EVALUATION OF THE PERFORMANCE OF EXPANDED BLACK COTTON SOIL AS A HYDROPONIC MEDIUM

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DECLARATION AND RECOMMENDATION

Declaration

I declare that this thesis is my original work and has not been submitted for award of any degree or diploma in any other University known to me.

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Recommendation

This thesis is the candidate's and has been prepared with our guidance as supervisors.

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ABSTRACT

The traditional system of producing crops using soil (geoponics) is currently facing major challenges resulting in food deficits. An alternative is the adoption of soil-less culture (hydroponics) which is regarded as key in increasing production of vegetables, herbs and ornamentals. The study aimed at preparing a hydroponic medium from black cotton soil and rice husks. The process entailed moulding, firing, size reduction and performance evaluation. The aggregates were evaluated on the basis of dry bulk density and saturated hydraulic conductivity. The investigations revealed that the optimal conditions for preparing the medium were 750°C, 30 minutes and 9:1 for firing temperature, time and ratio of black cotton soil to rice husk (on a weight basis) respectively. These conditions resulted in 33% reduction in bulk density from 1.43 g cm^{-3} to 0.954 g cm^{-3} and improvement in saturated hydraulic conductivity from $0.333*10^{-5}$ cm s^{-1} to 0.00385 cm s^{-1}, which falls between the ranges for Sandy Loam and Loamy Sand based on estimated values by the RETention Curve (RETC) model. The Hydrus 1D version 4.16.0110 model was used to estimate the hydraulic parameters of the expanded black cotton soil. The optimized values were 0.1 cm^3 cm^{-3}, 0.55 cm^3 cm^{-3}, 0.01, 1.91, 0.00368 cm s^{-1} and -1 for Θ_r, Θ_s, *ά*, *n*, K_s and *l* respectively. The measured *vs*. simulated values for water retention, $\Theta(h)$ resulted in R^2 of 0.83 and 0.0895 cm^3 cm^{-3} for the RMSE which showed that the model estimations could be applied to determine the water retention and hydraulic conductivity of the expanded black cotton soil aggregates at varied saturation. Further evaluation on performance of the medium was done by using it to grow tomatoes (cultivar *Anna F1*). Plant growth was assessed using stem elongation and enlargement; and root length density (RLD). The mean weekly stem elongation and enlargement rates for the crop grown on expanded black cotton soil were higher than those of the sampled black cotton soil (clay) by 4.42% and 9.69% respectively. However the mean RLD was 25654 m m^{-3} in black cotton soil compared to 18936 m m^{-3} for the expanded black cotton soil. This reduction of 26% is however beneficial because it can allow the crops to be planted using smaller volumes of the expanded black cotton soil. The findings showed that the expansion of the black cotton soil by incorporating rice husks was achieved at lower firing temperature compared to commercially available expanded clay pellets fired at 1200°C.

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ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
ARS	Agricultural Research Service
ASTM	American Society for Testing and Materials
BCS	Black Cotton Soil
BD	Bulk Density
FAO	Food and Agriculture Organization
FC	Field Capacity
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IRRI	International Rice Research Institute
ISRIC	International Soil Reference and Information Centre
KALRO	Kenya Agricultural and Livestock Research Organization
Ksat	Saturated Hydraulic Conductivity
LBDC	Lake Basin Development Company
LSMean	Least Square Mean
NLWR	Non Limiting Water Range
RAW	Readily Available Water
RLD	Root Length Density
SAS	Statistical Analysis Software
SWRC	Soil Water Retention Curve
TAW	Total Available Water
USDA	United States Department of Agriculture
WP	Wilting Point
RMSE	Root Mean Squared Error
RETC	Retention Curve

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Black cotton soils contain a high amounts of expansive clay or montmorillonite to which they owe their specific properties. The soils occur mainly in hot environments such as the semi arid tropics which are marked by alternating wet and dry seasons. They cover an estimated 340 million hectares of the world's cultivable soils (Greenfield, 2004). In Africa, the soils are dominant in southern Sudan, Ethiopia, Kenya, Chad and north east Nigeria.

In Kenya, black cotton soils are found in the Tana River basin, Lambwe valley, Mwea and the lower parts of the Nyando River basin such as the Kano plains. The Kano plain offers a typical example of how the limitations of these soils can impact negatively on a community's economic and social wellbeing. The plain covers an approximated area of 43,000 hectares of which about 70% is covered by the black cotton soils (Da Costa, 1973). It lies at the head of Kavirondo Gulf near Kisumu at an altitude range of between 1,160 m and 1,300 m above mean sea level. The area suffers from seasonal flooding and unpredictable rainfall both of which dictate the success or failure of farming enterprises (Millman, 1973). The floods originate from the Nandi hills and often result in the crops being washed away. This problem is compounded by the fact that the black cotton soils in the area have poor drainage hence water-logging also occurs. The high water holding capacity of black cotton soil is deceptive, since not all the water is readily available to the plant due to shrinkage and cracking (Eswaran and Cook, 1988). When the rains fail, the soils dry up and in the process contract, leading to the formation of wide deep cracks. Irrigated agriculture has been introduced in some parts of the plains notably West Kano Irrigation Scheme and Ahero Rice Irrigation Scheme to address the food situation. However, the crops grown have been limited to rice and sorghum. Sugarcane is also grown around areas such as Kibos, Miwani, Muhoroni and Chemelil under both irrigation and rainfed conditions.

In order to improve agricultural productivity in an area like the Kano plains, there is need to improve the soil condition to enable it support a greater variety of crops, especially high value horticultural crops which require a medium range of soil moisture and good aeration hence the need for well drained conditions. The black cotton soils as they occur in nature are difficult to work on. When dry, they have a very hard consistency but become very plastic and sticky when wet. This behavior limits the workability of the soil to very short periods of optimum moisture content. In addition, the soils exhibit poor drainage due to very low hydraulic conductivity. The soils are generally categorized under Group D soils according the Hydrologic Soil Groups (USDA and Natural Resources Conservation Service, 2007). They have small pores that do not favour aeration or plant root penetration.

Hydroponics is described as a soil-less culture. It involves the growing of crops without soil. The plants are either grown in a mineral nutrient solution only or in an inert material such as coco coir, perlite, pumice, vermiculite, gravel, expanded clay amongst others. These aggregate materials are prepared such that their desired physical properties are close to desired soil condition for a given crop.

Commercial expanded clay pellets are prepared by firing clay to temperatures of between 1100^{o}C and 1200^{o}C in a kiln. However in this study the black cotton soil was mixed with rice husk which is an organic waste material before firing. The firing was done to combust the organic matter and also fused the clay particles into sand sized aggregates resulting in a more porous material with lower bulk density. This process resulted into an inert material devoid of chemical or biological activity but having improved physical quality. The performance of the expanded black cotton soil was evaluated based on preparation process and its suitability as a hydroponic medium.

1.2 Statement of the Problem

Black cotton soils are nutrient rich due to their self mulching nature but crop production is mainly hindered by the soils' physical properties. These properties are texture and moisture related due to the high amounts of expansive clay minerals present in the soil. The soils have low hydraulic conductivity which limits irrigation water application, uptake by plants and drainage. This has limited the choice of crops that can be grown and there is often crop failure due to erratic moisture regimes in the areas covered by these soils. The soils when used for rice production under irrigation results in large quantities of rice husk after processing. These are often disposed as waste posing a hazard to the environment. Hydroponics, as an alternative method of crop production can be adopted by utilizing composites of black cotton soil and rice husk to prepare expanded clay aggregates. However there is limited information on the required mixing ratios of the black cotton soil and rice husk, firing temperatures and the time required for firing to result in lower bulk density and improved water flow for better crop growth. Provision of relevant information on process requirements together with performance data of expanded black cotton soil for use a hydroponic medium is necessary for the adoption of the technology by farmers and other stakeholders in the agricultural sector.

1.3 Objectives

The broad objective was to evaluate the performance of expanded black cotton soil as a hydroponic medium when prepared under varied clay-rice husk mix ratios, firing temperatures and time.

The specific objectives are;

i) To evaluate the effect of black cotton soil – rice husk mix ratio, firing temperature and firing time on bulk density and hydraulic conductivity.
ii) To estimate the hydraulic conductivity and moisture retention of the expanded black cotton soil under varied saturation using HYDRUS model.
iii) To evaluate the suitability of the expanded black cotton soil medium for plant growth using stem elongation, enlargement rates and root development parameter.

1.4 Research Questions

i) How does the clay – rice husk mix ratio, firing temperature and time affect the bulk density and hydraulic conductivity of the expanded black cotton soil?
ii) What are the hydraulic conductivity and moisture retention functions for the expanded black cotton soil as estimated using HYDRUS 1D model?
iii) How does the tomato crop perform on varied textures of the expanded black cotton soil in terms of stem growth and root development?

1.5 Justification

The black cotton soils are mainly found in the semi-arid tropics and are generally characterized by low agricultural productivity. The soils are difficult to cultivate and the rainfall in these areas is often low, erratic and highly seasonal and the socio-economic resources are limited. Due to these harsh environmental conditions, crop production is inadequate to meet the needs of the rapidly increasing populations (Swidale, 1988). Agricultural production has therefore become a risky undertaking with mass crop failures being frequently reported. Irrigation is often recommended to improve production.

Soil forms important component in the technical feasibility evaluations for any irrigation project. It determines the method and frequency of irrigation as well as the type of crops that can be grown. In order to expand the range of crops that can be grown in areas with black cotton soil, the soil as a natural medium needs to be improved so that it can acquire the chemical and physical properties necessary for improved yields. The chemical properties can be improved by addition of a wide range of commercially available ingredients such as organic and inorganic fertilizers. However, the physical properties offer a greater challenge. These properties include water flow and retention, aeration and bulk density all of which are affected by the soil's texture.

For sustainability, local problems are best addressed using locally available materials. Some of the areas with black cotton soil are used for production of paddy rice whose global production is approximately 650 million tones per year. For each kilogram of milled rice, about 0.28 kg is rice husk. This result in a large quantity of rice husk whose collection and disposal is difficult and expensive and is often left unused or burnt (Mansaray and Ghaly, 1997). Using the material to improve black cotton soils would result in reduction of waste and reduce the environmental hazard caused by field disposal and burning.

CHAPTER TWO
LITERATURE REVIEW

2.1 Nature and Occurrence of Black Cotton Soils

The black cotton soils are classified as Vertisols both under the USDA Soil Taxonomy and the FAO soil classification systems. The name black cotton soil is believed to have first been used in India. This is because the areas with black or grey soils were found suitable for growing cotton (Ikitoo *et al*., 2011). The soil is known as *regur* (India), *vlei* soil (South Africa) and *margalites* (Indonesia). They have a high content of expansive clay minerals that shrink and swell depending on the moisture content. They have clay content of at least 30% to a depth of at least 50 cm and wide, deep cracks that open and close periodically. In addition, they exhibit evidence of soil movement (e.g. slickensides, wedge-shaped aggregates), have varied soil temperature regimes and the soil moisture regime is erratic to allow for cracking in dry season and swelling in wet season.

The soils mainly occupy the hot environments in the semi arid tropics with marked alternating wet and dry seasons. Seasonal variations in precipitation and temperature result in the weathering of primary and secondary minerals during the wet season and the accumulation of basic cations in the dry season. These processes favour the formation of the black cotton soils from a wide variety of parent material (Grunwald, 2013). The natural vegetation is predominantly grass, savannah, open forest or desert shrub. Trees that grow in these soils are limited to the deep rooted types such as acacia trees whose roots can withstand the frequent cracks on the soil. Although the black colour was originally being attributed to organic matter, the soils have been found to have low organic matter content of between 1 and 6% and even less than 1% in some areas (Virmani *et al*., 1982). The variations in soil colour are attributable to the drainage status of the soil. The black colour is therefore indicative of poor drainage conditions while, where there is improved drainage; the soils are more reddish and have stronger chroma (Millman, 1973; ISRIC-World Soil Information, 2007).

The soils cover an approximated 340 million hectares in the world. In the tropics, they cover about 200 million hectares of land mainly in the arid and semi arid tropics which receive average annual rainfall of between 500 mm and 1000 mm. They are common in lower landscape positions such as dry lake bottoms, river basins, lower river terraces and other lowland areas that are periodically wet in their natural state. They may also be found in lower foot slopes or as residual soils or even on gently sloping hillsides. The soils are found in Australia, India, South America, United States, Indonesia, Burma, some countries in Europe and Africa (Ranjan and Rao, 2005), It occupies 99 million hectares (3.5%) of Africa's total land mass (Ikitoo *et al.*, 2011). The black cotton soils are found in Sudan mainly in southern Sudan where they cover approximately 40 million hectares being 16% of the land area; Chad which has a coverage of 16.5 million hectares and Ethiopia with about 10 million hectares. In Kenya, the soils cover approximately 2.8 million hectares (5% of land mass) in various locations including the Kano plains, Athi, Mwea and Transmara. In the Kano plains it covers about 70% of the plain's total area of about 43,000 hectares (Da Costa, 1973).

