumption (Wh)
0.00	200	40	
2.30	200	38	
12.60	200	34	
23.23	200	34	169.603
29.72	200	34	
38.55	200	32	
48.32	200	33	165.550
60.92	200	33	
74.33	200	36	179.515
93.37	200	38	144.653
104.18	200	39	
117.48	200	40	190.522
129.58	200	39	
143.77	200	40	207.638
152.05	200	40	
166.38	200	42	185.457
175.50	200	44	
189.18	200	44	200.640
202.05	200	45	
213.03	200	48	221.805
228.42	200	45	
237.17	200	45	
238.85	200	44	230.629
			1896.012



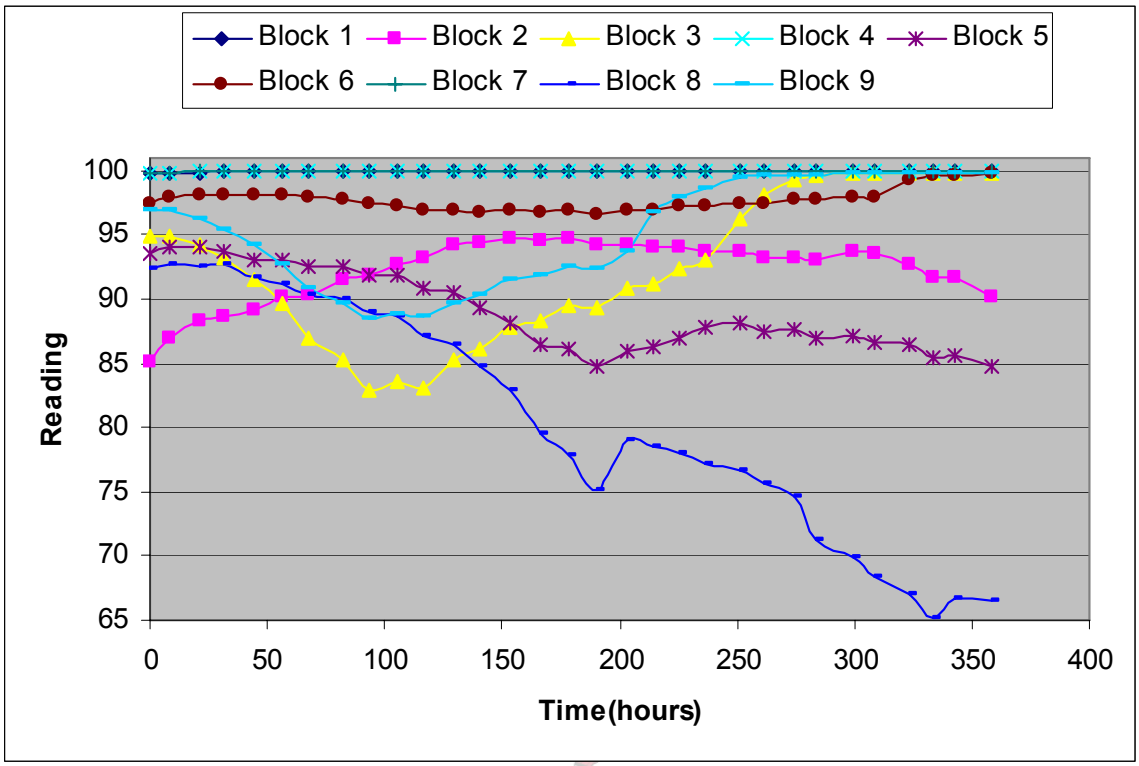
Test no. 12	
Aimed moisture:	8.00% by weight
True moisture:	8.83% by weight

Electric current:	200 mA
Fines:	30%
Treatment period:	15 days

Area no.	ω (%)
1	12.63
2	10.30
3	12.45
4	13.73
5	8.03
6	13.47
7	14.15
8	7.73
9	12.53

Time (days)	Reservoir (g)
1.3	48.0
1.8	61.6
2.8	104.5
3.9	117.3
4.9	110.9
5.9	110.2
6.9	117.9
7.4	51.2
8.9	121.5
9.9	85.7
10.9	87.1
11.8	74.7
12.8	71.0
13.9	64.3
15.0	52.5
	1278.4

Time (hours)	Current (mA)	Volts (V)	Total energy consumption (Wh)
0.00	200	30	
8.47	200	30	
21.03	200	40	140.222
31.40	200	29	
44.08	200	31	138.300
56.47	200	30	
67.88	200	33	149.940
82.12	200	32	
93.52	200	34	169.180
105.42	200	34	
116.62	200	36	161.700
129.03	200	34	
140.77	200	36	169.050
153.30	200	36	
166.48	200	40	195.447
177.90	200	40	
189.98	200	0	163.200
203.22	200	40	
214.35	200	42	159.627
225.15	200	43	
236.62	200	46	198.173
251.13	200	53	
261.08	200	53	259.347
274.03	200	52	
284.02	200	61	259.147
298.97	200	82	
308.08	200	85	401.913
322.97	200	71	
333.62	200	82	390.660
342.97	200	79	
358.00	200	87	404.763
			3360.669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65
0
50
100
150
200
250
300
350
400
Time(hours)

Test no. 13	
Aimed moisture:	6.00% by weight
True moisture:	5.80% by weight

Electric current:	0 mA
Fines:	30%
Treatment period:	7 days

Area no.	**ω (%)**
1	15.91
2	14.08
3	5.54
4	13.15
5	9.89
6	6.58
7	11.82
8	6.32
9	5.77

Pectora roborant cultus recti

Test no. 14	
Aimed moisture:	6.00% by weight
True moisture:	6.11% by weight

Electric current:	0 mA
Fines:	30%
Treatment period:	10 days

Area no.	**ω (%)**
1	14.52
2	13.97
3	6.60
4	12.66
5	12.82
6	6.70
7	11.52
8	7.20
9	5.80

Pectora roborant cultus recti

Test no. 15	
Aimed moisture:	6.00% by weight
True moisture:	6.14% by weight

Electric current:	0 mA
Fines:	30%
Treatment period:	14 days

Area no.	**ω (%)**
1	15.96
2	14.52
3	7.51
4	13.45
5	12.60
6	6.32
7	13.82
8	8.47
9	5.66

Pectora roborant cultus recti

Test no. 16	
Aimed moisture:	6.00% by weight
True moisture:	5.46% by weight

Electric current:	200 mA
Fines:	30%
Treatment period:	7 days

Area no.	ω (%)
1	16.13
2	13.96
3	12.76
4	14.09
5	11.05
6	12.01
7	12.66
8	8.54
9	11.37

Time (days)	Reservoir (g)
7.0	0.0
	0.0

Time (hours)	Current (mA)	Volts (V)	Total energy consumption (Wh)
0.00	200	104	
13.55	200	88	
23.87	200	83	437.617
39.50	200	81	
46.75	200	79	366.080
62.82	200	72	
73.72	200	73	391.065
85.88	200	66	
96.28	200	63	291.024
111.37	200	58	
121.25	200	55	282.161
133.08	200	50	
144.20	200	50	229.500
155.22	200	45	
168.03	200	43	209.704
			2207.151