2.2 Black Cotton Soils and Agriculture

Black cotton soils are important for agriculture in the semi-arid tropics. This is because in these environments, they are considered the most productive soils due to their high water holding capacity. However, this water holding ability has been described as deceptive since not all the water held by the soil is readily available for crop use (Eswaran and Cook, 1988). In addition, the soils have high susceptibility to erosion, poor infiltration rates, low permeability and are difficult to drain.

2.3 Soil Physical Properties: Determination and Ranges

2.3.1 Texture

Soil texture is determined by separating and weighing the sand, silt and clay through a procedure known as the mechanical sieve analysis (ASTM D6913). A commonly used textural classification is the USDA classification. The soils are graded by sifting them through a series of soil test sieves of successive smaller screen sizes. The amount of soil collected on each sieve is weighed and the percent of total sample weight retained is recorded for each sieve. Separation of the silt and clay fractions is obtained through the hydrometer or pipette method which is based on Stoke's law which is given by;

$$v_t = \frac{d^2 g(\rho_s - \rho_f)}{18\eta} \tag{2.1}$$

$$t = \frac{18h\eta}{d^2 g(\rho_s - \rho_f)} \tag{2.2}$$

Where; v_t = terminal velocity (m/s)

d = particle diameter (m)

g = acceleration due to gravity (m/s^2)

ρ_s = particle density (kg/m^3)

ρ_f = fluid density (kg/m^3)

η = dynamic viscosity of fluid (Pa)

t = the time (sec) required for a particle to fall through a height, h (m)

Dry sieving is done by first conditioning the soil through drying and pounding to break the aggregates into individual particles. However, wet sieving is often applied where the proportion of clay in a sample is high. From the resulting grading curve (semi-log plot of percent finer against sieve opening size), values of D_{10}, D_{30}, D_{60}, corresponding to particle diameters at 10%, 30% and 60% finer respectively are obtained and used to compute the coefficient of concavity, C_c (measure of shape of the curve between D_{10} and D_{60}) and the coefficient of uniformity, C_u using the relations given in Equation 2.3. The values of C_c and C_u are used to determine whether the soil is well graded or poorly graded. The gradation curve gives the range of particle sizes present in a soil and the type of distribution of various size particles. The value of D_{10} gives the effective size of the soil.

$$C_U = \frac{D_{60}}{D_{10}} \quad \text{and} \quad C_C = \frac{D_{30}^2}{D_{10}D_{60}} \tag{2.3}$$

Black cotton soils have high clay contents above 30% but commonly between 40% and 60% although cases of up to 80% clay content has been reported. The clay content is in most cases uniform throughout the profile up to a depth of 50 cm or more (Virmani *et al*., 1982). The clay minerals are mainly the 2:1 type montmorillonites and smectites.

2.3.2 Porosity and Void Ratio

The porosity, P of a soil medium is defined as the relative volume of pores. For black cotton soils, porosity varies depending on the moisture content due to the swelling and shrinking characteristics. Porosity is given by Equation 2.4 as;

$$P = {V_p}/{V_t} \tag{2.4}$$

Where; V_p is the volume of pores

V_t is the total bulk volume of sample

Since both V_p and V_t changes by reducing when the soil dries and increases when the soil is wetted, the void ratio, e is often adopted as a better representation relating the volume of pores to that of the soil solids, V_s and is given as;

$$e = \frac{V_p}{V_s} \qquad = \qquad \frac{P}{1-P} \qquad (2.5)$$

Although the black cotton soils exhibit high porosity values ranging from 0.4 to 0.7, the bulk of the pore spaces fall within the categories of sub-microscopic and capillary pores (less than 1 mm in diameter). The proportion of macro-pores (greater than 1 mm) is often limited and may only be present when the soil is dry and have cracks.

2.3.3 Structure

The structure of the soils is almost a temporal characteristic. The size, shape and consistence of the structural elements are all greatly influenced by the moisture regime at the time the soil is inspected. A common structure is the angular blocky structure with wedge shaped aggregates. Large blocks indicate that the soils resist movement of water and air. A desired structure is the granular or crumb structure which allows water to flow freely in soil.

2.3.4 Bulk density

The bulk density of the soils also varies greatly. Higher bulk densities are obtained when the soils are dry. It may therefore vary between 1 g cm^{-3} and 2 g cm^{-3}. According to Eswaran and Cook (1988), when the soil is dry, the tissue-paper sheets of montmorillonite pack against each other to form a very compact, low porosity aggregate. The bulk density then can change from about 1.33 g cm^{-3} at 0.00305 mH_2O tension to more than 1.8 g cm^{-3} at oven dry conditions. It has been found that few roots can penetrate a medium with a bulk density greater that 1.6 g cm^{-3}.

2.3.5 Consistency

Because of their high clay content, the black cotton soil have high plastic limit and liquid limit resulting in high plastic index (PI) greater than 35%. This is considered very high plasticity compared to clay loam with medium plasticity and having a plastic index of between 10 and 20%. The soils have very hard consistency when dry but when wet, they become very plastic and sticky. They are friable only over a narrow range of moisture content, just at the onset of the rains. The consistency of the soils affects tillage operations. When the soil is dry it requires heavy machinery to work on while when wet, the soil becomes very plastic, sticks on the tillage implements and there is high risk of formation of hard pan below the plough bottom. Tillage should therefore be done at moisture contents close to, but not at field capacity (Eswaran and Cook, 1988)

2.3.6 Swelling and Shrinkage

Swelling is caused by the addition of moisture into the soil. When there is a loss of moisture, shrinking occurs. The reduction in soil volume continues until certain threshold moisture content is reached below which deep cracks wider than 1cm starts to form (Kutilek and Nielsen, 1994). The shrinking force tends to crush plant roots. For the montmorillonite, swelling takes place in three stages;

i) In the first stage, the distance between two sheets of clay is less than 2 nm. This distance increases in discrete steps as water is added.

ii) The second stage is attributed to the bonding of water molecules to the solid surface with the distance between neighbouring sheets rising smoothly up to tens of nanometers.

iii) During the third stage, the sheets are completely separated and form an arrangement caused by the edge to face and edge to edge forces.

Swelling and shrinkage of soils adversely affect the stability of structures built on them. This may result in frequent failure of water conveyance and distribution structures.

2.3.7 Soil Water

Soils are important reservoirs of fresh water. They transform the non continuous rainfall into a continuous flow of water to the roots of plants hence their importance to agriculture. Soil water can be defined by;

i) Soil Water Content

Soil water content can be expressed on a mass basis (gravimetric) or on volume basis. It indicates the proportion of the amount of water relative to that of soil. Equations 2.6 and 2.7 are used to compute the gravimetric and volumetric water contents respectively.

$$\theta_g = 100\left(\frac{M_w}{M_s}\right) \quad (2.6)$$

$$\theta_v = 100\left(\frac{V_w}{V_t}\right) = \theta_g\left(\frac{\rho_b}{\rho_w}\right) \quad (2.7)$$

Where: θ_g = gravimetric water content (%)

θ_v = volumetric water content (%)

M_w = Mass of water (g)

M_s = mass of solids (g)

V_w = volume of water (cm^{-3})

V_t = total volume of soil sample (cm^{-3})

ρ_b = dry bulk density of the soil (g cm^{-3})

ρ_w = density of water (g cm^{-3})

ii) Soil water regimes

Four moisture levels are important when evaluating water availability in the soil and to plants. These are the saturation point *(SP)*, field capacity *(FC)*, wilting point *(WP)* and oven dry *(OD)* water contents. For agricultural purposes, the main concern is on the field capacity and wilting points. The field capacity of soil is the water remaining after free drainage of rainfall or irrigation water and is approximated as the water content of soil at a matric potential of 33 kPa.

Wilting point is the water held tightly by the soil that it cannot be taken up by plants. It is based on the premise that the plant will wilt at this moisture content. However there are some plants that have leaves that may not wilt e.g. cactus. Although it is assumed a constant, research has shown otherwise. Its value is dependent on the soil profile, transpiration rate and temperature. For practical purposes it is estimated to be the moisture content at a matric potential of 1500 kPa (Kirkman, 2014; Lal and Shukla, 2005).

iii) Available water

The amount of water between *FC* and *WP* is known as the total available water *(TAW)* expressed in equivalent depth of water as;

$$TAW = (FC - WP) * 10 \text{ (mm m}^{-1}\text{)} \tag{2.8}$$

This equation assumes that FC is the upper limit of available water but this is not often the case because the water held by the soil can be used by plant even during rapid drainage (Kirkman, 2014). The limiting factor in uptake of water by plants is therefore soil aeration. The air filled porosity should therefore exceed 10%.

Theoretically, plants are able to obtain water from the soil if the content exceeds the wilting point but the actual rate of transpiration decreases in response to declining water content. Between WP and FC, there is a critical moisture content below which plants start to be stressed. The moisture range between critical point and FC is referred to as the readily available water (RAW). It is also referred to as the non limiting water range (NLWR) as discussed by Kirkman (2014). The black cotton soils have relatively high water storage capacity because of their clay content and high porosity. Values of available water between 200 mm and 300 mm have been recorded within a profile of 1 m depth (Virmani, 1988). This is high compared to that of red clays (Alfisols) which have average water storage capacity of 150 mm. However, the range of readily available water in black cotton soil is low because of the high affinity with which the water molecules are held to the clay particles resulting in elevated permanent wilting point.

iv) Soil water potential

This is defined as the amount of work that a unit quantity of water in an equilibrium soil-moisture system is capable of doing when it moves to a pool of water in the reference state at the same temperature (Lal and Shukla, 2005). Total soil water potential for swelling soil under unsaturated conditions consists of;

$$\Phi_t = \Phi_m + \Phi_z + \Phi_o + \Phi_n \quad (2.9)$$

Where *t, m, z, o,* and *n* refer to the total, matric, gravitational, osmotic, and overburden potential respectively.

Φ_m exists only in unsaturated soils. It is due to the effects of soil solids, interfacial curvature due to surface tension and forces of cohesion and adhesion of the soil matrix. Φ_z is due to the position of soil water. It is the energy required to move an infinitesimal amount of pure, free water from the reference elevation to the soil water elevation. It is determined by the elevation of the point relative to the reference level. Φ_o is due to the presence of solutes in soil moisture that affect its thermodynamic properties. Φ_n is due to the mechanical pressure exerted by the unsupported solid material on the soil water. It is the change in energy per unit volume of soil water due to the weight of the unsupported soil above the soil water. The moisture content at a given potential for black cotton soils has been found to decrease with depth due to the compression effect on matric potential (Virmani *et al*., 1982).

2.3.8 Infiltration

High infiltration rates are observed in dry soils with cracks on the surface. However, once the soil surface is thoroughly wetted and the cracks have been sealed, the rate of water infiltration becomes almost nil (ISRIC – World Soil Information, 2007). For example, in a study of infiltration rates in India, observations were made as in Table 2.1 below.

Table 2.1: Initial and equilibrium infiltration rates of a Vertisol at ICRISAT Center, near Hyderabad, India.

Time from start (hr)	Infiltration rate (mm hr^{-1})
0-0.5	76
0.5-1.0	34
1.0-2.0	4
After 144	0.21 $\pm$ 0.1

Source: Swindale, (1988)

Infiltration is important in soils since it affects the rate of ponding and subsequent runoff resulting from rainfall. It influences the rate at which water is taken in by the soil hence the choice of irrigation water application method since the rate of water application must not exceed the infiltration rate, otherwise runoff would result. Because of their relatively low infiltration rates, the black cotton soils have usually been irrigated by surface water application methods which are wasteful in terms of water and energy resources and also limit the choice of crops that can be grown. Runoff increases the risk of soil erosion. Once the surface of the soil seals at the beginning of a rainfall event, continued rainfall is lost through surface flow.

2.4 Soil Hydraulic Properties

2.4.1 Soil Water Retention

The soil water potential expressed as a head, h is related to the soil water content, Θ. The function $\Theta(h)$ when plotted is called the soil water retention curve (SWRC) or the soil moisture characteristic curve. The value of h is often plotted on a logarithmic scale since it often extends over three to four orders of magnitude for fluctuations of Θ commonly occurring in the field (Kutilek and Nielsen, 1994). SWRC can be determined either by direct measurements in the field or in the laboratory using undisturbed core samples.

2.4.2 Hydraulic conductivity

The potential for water flow in a porous media is defined by the hydraulic gradient, i which is expressed mathematically as;

$$i = \frac{dh}{dx} \qquad (2.10)$$

Where; h is the total potential measured over distance, dx between points 1 and 2.

The Darcy equation which was derived by Henri Darcy in 1856 is useful in predicting flow in a porous medium such as soil. The Darcy velocity, v is given by;

$$v = -K^*i \tag{2.11}$$

Where K = the hydraulic conductivity of the soil (cm s^{-1})

i = the hydraulic gradient

The *(-)* sign signifies that flow is in the direction of falling groundwater head.

The Darcy velocity in the equation is an artificial velocity since it assumes that the flow occurs through the whole cross section of the medium. However, in practice, flow only occurs through certain pores and fissures hence an approximation of the actual velocity can be obtained by dividing the Darcy velocity by the effective porosity. The hydraulic conductivity under unsaturated conditions is a function of soil water content. In this case, the Darcy equation becomes;

$$v = -K(\theta_v)\frac{dh}{dx} \tag{2.12}$$

Where $K(\Theta_v)$ = hydraulic conductivity at given volumetric water content

A soil's hydraulic conductivity is influenced by the size, shape, and continuity of the pore spaces, which in turn are dependent on the soil bulk density, structure and texture. Soils with slow, very slow, rapid or very rapid hydraulic conductivity classification are considered poor for irrigation. The black cotton soils normally have very slow hydraulic conductivity within the range of that of clay soils of 10^{-9} to 10^{-5} cm s^{-1} (Chow *et al.*, 2012). This explains why the soils are poorly drained.

2.5 Main Production Constraints of Black Cotton Soils

The black cotton soils are generally difficult to work because of the hard consistence when dry and very plastic and sticky when wet therefore limiting their workability to a very short period just at the start of the rainy season when the moisture levels are just below field capacity. However for most farmers, the timing of tillage operations is often difficult because of the unpredictable pattern of the rains and also lack of appropriate tillage equipments. The sticky nature also makes the soil to pack under wheels, animal feet and clog cultivation implements. Where the soils are cultivated, close attention needs to be paid so as not to create a hard pan that may further restrict root penetration and downward movement of water (Ozzoy and Aksoy, 2007).

The soils are also imperfectly to poorly drained such that once they attain field capacity, there is practically no movement of water as a result of the low hydraulic conductivity. Continued rainfall would therefore lead to runoff resulting in soil loss and crop damage. Table 2.2 give a summary of management related constraints that impacts on the soil's suitability for agricultural production.

Table 2.2: Summary of Physical Characteristics of Black Cotton Soils that limit their suitability for Agriculture

Property	Soil Behaviour
Erodibility	The soils are highly susceptible to erosion because of its fine particles which are easily carried away by water or air. Erodibility factors of between 0.3 and 0.44 have been determined (Freebairn *et al.*, 1996)
Infiltration	High infiltration rates are observed in dry soils with cracks on the surface. However, once the soil surface is thoroughly wetted and the cracks have been sealed, the rate of water infiltration becomes almost nil (ISRIC – World Soil Information, 2007) hence high water application rates result in ponding at the soil surface. This limits the choice of the method for water application during irrigation.
Hydraulic conductivity	The black cotton soils normally have very slow hydraulic conductivity within the range of that of clay soils of 10^{-9} to 10^{-5} cm/s (Chow *et al.*, 2012). This leads to poor drainage conditions.
Porosity	This varies depending on the moisture content of the soil due to the swelling and shrinking characteristics but ranges between 0.4 to 0.7
Soil structure	This is a temporal characteristic whose size, shape and consistence is greatly influenced by the moisture regime. The most common structure is the sub angular to angular blocky type with wedge shaped aggregates
Consistence	The soil has a very hard consistence when the soil is dry but when wet, it becomes very plastic and sticky. The moisture at which the soil is friable is within a very narrow range just at the onset of the rains. This greatly affects the workability of the soil (Ozzoy and Aksoy, 2007).
Bulk density	This also varies with moisture content. Higher bulk densities are obtained when the soil is dry. Bulk densities range between 1 g/cm^3 to 2 g cm^{-3} (Eswaran and Cook, 1988)

Swelling and shrinkage	Loss of soil moisture results into a reduction in soil volume until a certain threshold moisture content is reached below which deep cracks wider than 1 cm starts to form (Kutilek and Nielson, 1994). The shrink-swell characteristic of the soil can shred or strangle the crop roots (Eswaran and Cook, 1988)
Available water	The total water holding capacity for the soil is high with values between 200 mm and 300 mm being recorded in a profile (Virmani, 1988). However the range of readily available water is low because of the high affinity with which the water molecules are held by the clay particles

2.6 Soil Management Practices for Improved Crop Production

Based on the above constraints, various management practices have been suggested and adopted for black cotton soils. These management practices combined with improved cultivars and cropping systems offer varied degrees of productivity and sustainability. The practices include:

2.6.1 Soil heating and burning.

Burning causes the clay fraction to fuse to sand sized particles. This method has mainly been practiced in Ethiopia. The soil is left fallow for 10 -20 years after which the land is ploughed towards the end of the dry season. The top soil is then heaped and burnt. The temperature at the centre of the heap may exceed 650 ^{o}C making the clays to loose their crystalline and colloidal properties (Ahmad, 1996). However, it is constrained by the high energy losses since open fires are often used which are also destructive to vegetation and soil organisms. There is no uniformity in soil heating either across the land surface or depth wise. Since there is no controlled heating, the temperatures attained may be too low to make any significant impact on the soil properties or too high to result in stone like materials that may require re-weathering to make them suitable for crop production.

2.6.2 Flood Fallowing

This is achieved by flooding the land for 6-9 months until the land is submerged to a depth of 30 - 45 cm. The gases produced by anaerobic fermentation of organic matter and redistribution of oxides help initiate aggregation and improve rooting conditions (Ahmad, 1996). This method requires large amounts of water to be able to satisfy the flooding and high evaporation requirements.

2.6.3 Deep Ploughing

This is a method of tillage applied on black cotton soils to break the hardened sub soil and hence improve the hydraulic properties of the soils. However, due to the high amounts of swelling clays, tillage which aims at changing the natural aggregation is relatively short lived and fight against the natural forces (Yule and Willcocks, 1996) Heavy machinery is required to pull the implements through the soil. The cost of using such machinery is often out of reach of most farmers.

2.6.4 Surface Drainage

Since sub-surface drainage is not feasible in these soils, special attention is often given to surface drainage systems. This include shaping the land through the use of cambered beds, ridges, furrows, bunding and broadbanks which have been applied in a number of countries including Ghana, India and the USA (Eswaran and Cook, 1988). However, according to Swindale (1988), these technologies have had limited success.

2.6.5 Use of Soil Amendments

Various methods have been suggested for the improvement of the black cotton soil. These include the use of soil amendments such as organic matter and sand. Some farmers also use borrow soil. This is reportedly being practiced in Kenya where tree planting holes are filled with red Alfisols brought from other areas (Eswaran and Cook, 1988). This method is only feasible where such soils are available close to the farms otherwise the cost of transport may be prohibitive. In addition, use of borrow soil may introduce undesirable chemical and biological characteristics to an area.

Sand can been used to improve the texture of the soils. The use of sand is based on the presumption that it will impart its good drainage and aeration. However, apart from the unavailability of the sand within the localities together with the accompanying costs, Chalker-Scott (2009) argues that in order to make any appreciable impact, a soil must consist of nearly 50% sand by total volume before it takes on the characteristics of sandy soil. Mixing sand and clay often results into a heavier, denser soil with less total pore space than either the sand or clay alone. The other challenges are in terms of the cost of procuring and transporting the sand to site and carrying adequate mixing in the normal root depth ranges required by crops. The increased demand for sand by the construction industry has also made it expensive reduced availability.

When organic matter is used, large amounts are required in order to change both the texture and structure of the clay appreciably. Even when this is achieved, it can only be beneficial in the short term because the organic matter will with time, be broken down into fine particles with physical properties similar to the clay itself.

2.6.6 Irrigation

Irrigation problems specific to the black cotton soils include water use regulation and efficiency; water quality and its monitoring; and water conducting systems. Water application is limited by the soil's intake rates due to the cracking and sealing of the soil. The swelling and shrinking of the soil affects the stability of irrigation structures and due to non uniformity of leaching, salinization becomes difficult to remedy (Ahmad, 1996). Surface irrigation methods as practiced in the Kano plains narrows down the range of crops grown to crops such as rice, sugarcane, cotton. This method of irrigation waste water and in cases where the land is not leveled may result in severe erosion.

2.7 Rice Husk

Rice husk is the coating on a seed or grain of rice. It is also referred to as rice hull andis formed from hard materials, including silica and lignin, to protect the seed during the growing season. Each kg of milled white rice results in roughly 0.28 kg of rice husk as a by-product of rice production during milling (http://www.knowledgebank.irri.org). According to Habeeb and Mahmud (2010), it accounts for approximately 20% of the annual world production of rice estimated to be 647.9 million tons.

Rice is the second most cultivated crop both in terms of area and production in the world. Table 2.3 gives a summary of selected physical and chemical properties of rice husk (Sutas *et el.,* 2012*;* Mansaray and Ghaly, 1997)

Table 2.3: Properties of Rice Husk

Property	Range of values		Unit
	Minimum	Maximum	
Moisture content	5	16	%
Bulk density	83	125	Kg/m^3
Length	6.2	10	mm
Width	1.7	2.4	mm
Volatile matter content	63	70	%
Fixed carbon (% dry basis)	10.2	14.5	%
Ash content	15.3	24.6	%

The collection and disposal of rice husk has been difficult and expensive hence left as waste material or simply burned but also has some uses. Mansaray and Ghaly (1997) studied the properties of rice husk when used fuel in which they analyzed various varieties of rice. It was concluded that rice husk forms a unique biomass material that can be used as fuel.

Sutas *et al*. (2012) added rice husk to clay in ratios ranging from 0 to 10% and determined the effect on bulk density of clay bricks. The mixtures were fired at 700^{o}C. It was observed that the higher rice husk ratio increased the pore volume and decreased the bulk density.

Habeeb and Mahmud (2010) used rice husk ash as a cement replacement material. It was concluded that the ash is efficient as a pozzolonic material due to the high content of amorphous silica.

2.8 Hydroponics

The term hydroponics is derived from two Greek words; *hydro* meaning water and *ponos* meaning working, thus literally meaning ‘water working’. In practical use, it means growing plants in a water and nutrient solution without soil or ‘soil-less culture’. Soil has simply been the holder of plant nutrients, a place where plant roots traditionally live and a base of support for the plant structure. If the nutrients are availed to plants in other ways, then soil would not necessarily be required thereby limiting its accompanying negative characteristics such as unfavourable compaction, poor drainage, degradation (Singh, 2009).

The technology can be traced back to 1936 when the word 'Hydroponics' was coined by Dr. W.F. Gericke (Murali, *et al.*, 2011). Commercially, the technology is currently adopted in most countries (mainly in the Western world) to grow vegetables, herbs and ornamentals. Among the leading countries in adoption of the technology are Israel, England, Australia, Netherlands, Spain and Canada (Carrunthus, 2005; Murali, *et al.*, 2011). In Africa, it has been adopted in South Africa and Kenya mainly for growing vegetables and ornamentals.

Common hydroponic systems include aquaculture or aquaponics where the plants are grown with their roots immersed in water containing dissolved nutrients; aggregate culture where inert porous medium is used to support the plant roots; and aeroponics where the plant roots are hung in air and misted regularly with nutrient solutions.

Recent advances in hydroponics technology make it a suitable alternative for crop growing in areas with black cotton soils. When combined with controlled environment agriculture such as greenhouses, it may result in increased quantity and quality of produce. It is also feasible where land is scarce. The challenge therefore is to develop a cost effective system relevant to local conditions. According to Carrunthers (2005), these include the need to develop water-efficient, sustainable growing systems to supply high quality, safe products that are needed for quality life while maintaining a healthy planet.

2.8.1 Advantages and Limitations of Hydroponics

The following are some of the reasons for the preference towards hydroponics (Wahome, *et al.*, 2011; Singh, 2009; Carrunthus, 2005):

i. Plants grow up to 50% faster than in soil because they have easy access to nutrients and water.
ii. Plants become ‘vacation proof’ and ‘neglect resistant’.
iii. Nutrients are directly available to plants and do not get bound up.
iv. Little or no pesticides are necessary because plants start from disease free medium.
v. Smaller containers can be used because roots can grow without being root bound.
vi. Gardening is possible where it would not be normally e.g. rocky areas.
vii. Less labour is required because there is no digging or weeding
viii. Better quality produce and higher yield due to increased control over growing conditions.