Pectora roborant cultus recti

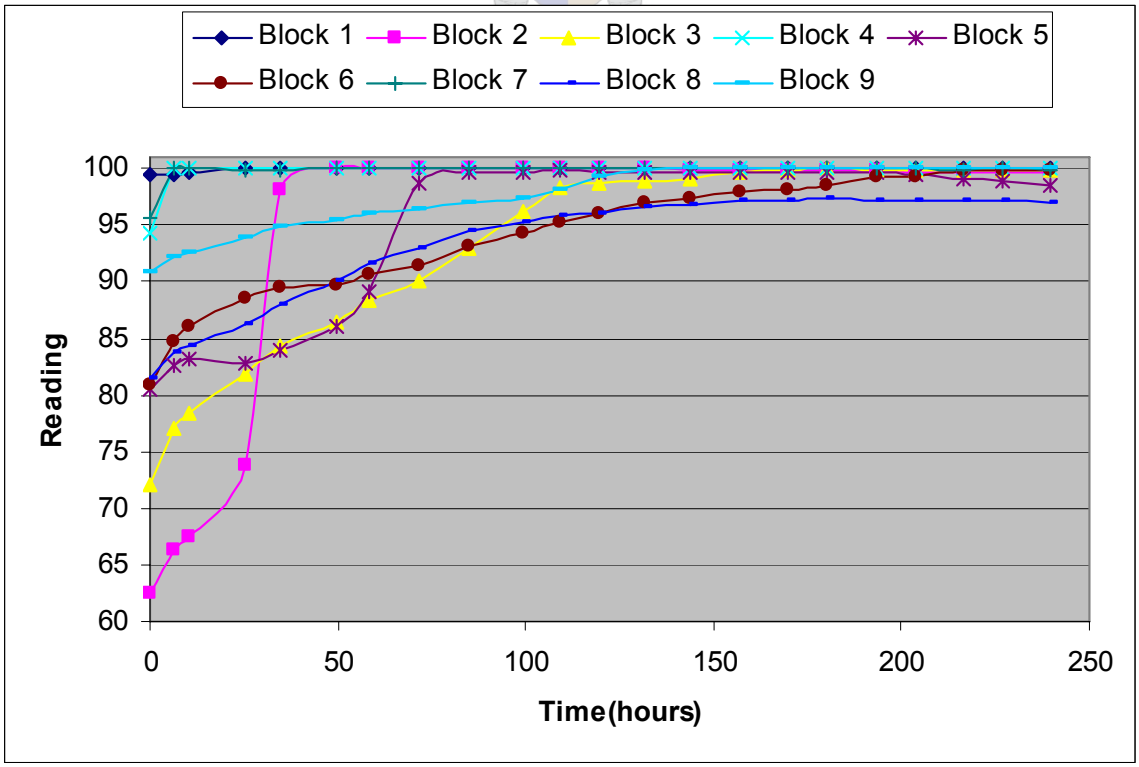
Test no. 17	
Aimed moisture:	6.00% by weight
True moisture:	6.53% by weight

Electric current:	200 mA
Fines:	30%
Treatment period:	10 days

Area no.	ω (%)
1	16.08
2	15.50
3	14.54
4	14.54
5	13.33
6	15.42
7	16.57
8	11.92
9	15.20

Time (days)	Reservoir (g)
9.4	126.0
10.0	26.3
	152.3

Time (hours)	Current (mA)	Volts (V)	Total energy consumption (Wh)
0.00	200	80	
6.22	200	66	
10.48	200	62	
25.13	200	59	335.53
34.67	200	58	
49.68	200	61	292.145
58.52	200	59	
71.65	200	59	259.207
84.95	200	55	
99.13	200	53	296.820
108.95	200	48	
119.33	200	49	195.940
131.53	200	44	107.360
156.77	200	41	
169.58	200	40	308.205
180.25	200	40	
193.17	200	41	191.025
203.83	200	41	
216.25	200	45	198.517
226.75	200	44	
239.43	200	50	217.923
			2402.672



Test no. 18	
Aimed moisture:	6.00% by weight
True moisture:	5.46% by weight

Electric current:	200 mA
Fines:	30%
Treatment period:	15 days

Area no.	ω (%)
1	17.52
2	15.67
3	15.44
4	12.17
5	13.54
6	13.24
7	12.30
8	11.98
9	13.58

Time (days)	Reservoir (g)
9.0	11.0
9.9	44.6
11.0	76.2
12.1	68.1
14.5	68.6
14.9	59.2
	327.7

Time (hours)	Current (mA)	Volts (V)	Total energy consumption (Wh)
0.00	200	107	
9.25	200	80	
22.65	200	79	401.660
37.67	200	75	
47.18	200	77	372.856
60.37	200	73	
70.17	200	73	335.654
85.62	200	68	
93.80	200	64	311.916
119.85	200	53	276.130
143.75	200	51	243.780
155.00	200	49	
166.35	200	49	221.480
181.62	200	48	
191.25	200	49	241.530
205.05	200	48	
216.15	200	51	493.020
229.43	200	49	
238.02	200	51	218.700
252.33	200	50	
262.75	200	53	254.719
276.98	200	56	
289.22	200	63	314.993
325.17	200	60	431.400
334.83	200	71	137.172
347.77	200	73	
358.17	200	81	359.436
			4614.446

Test no. 19	
Aimed moisture:	8.00% by weight
True moisture:	8.39% by weight

Electric current:	0 mA
Fines:	20%
Treatment period:	7 days

Area no.	ω (%)
1	10.04
2	9.16
3	8.08
4	8.28
5	8.10
6	7.89
7	8.69
8	8.19
9	8.22

Pectora roborant cultus recti

Test no. 20	
Aimed moisture:	8.00% by weight
True moisture:	8.45% by weight

Electric current:	0 mA
Fines:	20%
Treatment period:	10 days

Area no.	**ω (%)**
1	10.83
2	9.28
3	9.84
4	8.94
5	8.28
6	8.37
7	9.36
8	8.19
9	8.35

Pectora roborant cultus recti

Test no. 21	
Aimed moisture:	8.00% by weight
True moisture:	7.63% by weight

Electric current:	0 mA
Fines:	20%
Treatment period:	15 days

Area no.	ω (%)
1	8.75
2	8.72
3	8.05
4	8.03
5	8.31
6	7.53
7	8.48
8	8.14
9	8.10

Pectora roborant cultus recti

Test no. 22	
Aimed moisture:	8.00% by weight
True moisture:	7.32% by weight

Electric current:	200 mA
Fines:	20%
Treatment period:	7 days

Area no.	ω (%)
1	8.82
2	7.58
3	6.17
4	7.85
5	7.23
6	6.54
7	7.66
8	7.01
9	6.40

Time (days)	Reservoir (g)
0.9	90.6
2.0	145.5
3.0	128.2
3.9	116.6
5.0	122.7
6.0	117.0
6.9	100.2
	820.8

Time (hours)	Current (mA)	Volts (V)	Total energy consumption (Wh)
0.00	200	39	
13.62	200	36	
21.49	200	36	159.026
47.87	200	41	216.316
71.82	200	42	201.180
83.02	200	43	
94.37	200	45	198.440
109.63	200	46	
119.27	200	49	236.550
133.07	200	48	
144.17	200	51	246.510
157.45	200	49	
165.80	200	52	218.463
			1476.485

Pectora roborant cultus recti

Test no. 23	
Aimed moisture:	8.00% by weight
True moisture:	8.46% by weight

Electric current:	200 mA
Fines:	20%
Treatment period:	10 days

Area no.	ω (%)
1	5.95
2	7.37
3	5.92
4	5.07
5	5.46
6	7.48
7	6.28
8	5.56
9	6.57

Time (days)	Reservoir (g)
1.9	214.1
2.8	118.7
3.7	129.9
4.7	138.3
5.7	118.3
6.7	92.1
7.8	104.5
8.8	77.0
10.0	72.3
	1065.2

Time (hours)	Current (mA)	Volts (V)	Total energy consumption (Wh)
0.00	200	39	
18.63	200	40	147.177
27.80	200	40	
44.35	200	44	216.048
54.85	200	45	
65.17	200	46	189.462
75.88	200	46	
89.28	200	48	226.634
104.30	200	50	
113.83	200	53	252.865
127.02	200	53	
136.80	200	59	257.264
152.27	200	62	
160.45	200	68	307.450
186.48	200	89	463.334
210.43	200	107	512.530
221.63	200	111	
233.00	200	127	
240.55	200	119	716.856
			3289.620