However, the technology also experiences some limitations. These include;

i. High initial capital expenditure especially when combined with controlled environment agriculture
ii. It requires considerable degree of management skills compared to open field agriculture
iii. Because of the costs involved, it is appropriate for high value crops
iv. Yields may reduce when the temperature of the solution increases.

2.8.2 Hydroponic Systems

Hydroponic systems are broadly categorized as aeroponics, aquaponics and aggregate culture. In **aeroponics**, the roots of plants are kept in an environment saturated with fine drops of nutrient solution. This system has the major advantage of excellent aeration and wide range of crops that can be grown. It also uses relatively less water. Although its commercial viability has been argued for, it has not been commonly adopted and is mainly limited to laboratory studies.

Most **aquaponic systems** combine aquaculture (fish farming) with crop production. In aquaponics, the crops are supported so that their roots hang in a nutrient solution. This system is considered to offer increased water use efficiency. However, Roe and Modmore (2008) argues against the viability of most aquaponic or aquaculture systems. He notes that there is still lack of sufficient aquaponic data which meet the scientific standards for modeling under a variety of biotic and abiotic conditions. Most aquaponic investors are also not sufficiently skilled on the dynamics involved. Of major concern is that 1kg of water can only hold 8 mg of air no matter whether aerators are used or not. This means that only certain species of plants can survive for long before being waterlogged.

Aggregate systems use inert solid material which has most of the desirable physical properties of soil such as flexibility, being friable, good water holding properties, easily aerated and drained. The growing medium cannot grow anything on its own since it does not supply plant nutrients. The nutrients are supplied to the plants by a nutrient solution. However, Safrovitz (2011) observes that many growers are confused or reluctant to use some mediums due to lack of experience, lack of performance information and/or ignorance regarding use of the medium in the short or long term.

If prepared properly, the aggregate medium can improve growth of crops including a wide variety of vegetables, ornamentals and some fruits. Successful adoption of aggregate media can reduce both costs and risk associated with importing soils whose chemical and biological quality has not been ascertained.

Although hydroponic systems have been developed and adopted in several parts of the world, Safronovitz (2011) observes that there is a general uncertainty in the use of available growing media. Many growers are confused or reluctant to use some hydroponic media due to lack of experience, lack of performance information, and/or ignorance. The development of such media therefore needs to be evaluated and results communicated to the growers so that they can make informed choices.

Singh (2009) also notes that there is generally a negative attitude towards hydroponic technology because of the influx of 'instant experts' being the biggest danger to the growth and development of hydroponics. These self styled authorities often make extravagant claims and sell many shabby, poorly made copies of workable hydroponic units just for their own financial benefit. The challenge is therefore to academicians and institutions to take up their rightful role in the development of efficient, properly designed equipment for the technology to be economically viable.

Successful adoption of hydroponic technology in Kenya will provide a boost to the agricultural sector on which about 75% of the population depends on for food or income. This sector also contributes 26% and 60% to the country's gross domestic product and foreign exchange respectively (Mzoba, 2012). However the full potential has not been achieved and can be enhanced.

There are several types of commercially available aggregate media. Singh (2009) has categorized these into four groups.

i) inorganic natural media e.g. gravel
ii) organic natural media e.g. rice husk
iii) inorganic artificial media e.g. rockwool
iv) organic artificial media e.g. polyphenol

Commonly used aggregate media in hydroponic systems have been discussed by Kevin, (2011), Singh (2009) and White (2004). They include;

a) Rockwool

This is a popular growing medium produced from volcanic rock and limestone which are melted at temperatures of 2500^{o}C or higher. The rock is melted and spun into fibrous cubes and growing slabs. It has high water holding capacity and can also retain as much as 20% air. It is inorganic, very light when dry, sterile and not degradable.

b) Perlite

This is volcanic rock which when heated in excess of 1000^{o}C, expands into light weight particles. It is often used in potting soil mixes to decrease soil density. It has good wicking properties but has poor water retention. Pertilite dust is also harmful to human health.

c) Vermiculite

This is a natural mineral which expands on the application of heat. It is formed by hydration of certain basaltic minerals. As hydroponic medium, it holds more water than perlite and has good wicking properties hence suitable for passive systems. It can also be used as a soil conditioner.

d) Crushed Granite

The granite rock is crushed and screened to a particle size of 2 mm. It is totally inert, but has relatively low water retention capacity. However, it can be re-used over a longer period of time. It offers good aeration and does not break down in structure. It has high density and therefore considered too heavy for some hydroponic systems.

e) Expanded Clay Pellets

These are round pellets formed out of clay in rotary kilns at about 1200^{o}C. This causes the clay to expand and become porous resulting in pellets which are inert, lighter in weight which does not compact over time. The pellets are rounded in shape and fall from the kiln in a grade of approximately 1 - 32 mm with an average dry bulk density of approximately 0.35 - 8 g cm^{-3}. Although these pellets are considered re-usable breaking a clay pellet after a crop has grown normally reveals root growth within the medium thereby casting doubt on reusability. Also, compared to other hydroponic media, they are relatively heavy and hence not suitable for certain hydroponic systems. In addition, they have been found to drain out fast because there is much space between the individual pellets.

f) Other hydroponic media

Other growing media for hydroponic systems are coarse washed river sand; coarse fir saw dust; coco coir, pumice and scoria which have different degrees of preference due to their varied characteristics (Singh, 2009).

2.8.3 Selection of Aggregate Medium

A good hydroponic medium should posses the following desirable characteristics;

i) It should be of light weight and low density
ii) It should be loose to allow easy root penetration
iii) It should drain easily
iv) It should have good water holding capacity
v) It should have moderate permeability to allow for easy movement of water, air and solute (nutrients) through it
vi) It should not compact and should remain friable over a wide range of moisture contents
vii) It should remain inert over at least one crop growing season.

Selection of a suitable medium therefore involves determination of its physical characteristics, plant performance and sometimes its cost and availability. Safrovitz (2011) carried out experimental trials to compare the performance between coco coir (palm pith), perlite, vermiculite, saw dust and also their mixes in different proportions. The trial used tomato crop which was subjected to similar environmental conditions and nutrient feed across the mediums. It was concluded that coco coir and perlite performed best among the mediums used in the trial but noted that results could vary depending on the hydroponic method used.

Common plant attributes that can be used to assess performance include leaf area index, stem growth and root development. Root and stem growth are affected by the composition and texture of the medium (Maloof, 2004). Root length density (RLD) is a critical factor in determining the crop's potential to uptake water and nutrients. RLD can be affected by irrigation method, growing medium texture and bulk density (Rangjian *et a*l., 2017). Water and nutrients taken up by the roots are transferred to the leaves through the stem for use in photosynthesis. The roots also provide anchorage to the plant have more surface area than the shoot system (Wahome *et al.*, 2011).

2.9 Methods of Determining Hydraulic Properties of Porous Medium

A large number of laboratory and field methods have been developed to determine soil hydraulic functions. Most of these methods are difficult to implement and are relatively costly. These methods are discussed in detail by Durner and Lipsius (2005). The characterization of soil water retention and unsaturated hydraulic relations over a wide range of volumetric water contents has been made possible by the increased availability of simulation models which are easy to use and are able to accurately predict flow of water and solute transport in soils. The models include indirect estimation of soil hydraulic properties from other easier to measure physical properties such as soil texture and structural characteristics. These involve the application of multi-step outflow techniques and the neural outflow techniques (Kosugi *et al.*, 2002; Hopman *et al.*, 2002; Dane *et al.*, 2002; Tuli *et al.*, 2001).

Functional descriptors of water flow and transport can also be derived from parameters of soil hydraulic functions such as in the use of pedotransfer functions to define land and soil quality indicators. For example, Minasny *et al.* (2004) successfully developed pedotransfer functions that simultaneously predicted water retention and hydraulic conductivity by neural network analysis. However, due to the spatial and temporal variability of soil properties, it was noted that the predictions may not be accurate outside the range of soil textures included in their training dataset. Schaap *et al.* (2001) notes that the practical application of pedotransfer functions is hampered by their very specific data requirements especially where one or several input variables are not available. A good pedotransfer function should therefore accept input data with varying degrees of detail as well as provide reliability measurement.

The use of neural networks to establish empirical pedotrasfer functions have the advantage that optimal, non-linear relations that link input data to output data are obtained and implemented in an iterative calibration procedure. This enables the models to extract maximum information from the data. Their disadvantage is that they contain a large number of coefficients that do not permit easy interpretation in explicit form.

Due to the existing variability in soil properties, the individual pedotransfer functions need to be tested for each soil type or porous medium to evaluate their suitability. If found to be physically realistic, they can be used to interpolate or extrapolate to parts of the hydraulic conductivity or retention curves for which little or no data is available. Results from previous research have however shown that the predictions work relatively well for the coarse textured soils but are less accurate for fine textured soil (van Genuchten *et al.*, 1991) but more recent developments are intended to even out the level of accuracy.

The Richards equation developed in 1931 has been traditionally used to describe water flow in unsaturated or partly saturated soils. It expresses the water flow as;

$$C\frac{\partial h}{\partial t}=\frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z}-K\right) \quad (2.13)$$

Where h is the soil water pressure head (with dimension L),

t is time (T),

z is soil depth (L),

K is the hydraulic conductivity (LT^{-1}),

C is the soil water capacity (L^{-1}) approximated by the slope *($d\Theta/dh$)* of the soil water retention curve, $\Theta(h)$ and

Θ is the volumetric water content (L^3L^{-3}).

In terms of moisture content, the same equation would be expressed as;

$$\frac{\partial \theta}{\partial t}=\frac{\partial}{\partial z}\left(D\frac{\partial \theta}{\partial z}-K\right) \quad (2.14)$$

Where D is the soil water diffusivity (L^2T^{-1}), defined as;

$$D=K\frac{dh}{d\theta} \quad (2.15)$$

Various models have been developed to estimate the hydraulic properties. These include;

2.9.1 The van Genuchten-Mualem (1980) model

$$\theta(h)=\begin{cases}\theta_r+\dfrac{\theta_s-\theta_r}{\left[1+|\alpha h|^n\right]^m} & h<0\\ \theta_s & h\geq 0\end{cases} \quad (2.16)$$

$$K(h)=K_sS_e^{\,l}\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \quad m=1-1/n,\ n>1 \quad (2.17)$$

Where h – pressure head [L]

θ_s - saturated water content [-]

θ_r - residual water content [-]

α, m, n - empirical parameters [1/L], [-], [-]

S_e - effective water content [-]

K_s - saturated hydraulic conductivity [L/T]

K_r - relative hydraulic conductivity [-]

$K(h)$ - unsaturated hydraulic conductivity at a given pressure head [L/T]

l – pore connectivity parameter [-]

2.9.2 The van Genuchten-Mualem model with an air-entry value of -2 cm,

$$K = \begin{cases} K_s S_e^{\,l} \left\{ \frac{1}{2} erfc \left[\frac{\ln\left(h/\alpha\right)}{\sqrt{2n}} + \frac{n}{\sqrt{2}} \right] \right\}^2 & h<0 \\ K_s & h>0 \end{cases} \tag{2.18}$$

Where *erfc* is the complementary error function.

2.9.3 Modified van Genuchten (1988) type equations

$$\theta(h) = \begin{cases} \theta_a + \frac{\theta_m - \theta_a}{\left(1 + |\alpha h|^n\right)^m} \\ \theta_s \end{cases} \tag{2.19}$$

$$K(h) = \begin{cases} K_s K_r(h) \\ K_k + \frac{(h - h_k)(K_s - K_k)}{h_s - h_k} \\ K_s \end{cases} \tag{2.20}$$

2.9.4 The equations of *Brooks and Corey* (1964)

$$S_e = \begin{cases} |\alpha h|^{-n} \\ 1 \end{cases} \text{ at } h < -1/\alpha \text{ and } h \geq -1/\alpha \text{ respectively} \tag{2.21}$$

$$K = K_s S_e^{2/n + l + 2} \tag{2.22}$$

Where;

S_e is the effective saturation given by;

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{2.23}$$

2.9.5 The log-normal distribution model of *Kosugi* (1996)

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \begin{cases} \frac{1}{2} erfc\left\{ \frac{\ln\left(h/\alpha \right)}{\sqrt{2n}} \right\} \\ 1 \end{cases} \text{ at } h<0 \text{ and } h \geq 0 \qquad (2.24)$$

The residual water, Θ_r content specifies the maximum amount of water in the soil that will not contribute to liquid flow. The saturated water content, Θ_s of a soil denotes the maximum volumetric water content. *ά* is an empirical parameter whose inverse is referred to as the air entry value and *n* and *m* are pore size distribution parameters which affect the slope of the retention curve. The pore connectivity parameter, *l* for undisturbed soils as been estimated as a average of 0.5. However this leads to misinterpretation of hydraulic conductivity at low degrees of saturation. researchers found that negative values of *l* often yielded good fitting of experimental data (Smyl, 2018).