Pectora roborant cultus recti

Test no. 24	
Aimed moisture:	8.00% by weight
True moisture:	8.13% by weight

Electric current:	200 mA
Fines:	20%
Treatment period:	15 days

Area no.	ω (%)
1	7.27
2	6.40
3	6.95
4	6.03
5	6.00
6	7.99
7	6.90
8	5.80
9	6.56

Time (days)	Reservoir (g)
0.8	68.7
1.9	167.1
3.4	91.4
3.8	64.0
4.7	153.6
5.8	133.5
6.9	119.8
7.9	97.0
8.9	105.4
9.9	85.0
10.8	68.9
11.8	64.6
12.8	51.5
13.8	44.5
14.4	28.2
	1343.2

Time (hours)	Current (mA)	Volts (V)	Total energy consumption (Wh)
0.00	200	37	
8.12	200	35	
18.52	200	36	133.344
32.77	200	39	
45.10	200	40	209.982
80.95	200	50	358.500
90.55	200	48	92.160
113.88	200	50	233.300
129.87	200	50	
139.85	200	51	262.297
153.12	200	51	
164.90	200	55	265.530
175.50	200	58	
188.62	200	65	291.756
202.07	200	66	
214.62	200	69	351.000
226.62	200	73	
238.03	200	78	353.491
248.38	200	82	169.740
273.20	200	98	
284.28	200	102	718.000
296.75	200	104	
305.77	200	117	474.929
322.07	200	125	
331.05	200	140	669.920
345.23	200	158	
359.28	200	163	906.183
			5490.132

Test no. 25	
Aimed moisture:	6.00% by weight
True moisture:	6.28% by weight

Electric current:	0 mA
Fines:	20%
Treatment period:	7 days

Area no.	**ω (%)**
1	11.14
2	9.81
3	9.22
4	9.33
5	8.61
6	7.09
7	8.38
8	7.33
9	6.70

Pectora roborant cultus recti

Test no. 26	
Aimed moisture:	6.00% by weight
True moisture:	6.22% by weight

Electric current:	0 mA
Fines:	20%
Treatment period:	10 days

Area no.	ω (%)
1	12.43
2	10.87
3	10.61
4	10.71
5	9.63
6	8.65
7	10.95
8	8.77
9	7.88

Pectora roborant cultus recti

Test no. 27	
Aimed moisture:	6.00% by weight
True moisture:	6.29% by weight

Electric current:	0 mA
Fines:	20%
Treatment period:	15 days

Area no.	ω (%)
1	10.88
2	9.24
3	9.62
4	9.07
5	7.83
6	7.54
7	8.23
8	7.66
9	6.58

Pectora roborant cultus recti

Test no. 28	
Aimed moisture:	6.00% by weight
True moisture:	6.31% by weight

Electric current:	200 mA
Fines:	20%
Treatment period:	7 days

Area no.	ω (%)
1	11.50
2	10.30
3	9.09
4	9.27
5	8.47
6	9.14
7	9.48
8	7.76
9	9.00

Time (days)	Reservoir (g)
1.5	28.2
1.9	40.8
2.9	92.4
4.0	103.4
5.0	92.5
5.9	75.3
6.9	56.4
	489.0

Time (hours)	Current (mA)	Volts (V)	Total energy consumption (Wh)
0.00	200	65	
11.55	200	51	
21.55	200	49	237.050
34.80	200	50	
46.55	200	51	252.500
57.23	200	50	
70.30	200	54	247.000
83.72	200	53	
96.30	200	54	278.200
108.28	200	54	
119.72	200	54	252.936
130.08	200	54	
141.67	200	54	237.060
154.93	200	56	
165.98	200	59	279.565
			1784.311

Pectora roborant cultus recti

Test no. 29	
Aimed moisture:	6.00% by weight
True moisture:	5.88% by weight

Electric current:	200 mA
Fines:	20%
Treatment period:	10 days

Area no.	ω (%)
1	10.84
2	9.86
3	11.45
4	9.32
5	9.51
6	10.55
7	10.07
8	8.49
9	8.95

Time (days)	Reservoir (g)
1.0	24.6
2.0	81.7
3.0	100.7
4.1	123.6
5.6	227.5
6.5	86.9
7.0	62.1
8.3	168.6
9.1	139.8
10.0	104.7
	1120.2

Time (hours)	Current (mA)	Volts (V)	Total energy consumption (Wh)
0.00	200	54	
13.88	200	43	
24.92	200	43	232.587
38.27	200	43	
46.85	200	43	188.598
61.17	200	42	
71.58	200	43	210.205
85.82	200	42	
98.13	200	42	223.020
134.00	200	40	286.96
143.62	200	42	80.808
156.60	200	42	
166.85	200	43	197.455
182.92	200	41	
192.90	200	43	218.820
206.17	200	45	
217.93	200	46	227.773
228.55	200	48	
238.83	200	50	204.82
			2071.046

Pectora roborant cultus recti

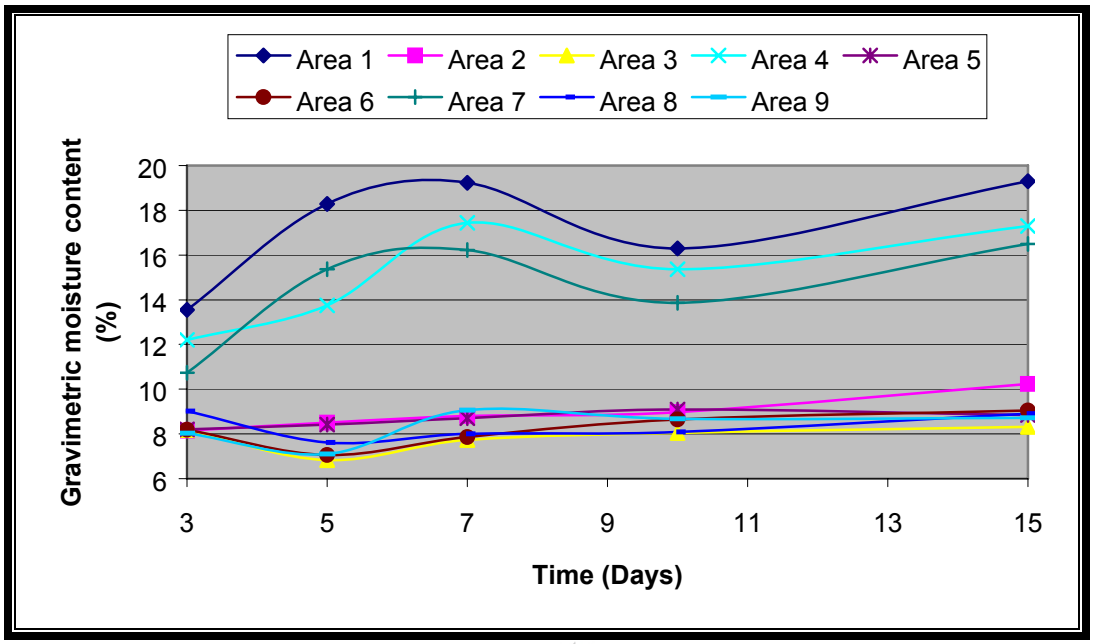
Test no. 30	
Aimed moisture:	6.00% by weight
True moisture:	5.52% by weight