2.10 Predicting the Hydraulic Parameters

The coefficients Θ_r, Θ_s, α, *m, n, l* and K_s used in solving the hydraulic functions are known as the hydraulic parameters. In order to estimate these parameters, various models with varied capabilities have been developed which apply the techniques of pedotransfer functions and neural networks to solve the equations for hydraulic conductivity and water retention. Some of these models are;

2.10.1 RETC Program

The **RET**ention **C**urve is a computer program for analyzing or predicting the unsaturated soil hydraulic properties. It is a public domain code which has been tested over a wide range of soil hydraulic datasets. It uses the parametric models of Brooks-Corey and van Genuchten to represent the soil water retention curve and the theoretical pore size distribution models of Mualem and Burdine to predict the unsaturated hydraulic conductivity functions from observed soil water retention data. (van Ganuchten *et al.*, 1991)

The RETC code can be used to fit any or all of the independent soil hydraulic parameters (Θ_r, Θ_s, *ά, n,m,l* and K_s) simultaneously to the observed data. It uses a non linear least squares optimization approach to estimate the unknown model parameter from observed retention and/or conductivity data. The output includes a matrix which specifies the degree of correlation between fitted coefficients in different hydraulic models. It also provides additional statistical information about the fitted parameters such as the mean, standard error, the T-value and lower and upper confidence limits. The T-value is obtained from the mean error, b_j and standard error, $s(b_j)$ as;

$$T = \frac{b_j}{s(b_j)} \qquad (2.25)$$

2.10.2 ROSETTA Model

The ROSETTA model version 1.1 was developed by the USDA – Agricultural Research Service in 2003. It can be used to estimate the following;

i) water retention parameters according to van Genuchten model of 1980

ii) saturated hydraulic conductivity

iii) unsaturated hydraulic conductivity parameters according to van Genuchten model and the Mualem model of 1976

It offers five pedotransfer functions that allow prediction of hydraulic properties with limited or more extended sets of input data in a hierarchical sequence as follows;

i) soil textural class

ii) sand, silt and clay percentages

iii) sand, silt and clay percentages and bulk density

iv) sand, silt and clay percentages, bulk density and water retention at 33 kPa

v) sand, silt and clay percentages, bulk density and water retention points at 33 kPa and 1500 kPa

The first model is based on a look up table that provides class average hydraulic parameters for each USDA soil textural class. The other four functions are based on neural network analyses and provide more accurate predictions when more input variables are used. In addition to the hierarchical approach, it allows prediction of the unsaturated hydraulic conductivity parameters from fitted van Genuchten retention parameters (ARS-USDA, 2016), An overview of the performance of the hierarchical models for the estimation of water retention parameters by Schaap *et al.* (2001) showed that correlations between fitted and estimated parameters increase and the root mean squared errors decreased when more predictors were used. The residual water content was more difficult to estimate for all models while the saturated water content was difficult to estimate without information on bulk density. The calculated mean errors also showed that the pedotransfer functions underestimated water retention and unsaturated hydraulic conductivity at relatively higher suctions.

2.10.3 HYDRUS Model

The HYDRUS 1D Version 4.16 is designed to simulate one dimensional movement of water, heat and multiple solutes in variably-saturated media. It includes modules for simulating carbon dioxide and major ion solute movement. It can be used to analyze water and solute movement in unsaturated, partially saturated or fully saturated media (Simunek *et al.*, 2013). It is applicable both in the field and laboratory studies. The code allows users to select from six types of models for the soil hydraulic properties, that is;

i) the van Genuchten-Mualem model,
ii) the van Genuchten-Mualem model with an air-entry value of -2 cm,
iii) modified van Genuchten type equations,
iv) the equations of *Brooks and Corey,*
v) the log-normal distribution model of *Kosugi* and
vi) the dual-porosity model

The HYDRUS 1D is a public domain windows based software. The model is applicable in a wide range of research on soil and water systems. For one dimensional uniform water flow in a partially saturated rigid medium, the Richard's equation has been modified using the assumptions that the air phase plays an insignificant role in the liquid flow process and that water flow due to thermal gradients can be neglected (Simunek *et al.*, 2009). Hence the equation in the form used in HYDRUS becomes;

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x} + \cos\alpha\right)\right] - S \qquad (2.26)$$

Where; h = pressure head (L)

Θ= volumetric water content (L^3L^{-3})

t = time (T)

x = spatial coordinate (L)

S = sink ($L^3L^{-3}T^{-1}$)

$\acute{\alpha}$ = angle between flow directions and vertical axis (i.e. $\acute{\alpha} = 0^o$ for vertical flow, 90^o for horizontal flow and $0^o < \acute{\alpha} < 90^o$ for inclined flow)

K = the unsaturated hydraulic conductivity (LT^{-1}).

The flow equation is solved numerically using the Galerkin type linear finite element scheme. The model has been applied successfully in various studies. Honar *et al*. (2011) used the model to study water movement in soil under sprinkler irrigation system and evaluated the soil hydraulic parameters with regard to depth during irrigation. Schneder *et al.* (2012) estimated the hydraulic properties of the concrete and mortar used as engineering barriers to near surface disposal of low level radioactive waste in which they found that the optimized *Ks* values were in agreement with literature values for similar concrete and mortar. Stump *et al*. (2012) investigated the differences in water flow and solute transport due to different land use in five long-term lysimeter studies in which HYDRUS 1D was modified to adjust the upper solute boundary conditions.

In general, the HYDRUS model can be used to simulate such processes as precipitation, irrigation, infiltration, evaporation, root water uptake (transpiration), soil water storage, capillary rise, deep drainage, groundwater recharge and lateral flow. It can also be used to evaluate surface runoff and estimate actual evapotranspiration from potential values (Simunek *et al*., 2012). The advantage of the models is that they are not limited to any particular spatial or temporal scale provided that the governing equations are formulated properly and can be used at that scale. The models have been used at scales ranging from small laboratory soil columns to agricultural applications for soil profiles up to several meters deep.

2.11 Scope and Limitations

Soil is an important natural medium for plant growth. However its suitability for agriculture can sometimes be hampered by some of its undesirable characteristics. In hydroponics, soil is replaced as a growing medium. The medium so selected should however have physical and hydraulic properties which imitate as much as is practicably possible those of an ideal soil based on the crop(s) to be grown.

Most of the hydroponic media currently available commercially have not been technically evaluated for suitability to local farming conditions. There is limited data on their preparation requirements and performance. Hence farmers find it difficult to select and adopt them for their hydroponic ventures. This study borrowed on the successes of expanded clay aggregates and seeks to improve on some of the limitations while setting standards for low cost processing and utilization adaptable to local areas using black cotton soil and rice husk as the primary raw materials.

The study was based on samples of black cotton soil obtained from a single location. This is despite the fact that soil properties are highly heterogeneous and anisotropic. The soil samples were therefore only considered representative to the extent of the study. The rice husk was from a milling plant which mainly process paddy rice grown in Western Kenya. Properties of rice husk vary with the variety as observed by Mansary and Ghaly (1997). However the samples used cannot be attributed to a particular rice variety. This is because during milling of rice, the rice husk produced is channeled to the same holding point and therefore cannot be segregated based on variety.

Several models have been developed and successfully applied to predict soil hydraulic properties from basic soil properties. However, the applicability of such models to artificially modified soil medium such as the expanded clay aggregates or other porous media also need to be evaluated in order to guide their adoption. The HYDRUS 1D model was used to estimate the hydraulic functions based on the van Ganuchten – Mualem equations.

CHAPTER THREE

MATERIALS AND METHODS

3.1 The Study Area

The black cotton soil samples were collected from the Kenya Agricultural and Livestock Research Organization (KALRO), Kibos Center. KALRO Kibos lies at an altitude of 1173 m above mean sea level, about 8 kilometers from Kisumu City in Kenya. It has heavy black clay soils (vertisols), which are fairly typical of the Kano Plains. Out of its 20 hectares land, 15 hectares is specifically set aside for experiments. The sampling site lies within the Kano plains which is synonymous with the lower course of Nyando River. The plain is sandwiched between the Nandi hills and the Nyabondo plateau and occupies an area of approximately 43000 ha. Figure 3.1 shows the Kano Plains and adjacent areas.

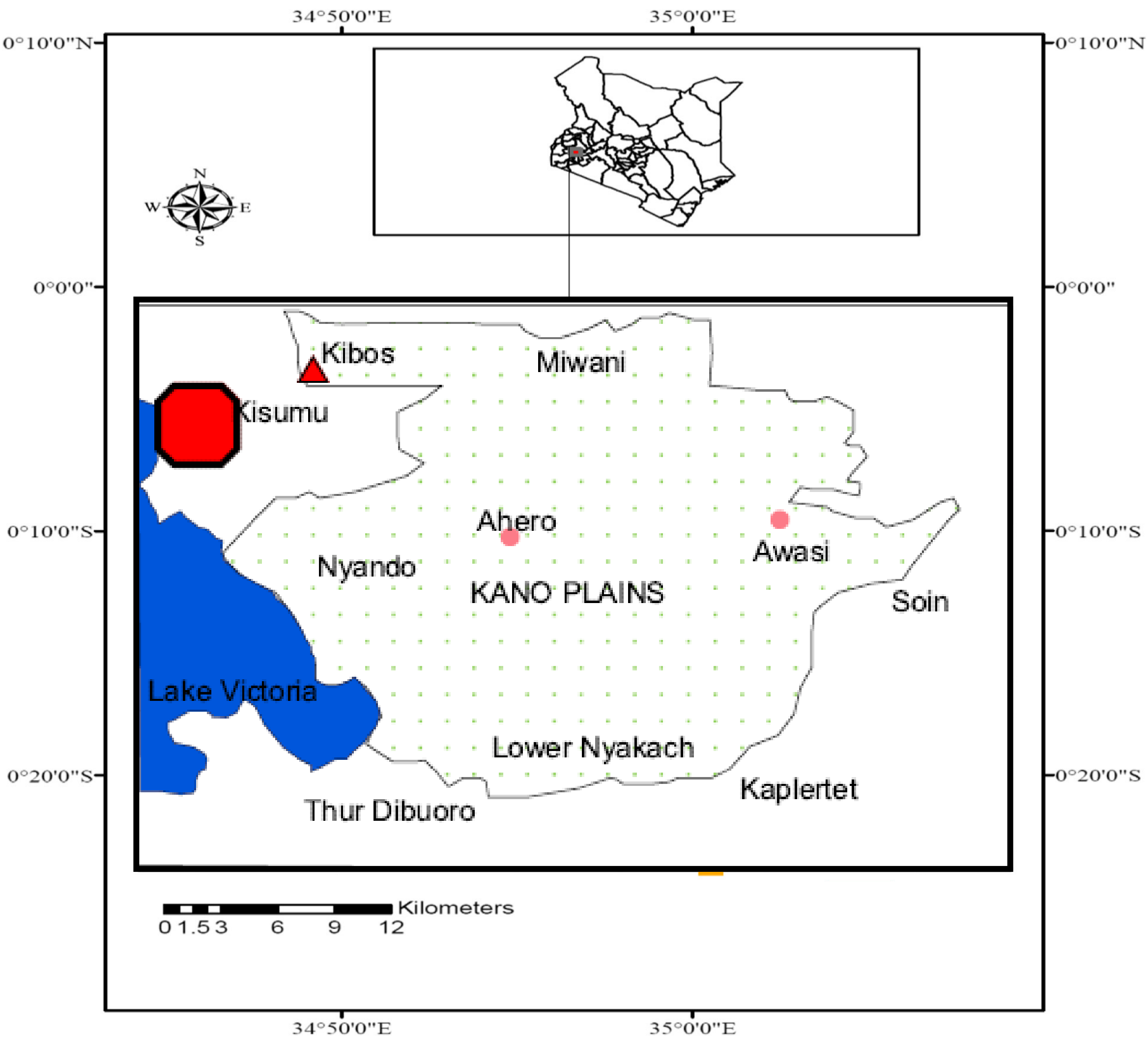

Figure 3.1: The map of Kano Plain, Kenya (Modified from Okayo *et al.*, 2015)

The plain comprises predominantly black cotton clay soils with moderate fertility and poor drainage. At least 40 000 ha of the plain is at risk of flooding because it lies in a flat terrain that does not allow easy flow of water into the waterways. The black cotton soils only allow slow infiltration of surface water into the ground further compounding the drainage problem. Floods in the area are mainly caused by the high rainfall amounts received in the upper reaches of Nyando River Basin in Kericho and Nandi areas (Nyakundi *et al.,* 2010).