Electric current:	200 mA
Fines:	20%
Treatment period:	15 days

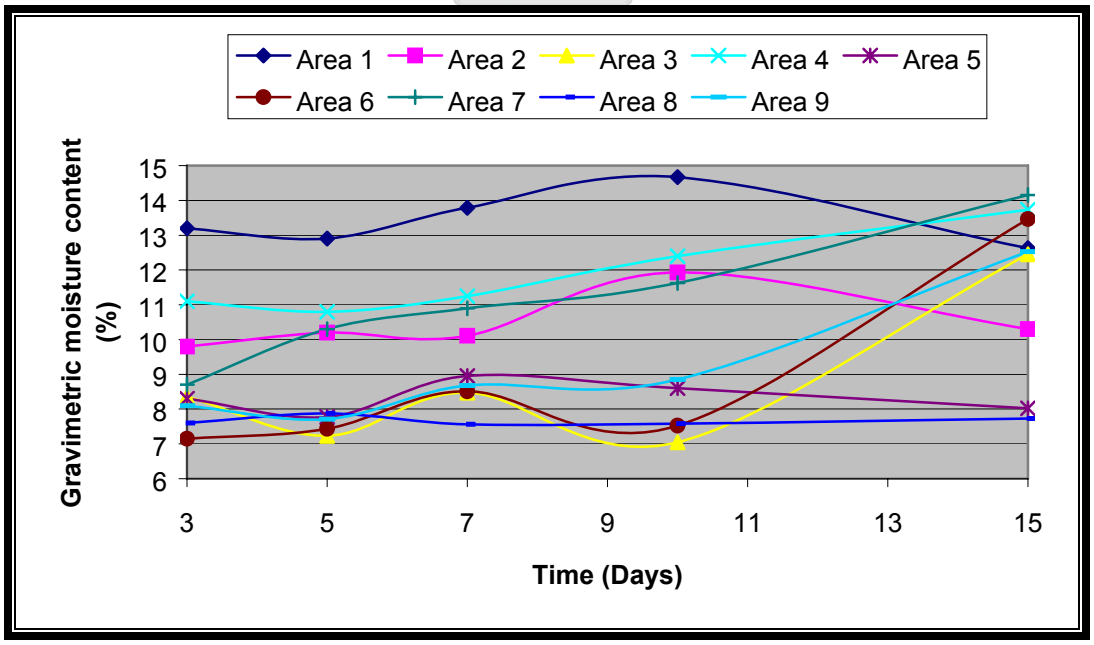
Area no.	ω (%)
1	10.11
2	9.36
3	10.59
4	8.15
5	7.96
6	9.31
7	9.44
8	8.61
9	8.29

Time (days)	Reservoir (g)
1.6	11.7
2.1	28.1
2.6	28.7
3.1	28.3
3.6	26.5
4.9	53.8
5.5	21.3
5.9	13.7
6.6	9.6
11.5	7.7
12.0	3.6
12.5	8.4
13.6	30.8
13.9	12.1
14.6	19.6
	303.9

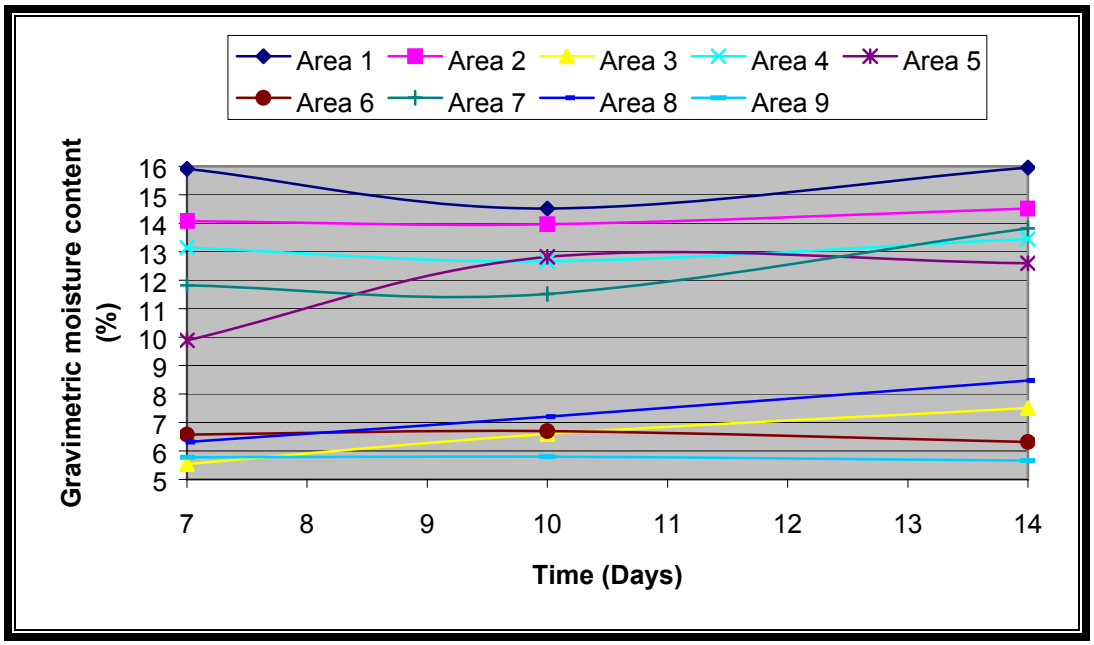
Time (hours)	Current (mA)	Volts (V)	Total energy consumption (Wh)
0.00	200	63	
14.63	200	60	
23.62	200	55	280.291
37.80	200	55	
50.02	200	59	300.960
62.27	200	60	
73.60	200	62	287.676
85.52	200	63	150.192
117.85	200	73	472.018
132.40	200	71	
143.18	200	73	364.752
158.32	200	76	
165.58	200	80	349.440
181.65	200	81	
192.57	200	88	456.131
204.73	200	88	
215.18	200	94	411.502
230.23	200	95	
240.10	200	105	498.400
251.93	200	110	
263.10	200	112	510.600
274.02	200	120	
286.95	200	123	579.555
300.55	200	126	
310.77	200	131	560.774
326.58	200	130	
334.73	200	136	637.336
350.85	200	145	
359.88	200	150	741.925
			6601.552



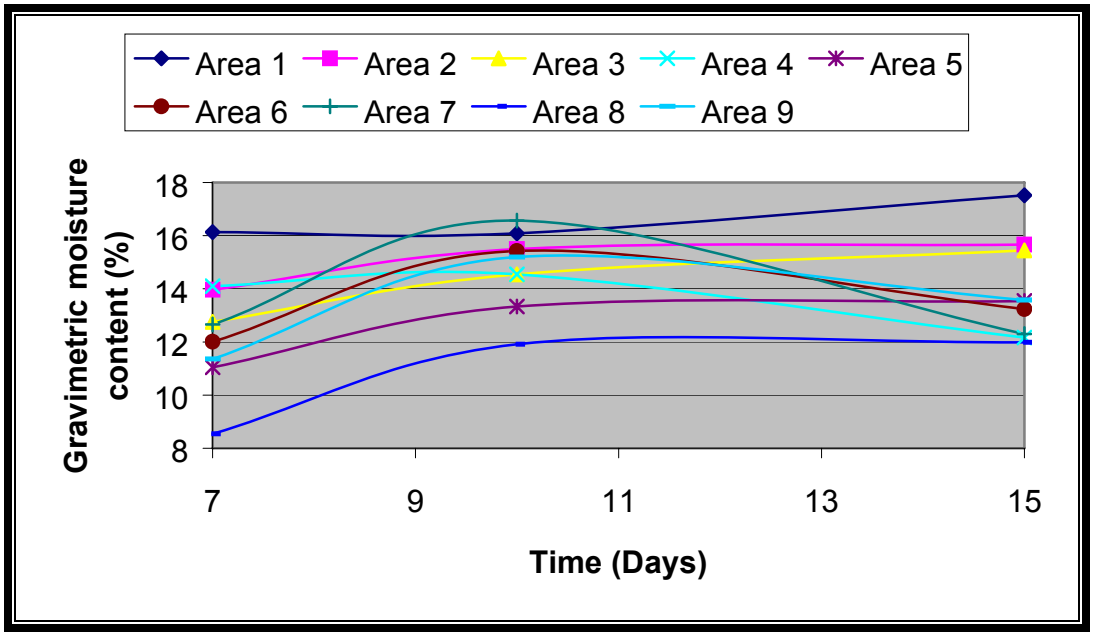
Moisture infiltration of 30% fines, 8% moisture content, 0 mA