The nearest, reliable metereological station is Kisumu which according to Thornwaite's criteria is classed as an 'Equatorial humid' station with an annual mean temperature of 24.5^{o}C, an evaporation rate of 1759 mm per annum and annual rainfall of 1270 mm (Millman, 1973). The area experiences a high variability in rainfall distribution making agriculture to be a risky undertaking with high incidences of crop failure either due to floods or rain failure. Therefore, the area is a net importer of food. The main crops currently grown in the area are sugarcane, cotton, rice, maize and sorghum (Onyango, 2002) but the potential to diversify further the choice of crops is high if the soil related problems are addressed. Rice is grown under irrigation either using water from Lake Victoria or from rivers Awach Kano and Nyando which pass through the area. The produce is processed in the privately owned mills and government owned mills such as the Lake Basin Development Company in Kisumu and the National Irrigation Board milling plant at Ahero. The milling process produces white rice used for human consumption, rice germ used to prepare livestock feed and rice husk which is often disposed as a waste material and to a lesser extent as bedding for livestock.

The rice husks were obtained from the Lake Basin Development Company (LBDC) Kibos rice mills. The mill has a though-put for cleaning and drying of 25,000 tons per hour and a milling capacity of 24000 tons per year. It is located about 2 km from KALRO, Kibos along the Kibos - Kisumu road.

3.2 Preparation and Evaluation of Expanded Black Cotton Soil

The black cotton soil and rice husk samples were transported to Egerton University, Njoro where the evaluations were undertaken. Wet sieving was done on the soil samples collected to ascertain that they were representative of the soils in the area. The results were therefore compared with those obtained from soil survey data for the area to establish that the samples were not from borrow soil or had not been adversely modified due to human action.

The black cotton soil was air dried, pounded to break the clods and mixed at predetermined ratios with the rice husks on a weight basis. The mixture was moulded after wetting with water into cylindrical blocks. This was accomplished by using a cylindrical galvanized iron mould and wooden extruder. The mould dimensions were 52 mm in diameter and 100 mm in height. The blocks were then dried in an oven at 105°C for a period of 48 hours before firing in an electric furnace at regulated temperatures. The oven drying process was aimed at expelling the water without combusting the organic matter present.

3.2.1 Black Cotton Soil – Rice Husk Mixing Ratios

The black cotton soil was mixed with rice husks at different ratios as given in Table 3.1. Rice husk is a light weight organic material and is easily combusted. By incorporating the rice husks, there was more room to vary porosity and subsequent bulk density of the blocks. This was achieved by varying the proportion of rice husk during preparation from 0 to 10% by weight.

Table 3.1: Black cotton soil to rice-husk mix ratios

Black cotton soil (% by weight)	Rice husk (% by weight)
90	10
95	5
97.5	2.5
100	0

Higher amounts of rice husk above 10% could not permit adequate bonding by the clay and collapsed when removed from the mould. This is because the volume of the rice husk far exceeded that of the black cotton soil. The bulk density of the fired blocks was determined based on the mass of the dried blocks and the internal volume of the mould assuming there was negligible shrinkage,

3.2.2 Firing Temperature and Time

The dry blocks were fired under varied but controlled temperatures in an electric furnace. The firing temperatures were 700°C, 750°C and 800°C. The temperature range was chosen because all clay bodies contain some measure of carbon, organic materials, and sulfur which burn off at between 300°C and 800°C. At 573°C, there is quartz inversion of silica which changes its crystalline form (Karaman *et al.*, 2006). The clay particles then fuse together at approximately 900^{o}C. Although the materials were not subjected to this temperature it is envisioned that the organic matter content would, at elevated temperatures higher than 600^{o}C lead to glowing combustion and the resulting flaming could boost the temperatures to between 800^{o}C and 1500^{o}C resulting in the desired fusion of the clay (DeBano, 1990).

The firing time was the duration from when the desired temperature was attained in the furnace until when the furnace was switched off. The times were 30 minutes, 60 minutes and 90 minutes for each of the temperatures. The bulk density of the fired block was determined from which the percent reduction was computed as;

$$\%changebd = \frac{\left(\rho_{b(unfired)} - \rho_{b(fired)}\right)}{\rho_{b(unfired}} * 100 \qquad (3.1)$$

Where ρ_b = bulk density of the blocks (g cm^{-3})

The subscripts *uf* and *f* represented unfired and fired conditions respectively.

3.2.3 Size Reduction

Size reduction of the expanded clay blocks was done mechanically to obtain smaller aggregates within the particle size range of soil. The aggregates were passed through a series of soil test sieves. This was done to separate them into gravel, coarse sand, fine sand, silt and clay sized aggregates. The aggregates retained in each sieve were mixed proportionately at predefined ratios. The sieves and mix proportions used were as described in Table 3.2;

Table 3.2: Soil Test Sieves used

Sieve number	Sieve opening size (mm)	Description of particles retained	Mix proportion (%)
4	4.750 mm	Discarded	
10	2.000 mm	Fine Gravels	10
20	0.850 mm	Coarse sand	40
200	0.075 mm	Fine sand	40
Pan		Clay and silt	10

3.2.4 Effect of Black Cotton Soil – Rice Husk Mix Ratio, Firing Temperature and Firing Time on Bulk Density and Saturated Hydraulic Conductivity.

The bulk density was computed as function of the dry mass divided by the total volume for the blocks before firing, after firing and for the aggregates upon size reduction. For the blocks, this was the mass of the block divided by the volume of the mould assuming no shrinkage. For the aggregates, a density bottle was used. The bottle filled with aggregates was slightly tapped to enable packing as would result if water was added. The bulk density was obtained from Equation 3.2 as,

$$\rho_b = \frac{M_{(a+b)} - M_b}{V_b} \tag{3.2}$$

Where ρ_b = dry bulk density in g cm^{-3}

$M_{(a+b)}$ = mass of aggregates plus bottle in grams

M_b = mass of empty bottle in grams

The saturated hydraulic conductivity was determined using the constant head permeameter due to the coarse textured properties of the resulting aggregates when compared with the original black cotton soils. For the constant head method, the saturated hydraulic conductivity, K_{sat} (cm s^{-1}) was computed using Equation 3.3 as;

$$K_{sat} = \frac{qL}{Ah} \tag{3.3}$$

Where q = discharge in cm^3 s^{-1}

L = length of specimen (cm)

A = cross-sectional area of the specimen (cm^2) and

h = constant head causing flow (cm)

The results were analyzed using the three-way factorial ANOVA at 5% level of significance. The factors were as summarized in Table 3.3 resulting in 36 experiments for each property evaluated.

Table 3.3: Experimental Factors and the Levels used

Factor	**Levels**			
	I	II	III	IV
Temperature (^oC)	700	750	800	
Time (minutes)	30	60	90	
Black cotton soil (%)	90	95	97.5	100

The factorial ANOVA was computed using the SAS studio. Tukey adjustment was used to determine the significant difference in the effects. Pearson correlation analysis was carried out to measure the strength and direction of association that existed between the variables measured.

3.3 Estimation of the Hydraulic Properties of Expanded Black Cotton Soil

The HYDUS 1D model was used to estimate the uniform water flow hydraulic parameters for the expanded black cotton soil. The model was used to determine the hydraulic conductivity and water retention functions for the medium based on the single porosity van Genuchten equations. The hydraulic parameters estimated were Ɵs, Θ_r, K_s, *n*, *ά* and *l* with the following being the input into the model;

i) Percent sand, silt, clay and bulk density

   This was based on the textural analysis of the medium.

ii) Boundary conditions

   The constant pressure head boundary was selected for both the upper and lower conditions

iii) Field Capacity

   This was obtained by allowing free drainage from a saturated sample

iv) Depth of profile

   Only a single layer was used in the simulation.

v) Data for inverse solution

   The input data was the pressure head (cm) and the corresponding moisture contents as determined using the pressure membrane apparatus.

3.3.1 Model Calibration and Inverse Parameter Estimation

Model calibration was done by manipulating the input parameters i.e. the hydraulic parameters within reasonable ranges until the model simulated results closely matched the observed variables. Of importance in this study was the matric potential. The pressure potential only exits under saturated condition, the osmotic potential is due presence of solutes. The gravitational depends on the distance to the reference elevation and can be neglected for small laboratory samples (Lal and Shukla, 2005). The measured water contents (Θ) for given values of pressure heads *(h)* corresponding to matric potential and saturated hydraulic conductivity were used in the calibration. To optimize the various parameters, parameter optimization was carried out. The HYDRUS model uses a Marquadt-Levenberg type parameter estimation technique for inverse estimation of soil hydraulic parameters

(Simunek *et al.*, 2012). The objective function, Φ to be minimized during the parameter estimation process in HYDRUS was defined by the equation;

$$\Phi(b,q,p)=\sum_{j=1}^{mq}v_j\sum_{i=1}^{nqj}w_{i,j}\left[q_j^*(x,t_i)-q_j(x,t_i,b)\right]^2+\sum_{j-1}^{mp}v_j\sum^{npji=1}w_i\left[p_j^*(x,\theta_i)-p_j(x,\theta_i,b)\right]^2+\sum_{j=1}^{nb}\hat{v}\left[b_j^*(x)-b_j(x)\right]^2 \quad (3.4)$$

The first term on the right side represented deviations between measured and calculated space-time variables where *mq* was the number of different sets of measurements, *nqj* is the number of measurements within a particular measurement set, $q_j^*(x,t_i)$ represents specific measurements at time t_i for the j^{th} measurement set at location *x*, $q_j(x,t_i,b)$ represents the corresponding model predictions for the vector of optimized parameters *b* (i.e. the soil hydraulic parameters), and v_j and $w_{i,j}$ are weights associated with particular measurement set or point, respectively. The first term included observed pressure heads and water contents.

The second term on the right side of the equation represented differences between independently measured and predicted soil hydraulic properties (retention, $\theta(h)$, and hydraulic conductivity, $K(h)$ data) for a single layer (x), while the terms *mp*, np_j, $p_j^*(x,\theta_i)$, $p_j(x,\theta_i, b)$, $v\hat{}_j$ and $w_{i,j}$ had similar meanings as for the first term but referred to the soil hydraulic properties. The last term of the equation represented a penalty function for deviations between prior knowledge of the soil hydraulic parameters, $b_j^*(x)$, and their final estimates, $b_j(x)$, with *nb* being the number of parameters with prior knowledge and v_j representing pre-assigned weights (Simunek *et al.*, 2013). Since the method required initial estimates of the unknown parameters, the ROSETTA program which is in-built in HYDRUS 1D was used.

3.3.2 Model Validation

The measured and model estimated water contents were used to determine how close the model simulates the actual flow characteristics, the simulated hydraulic functions were plotted against measured values and the goodness of fit (R^2) used to evaluate the model. Root Mean Squared Error (RMSE) was calculated from equation 3.5 as;

$$\text{RMSE} = \sqrt{\frac{\left(\sum_{i=1}^{n}(x_{oi}-x_{si})^2\right)}{n}} \quad (3.5)$$

where x_{oi} is the observed parameter value

x_{si} is the simulated value and

n is the total number of observations

3.4 Evaluation of Crop Growth

In this study the aggregate medium was prepared using black cotton soil mixed with rice husk at a ratio of 90:10 by mass and then fired at 750^{o}C for 30 minutes. The material was size reduced into various textures. Root and stem growth are affected by the composition and texture of the medium (Maloof, 2004). Root and stem development were assessed. The experiment was carried out at Egerton University's Tatton Farm. The area is located 00^{o}22' South of the equator, 35^{o}55' East and 2286 m above sea level. The experimental site receives an average annual rainfall of 1200 mm, and the averages of temperatures in the field ranges between 10.2 and 22.0 °C (Ng'etich *et al.*, 2014). The experimental trial was carried out using tomato crop *(Solanum lycopersicum cv. Anna F1)* grown in a greenhouse. Growth factors such as root length density (RLD), changes in stem diameter and height were measured.

The expanded black cotton soil was categorized as fine aggregates, coarse aggregates and a mix of fine and coarse aggregates. The fines had particle sizes corresponding to fine sand ranging from 0.075 – 0.85 mm, while the sizes for the coarse aggregates ranged between 0.85 – 2.00 mm. The mixed size aggregates comprised 40% each of fine and coarse aggregates; 10% for those less than 0.075mm while the remaining proportion was fine gravels (2.00 – 4.75 mm). The black cotton soil (clay) was also used as sampled from KALRO, Kibos as a control during the experiment.

The crops were planted in one-liter containers, each supplied with an average 130 ml of the nutrient solution daily throughout the growing period. The containers were perforated on the sides and at the bottom to enhance aeration and free drainage. They were placed in a single row and buried into the soil to provide better support. Plates 3.1(a) and 3.1(b) show the setup at various stages of the experiment.

Plate 3.1: (a) Crop at transplanting (b) Established tomato crop

The hydroponic nutrients were obtained from Hydroponics Africa with the following nutrient composition;

Table 3.4: Composition of the nutrient feed before dilution

Nutrient	Symbol	Parts per million
0.02% Potassium	K_2O	153
Copper proteinate	Cu	0.2
Zinc proteinate	Zn	0.3
Boron proteinate	B	0.7
Calcium	Ca	126
Manganese proteinate	Mn	1.97
Phosphate	P	50
Iron proteinate	Fe	28
Magnesium	Mg	48
Nitrogen	N	120

The nutrients were packaged in 1 kg packets as Hydro A and Hydro B as shown in Plate 3.2. Each nutrient feed was mixed at a rate of 2 g per liter of water. The nutrient solution was supplied from a raised tank through drip lines to each plant over a timed interval of 3 - 5 minutes every morning depending on the level of water in the tank to give the desired application rate of 130 ml per day for the whole duration of the experiment. The rate was computed based on the number of emitters and daily outflow of the nutrient solution from the tank.

Plate 3.2: Hydroponic Nutrients

The plant stem diameter and height were measured weekly. The stem height was measured using a meter rule with the measurements taken from the border of the container to the top of the main plant stem. The stem diameters were measured using a vernier caliper. The first measurements were taken 12 days after transplanting. This was to allow proper establishment of the seedlings. RLD was determined at the end of the trial period when the crops started to flower after six weeks. The total length of the roots was obtained by carefully cleaning off the medium and measuring the length of individual roots.

The weekly changes in diameter and height were computed as;

$$\Delta y(\%) = \frac{(y_{i-1} - y_i)}{y_{i-1}} x100 \qquad (3.6)$$

Where; y is the measured variable

i is the week since commencement of measurements.

The root length density was computed as;

$$RLD = \frac{L_r}{V_m} \qquad (3.7)$$

Where; L_r = total length of the roots (m)

V_m = volume of medium used (m^3).

CHAPTER FOUR
RESULTS AND DISCUSSIONS

4.1 Textural Analysis of Black Cotton Soil

Sieve analysis of the black cotton soil sampled from KALRO, Kibos which was used in the study was as given in Table 4.1 below;

Table 4.1: Particle Size Distribution of Sampled Soil

Particle size	Description	Proportion of total sample weight (%)		
		Sample 1	Sample 2	**Average**
2.00 - 4.75 mm	Fine Gravel	0.69	1.32	1.01
0.85 -2.00 mm	Coarse sand	5.68	6.00	5.85
0.075 - 0.85 mm	Fine sand	27.23	30.45	28.84
<0.075 mm	Silt and Clay	66.41	62.22	64.31

The results show the soil sampled was representative of the soils in the area based on previous analysis by Millman (1973) which found that the clay content of the top soils was between 35% and 60% and 40% to 70% for the subsoil and an average of 20% silt. Sieve test data and the grading curves for each of the samples are given in Appendix 2.

4.2 Effect of Black Cotton Soil–Rice Husk Mix Ratio, Firing Temperature and Firing on Bulk Density and Hydraulic Conductivity.

4.2.1 Bulk Density before Firing

The bulk density of the dried blocks was determined based on the dry weight and the volume of the mould. Plate 4.1 shows the blocks before firing. It was found that the bulk density increased linearly with an increase in percent black cotton soil.

Plate 4.1: Blocks before firing

The distribution of mean bulk density was as presented in Figure 4.1. It varied from 1.15 g/cm^3 to 1.44 g/cm^3 depending on the percent black cotton soil added as given in Table 4.2. The F value was 436.98 with R^2 of 0.976 indicating that the addition of rice husk had a significant effect on the resulting bulk density. This was attributed to the low density of the husks of approximately 0.1 g cm^{-3} (Mansaray and Ghaly, 1997), which results in a decrease in weight per unit volume of the block.

Table 4.2: Mean Bulk Density before Firing

		Unfired_BD (g cm^{-3})	
Level of BCS (%)	**N**	**Mean**	**Std Dev**
90	9	1.151	0.0185
95	9	1.248	0.0132
97.5	9	1.309	0.0230
100	9	1.441	0.0127

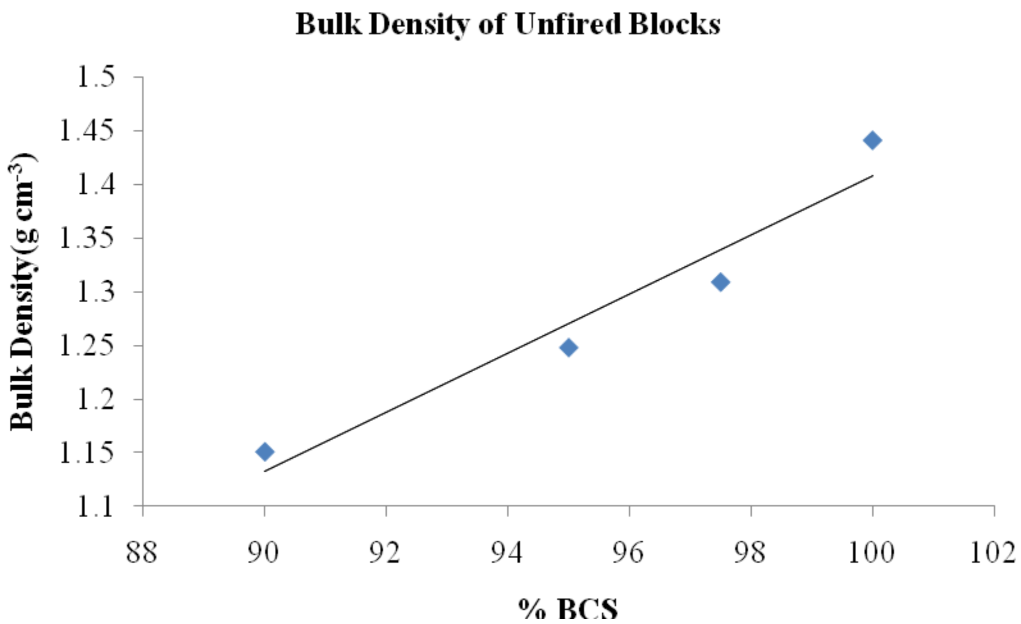

Figure 4.1: Distribution of the Bulk Density before Firing

4.2.2 Bulk Density after Firing (Before Size Reduction)

Upon firing of the blocks, the model gave an overall F-value of 4018.34 with R^2 and RMSE of 0.991 and 0.0219 respectively. Table 4.3 gives the effect of each of the parameters. It is noted that temperature and percent black cotton soil had significant effects on the bulk density while the time for firing did not. The interactions also did not produce significant effects.

Table 4.3: ANOVA for Bulk Density of the blocks after Firing

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Temperature	3	45.78644342	15.26214781	31727.3	<0.0001
Time	2	0.00067817	0.00033908	0.70	0.5135
BCS	3	0.60187408	0.20062469	417.06	<0.0001
Temperature*Time	4	0.00055017	0.00013754	0.29	0.8815
Time*BCS	6	0.00068317	0.00011386	0.24	0.9559
Temperature*BCS	6	0.00147150	0.00024525	0.51	0.7900

Application of heat energy combusted the rice husks and the higher the temperature, the greater was the combustion thereby increasing the pore volume of the blocks. Plate 4.2 shows the fired blocks.

Plate 4.2: Blocks after firing

The corresponding Pearson correlation coefficients were 0.026, -0.0193 and 0.941 for temperature, time and percent black cotton soil respectively. This indicated that the amount of rice husks added to the black cotton soil in the samples had the greatest effect on bulk density as was the case before firing. Based on changes in bulk density, the firing temperatures and time had least correlation within the ranges selected as shown in Table 4.4. The rice husks combusted thus increasing the pore volume of the blocks due to their high volatile matter content of about 63 – 70% of the rice husk. The average decrease in bulk density was 0.82% for every percent increase in rice husk ratio. A similar trend was observed by Sutas *et al*. (2012) in bricks made from clay, rice husk mixtures.

Table 4.4: Pearson correlation for Fired Black Cotton Soil Blocks

Pearson Correlation Coefficients, N = 36	
	Change BD
Temperature	-0.05073
Time	0.04501
BCS	-0.88110

4.2.3 Bulk Density after Size Reduction

The size reduction process resulted into aggregates corresponding in size to fine gravel (2.00 mm to 4.75 mm), coarse sand (0.85 mm to 2.00 mm), fine sand (0.075 mm to 0.85 mm) and the silt and clay (0.0 mm to 0.075 mm). These were mixed in the ratio 1:4:4:1. The ANOVA for the bulk density of the mixture resulted in model mean bulk density of 0.99 g cm^{-3}. The R^2 and the RMSE were 0.97 and 0.02 g cm^{-3} respectively. The model indicated statistically significant difference in the LSmeans. However, similar to the analysis of bulk density of fired blocks (before size reduction), time for firing did not have a significant effect as shown in Table 4.5. The interactions between percent black cotton soil and time as well as temperature also did not result in significant difference in the LSmeans.

Table 4.5: ANOVA for Bulk Density after Size Reduction

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TEMPERATURE	3	35.40594167	11.80198056	15329.1	<0.0001
TIME	2	0.00202222	0.00101111	1.31	0.3050
BCS	3	0.21269722	0.07089907	92.09	<0.0001
TEMPERATURE*TIME	4	0.01756111	0.00439028	5.70	0.0083
TIME*BCS	6	0.00584444	0.00097407	1.27	0.3421
TEMPERATURE*BCS	6	0.00399444	0.00066574	0.86	0.5471

The LSMeans for bulk density at different firing temperatures were as given in Table 4.6. Increasing the firing temperature resulted in a decrease bulk density across all the levels.

Table 4.6: LSMeans for Bulk Density based on Temperature

TEMPERATURE (^{o}C)	BD LSMEAN (g cm^{-3})
700	1.064
750	0.967
800	0.940

This gave a mean value of 0.989 g cm^{-3}. Figure 4.2 show the plot of LSmean bulk density against temperature.

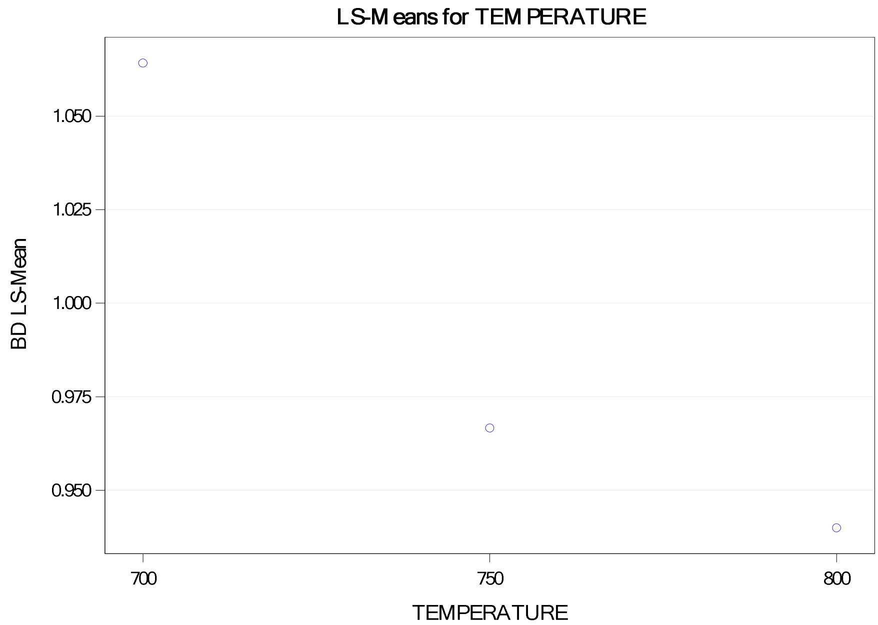

Figure 4.2: Least Square Mean for Temperature

The corresponding Tukey adjustment was as shown in Figure 4.3. Increasing the temperature from 750°C to 800°C did not result in a significant difference in the means between the two levels. Increasing the temperature increased the efficiency of combustion of the rice husks, led to burn off of carbon and sulphur and changed the structure of silica in both the soil and rice husk (Sutas *et a*l., 2012).