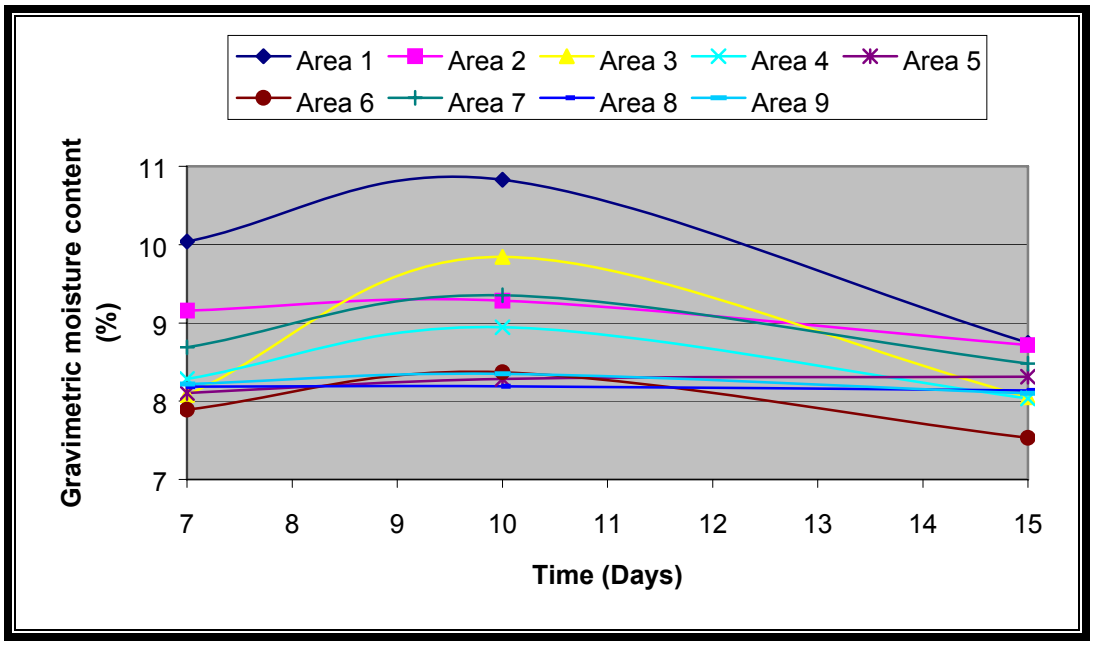
Moisture infiltration of 30% fines, 8% moisture content, 200 mA



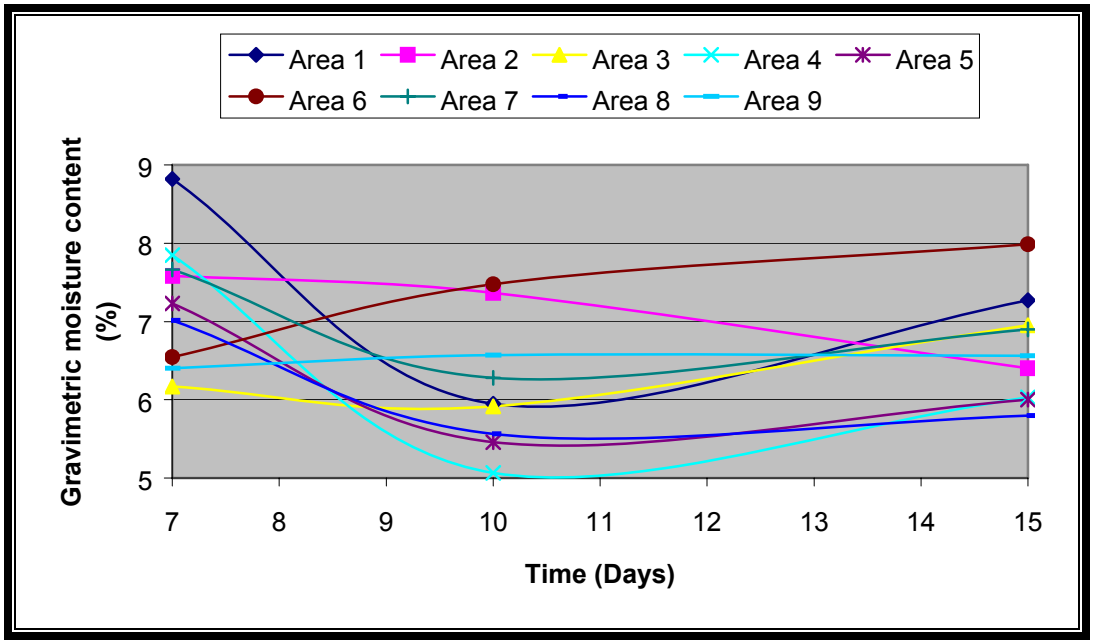
Moisture infiltration of 30% fines, 6% moisture content, 0 mA



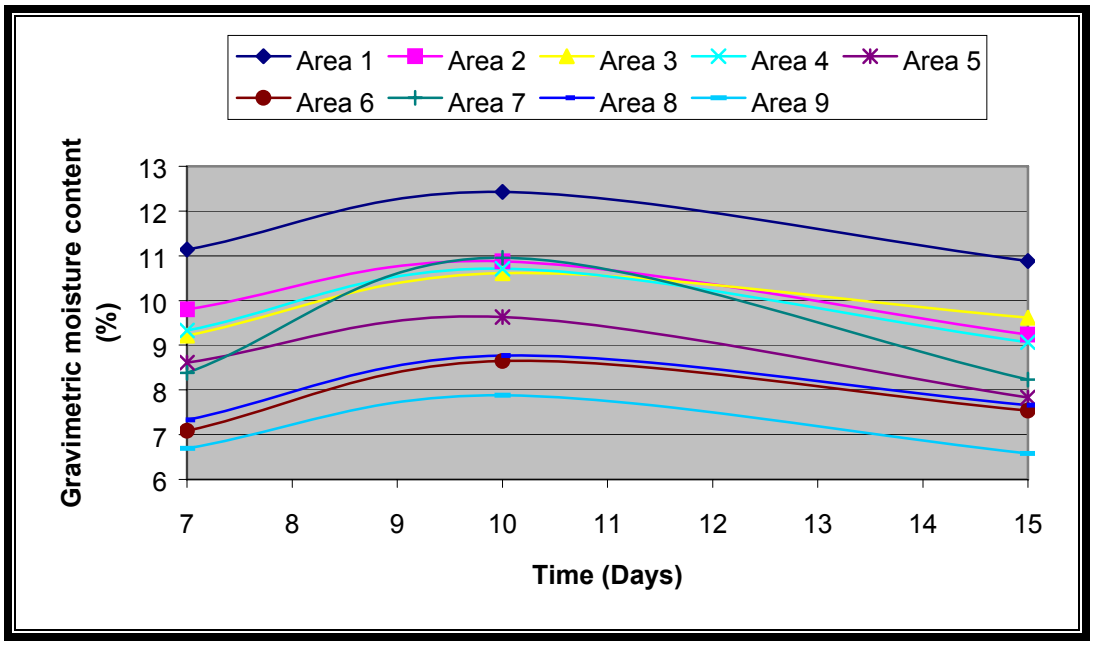
Moisture infiltration of 30% fines, 6% moisture content, 200 mA



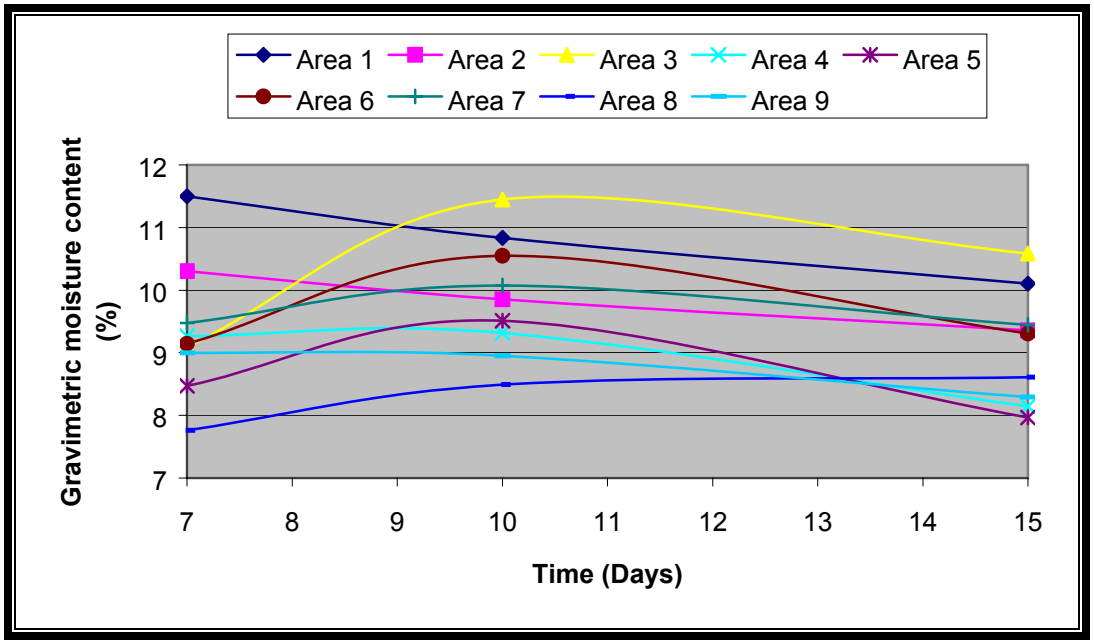
Moisture infiltration of 20% fines, 8% moisture content, 0 mA



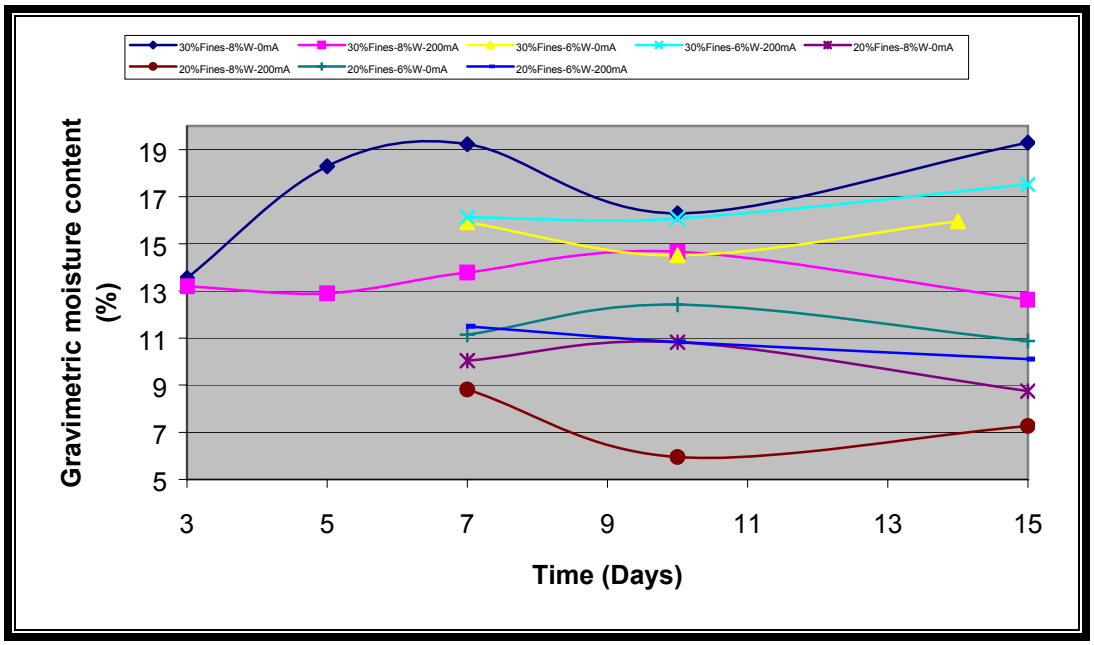
Moisture infiltration of 20% fines, 8% moisture content, 200 mA



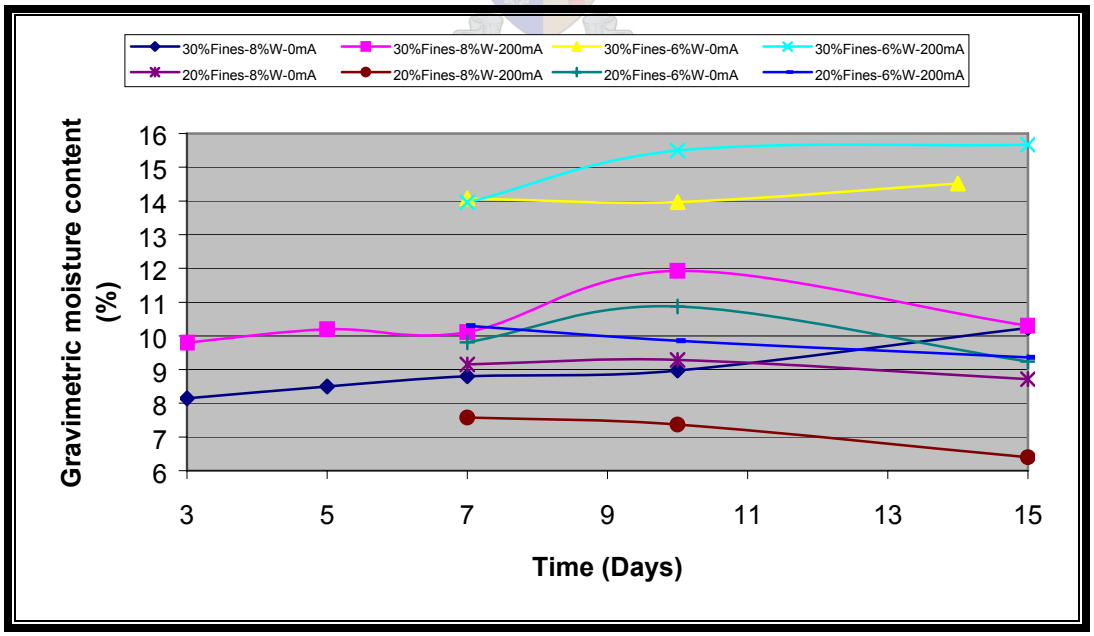
Moisture infiltration of 20% fines, 6% moisture content, 0 mA



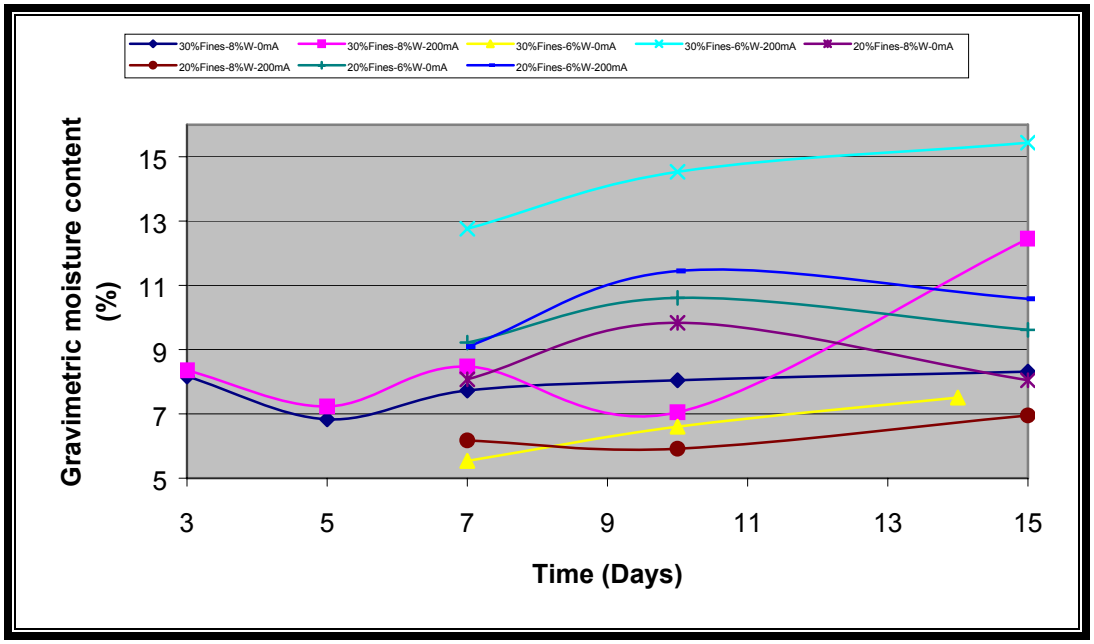
Moisture infiltration of 20% fines, 6% moisture content, 200 mA



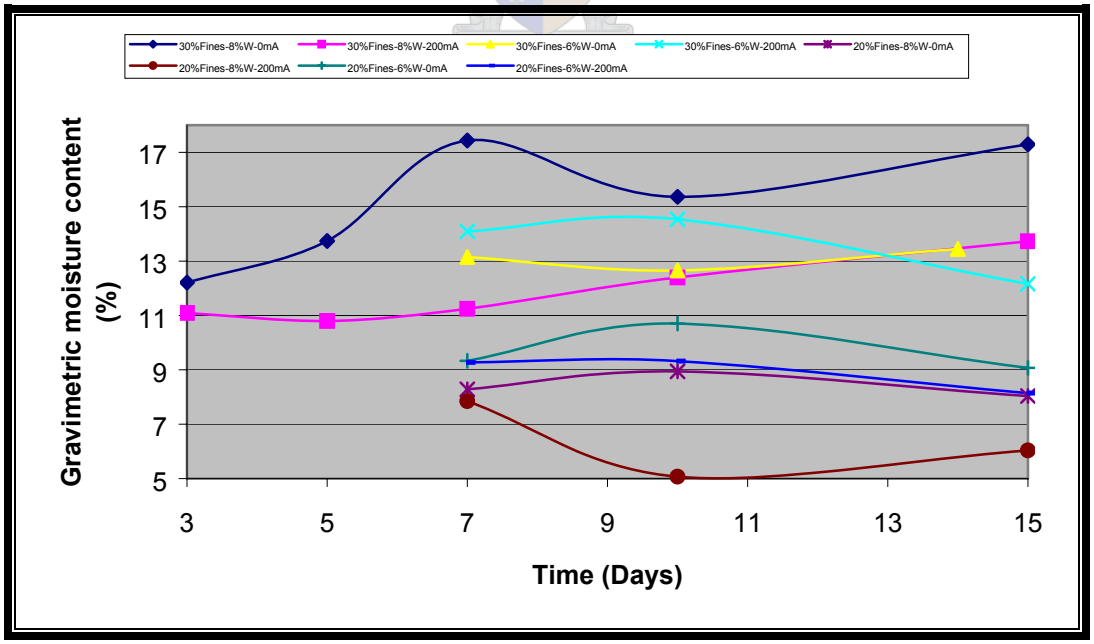
Moisture infiltration at area 1



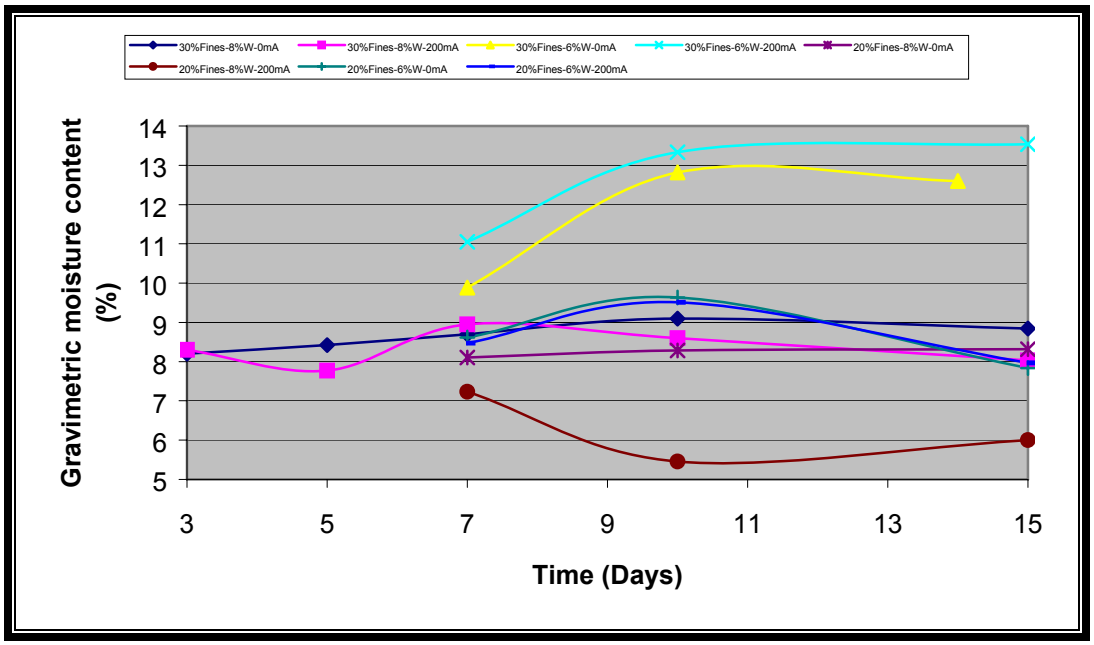
Moisture infiltration at area 2



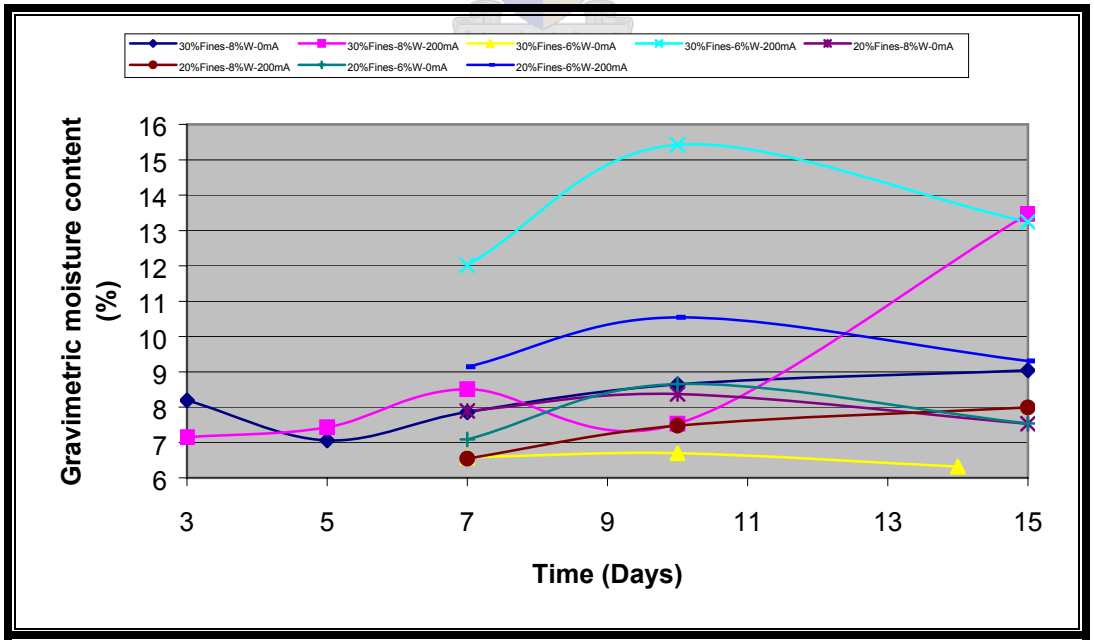
Moisture infiltration at area 3



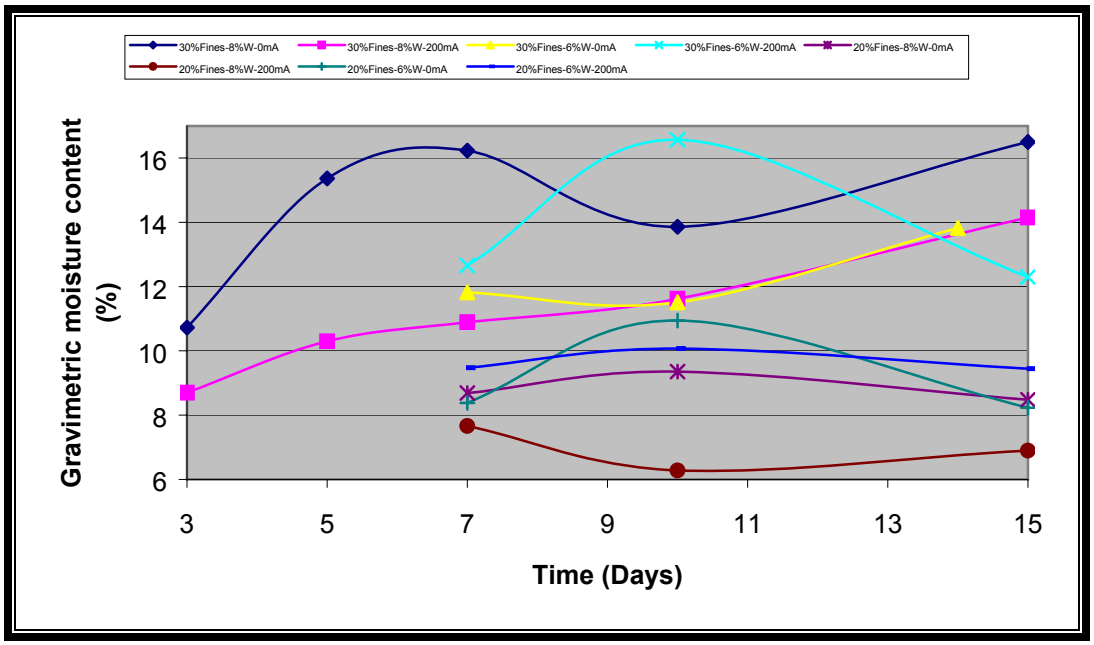
Moisture infiltration at area 4



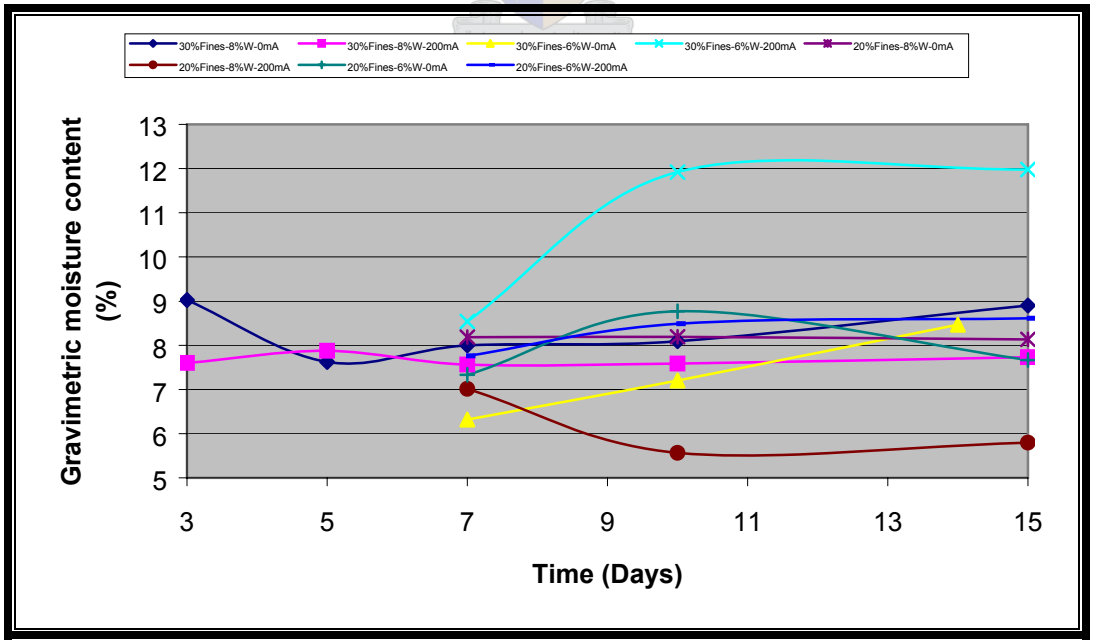
Moisture infiltration at area 5



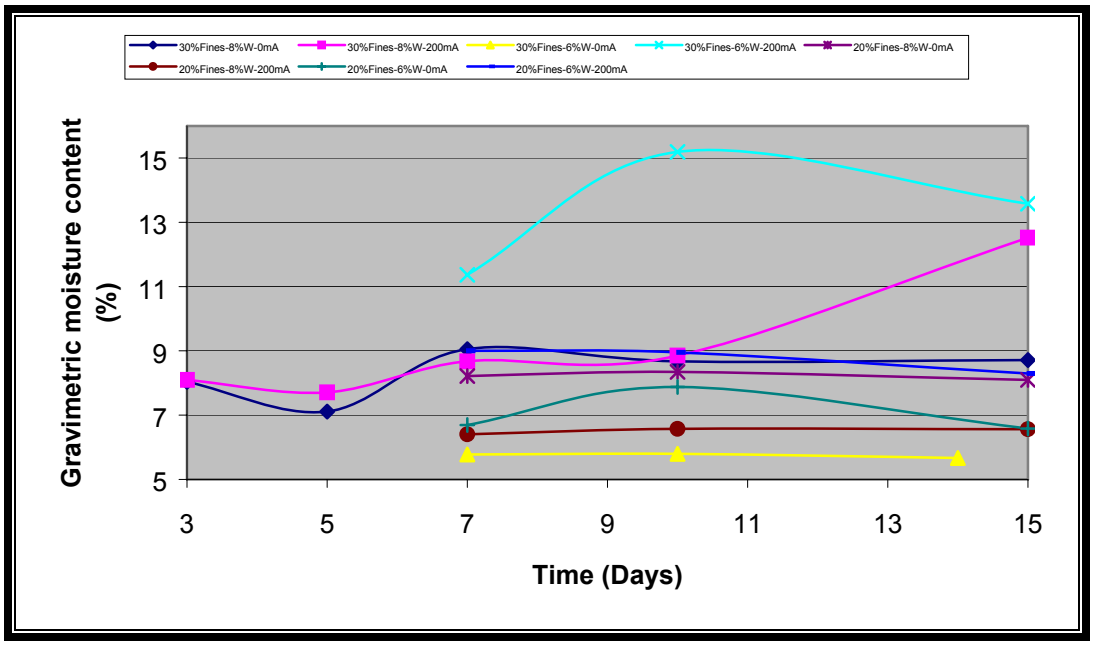
Moisture infiltration at area 6



Moisture infiltration at area 7



Moisture infiltration at area 8



Moisture infiltration at area 9