Based on the need to conserve energy during firing and hence reduce the cost of production of the expanded black cotton soil aggregates, the optimum firing temperature was 750°C resulting in LSMean bulk density of 0.967 g cm^{-3}.

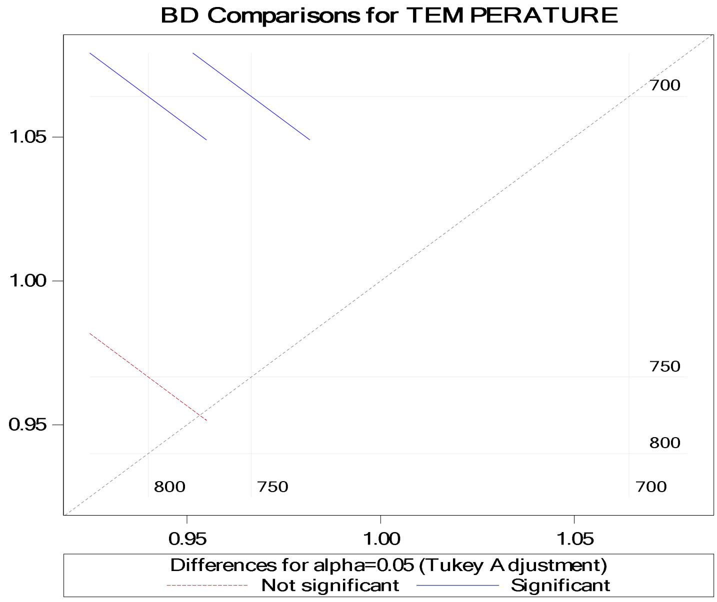

Figure 4.3: The Tukey Adjustment for Temperature

The LSMeans of bulk density based on the time of firing were 0.999, 0.991 and 0.981 g cm^{-3} for 30, 60 and 90 minutes respectively. The plot of these values was as in Figure 4.4.

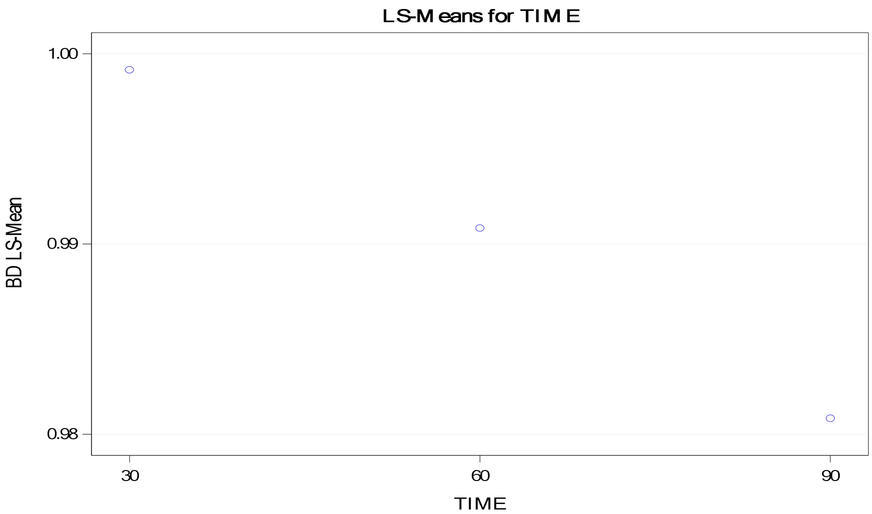

Figure 4.4: Least Square Means of Bulk Density for Time

There was a consistent decrease in LSmean bulk density within increase in time for firing. However based on the Tukey adjustment (at α = 5%) the difference in the LSmeans for bulk density of the blocks was not significant across all the levels as shown in Figure 4.5. The least time of 30 minutes was therefore the most cost effective in terms of energy requirements. In a previous study to determine the influence of firing temperature and time on clay bricks it was observed that prolonged firing time had no significant effects on the physical properties of clay bricks investigated. It was concluded that longer times were unnecessary and needed to be avoided to save time and energy (Karaman, *et al.*, 2006). Similar analysis were done for time and percent black cotton soil respectively.

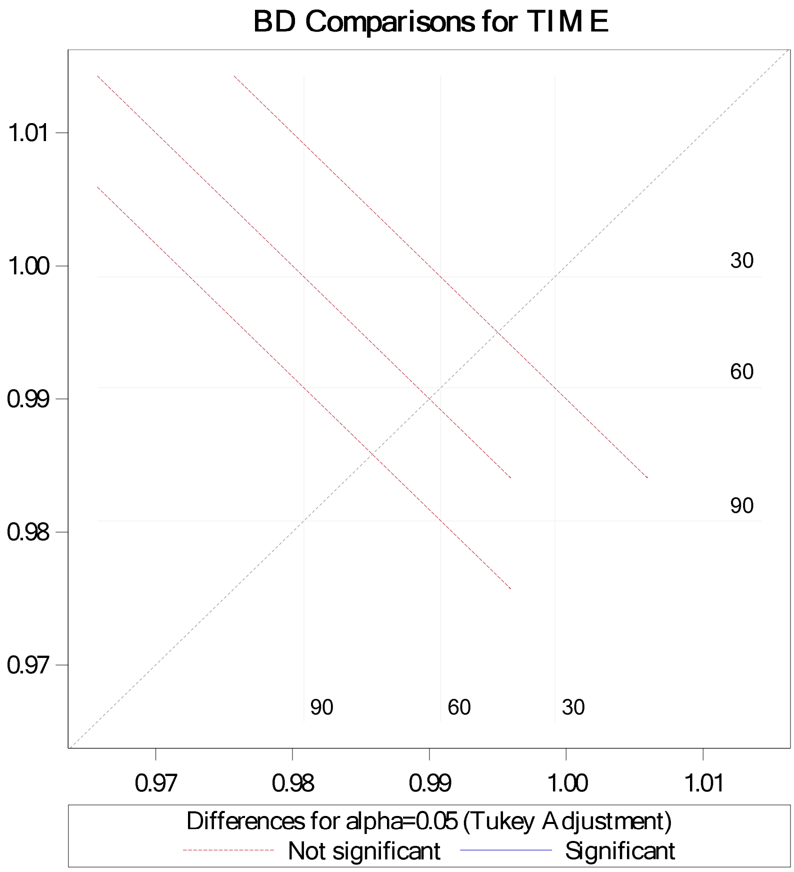

Figure 4.5: The Tukey Adjustment for Time

The minimum LSMeans of bulk density based on percent black cotton soil was achieved at 90% giving a value of 0.913 g cm^{-3} as summarized in Table 4.7. These results indicated that the bulk density reduced with corresponding increase in ratio of rice husk that was added.

Table 4.7: LS Means for Bulk Density based on Percent Black Cotton Soil

BCS (%)	BD LSMEAN (g cm^{-3})
90	0.913
95	0.956
97.5	0.974
100	1.118

A plot of the values was as shown in Figure 4.6.

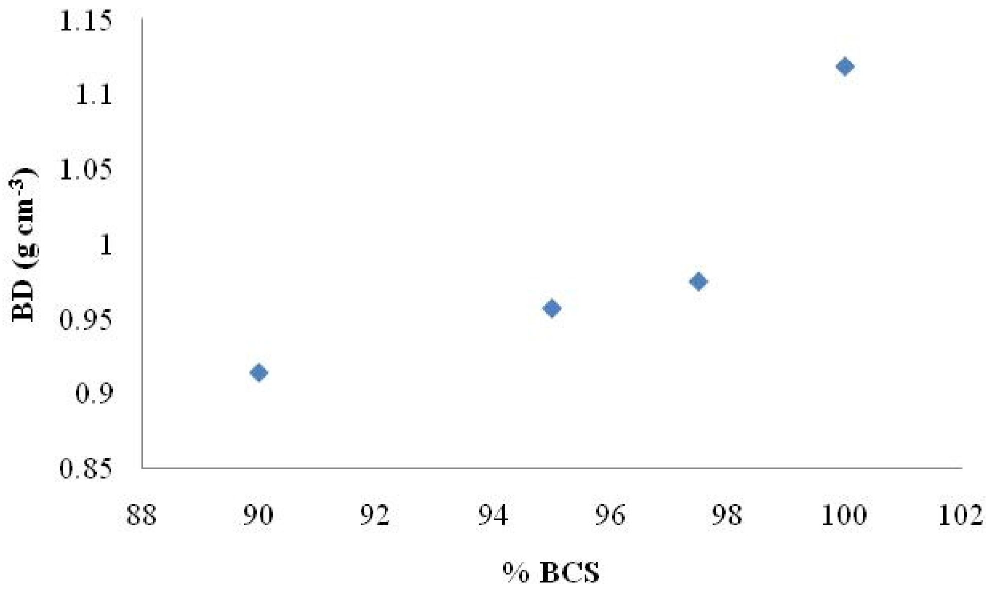

Figure 4.6: LSMeans of Bulk Density for Black Cotton Soil

Significant difference in the LSmeans was observed across all the levels of black cotton soil except between 95% and 97.5% as shown in Figure 4.7. These results generally agree with the findings by Sutas (2012).

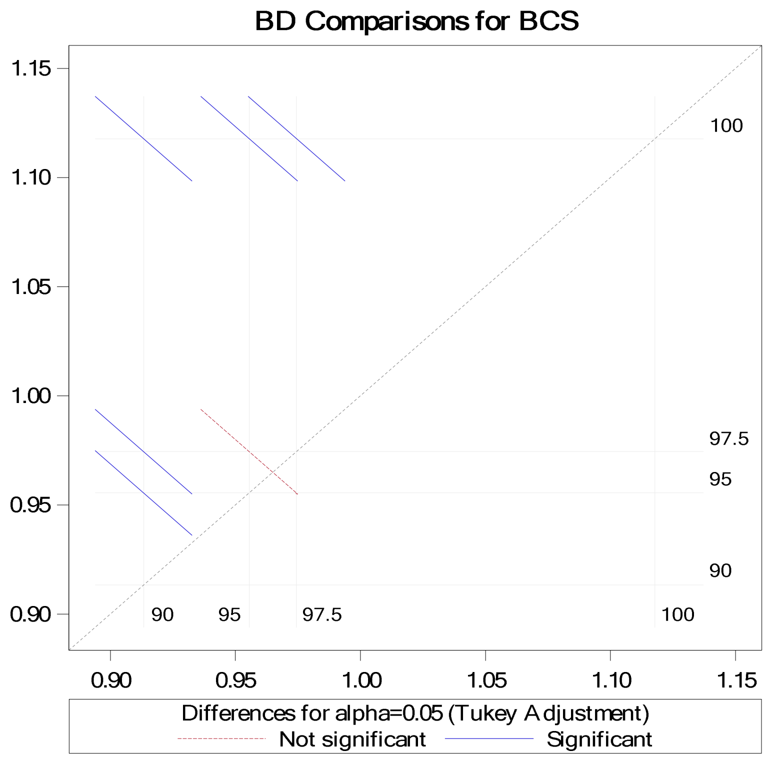

Figure 4.7: The Tukey Adjustment for Percent Black Cotton Soil

A combination of selected factor levels for the production of the expanded black cotton soil aggregates was 750°C, 30 minutes, 90% for firing temperature, time and percent black cotton soil respectively which resulted in bulk density of 0.94 g cm^{-3}, although the lowest value of 0.83 g cm^{-3} was obtained for a combination of 800°C, 30 minutes and 90% black cotton soil but this would be uneconomical in terms of the energy demand required to raise the temperature from 750 to 800°C. The process at these factor levels was therefore able to appreciably reduce the bulk density by 34% from 1.43 g/cm^3 for the original black cotton soil to 0.94 g cm^{-3}. This reduction in weight per unit volume of a growing medium is beneficial in terms of improved root penetration, inertness and increased drainage. However, the bulk density was still higher than those of commercially available expanded clay pellets which range between 0.35 to 0.8 g cm^{-3}. In this study, this could be improved by reducing the amount of fines in the medium. Table 4.8 gives the corresponding bulk densities for various aggregate size ranges at 750°C, 30 minutes, 90% black cotton soil factor levels.

Table 4.8: Bulk Density of Aggregates at various Size Ranges

Size range (mm)	Bulk density (g cm^{-3})
2.00 – 4.75	0.868
0.85 – 2.00	0.835
0.075 – 0.85	0.750

Although the bulk density of the fine aggregates (0.0 to 0.075 mm) was 0.750g cm-*3* being the lowest, when mixed with the coarse aggregates, they occupy the larger pore spaces resulting in an increase in density. Reducing the proportion of the fines would therefore lower the bulk density but compromise the water holding capacity as is the case with expanded clay pellets.

Pearson correlation analysis for the independent variables gave coefficients of -0.511, -0.076 and 0.67 for temperature, time and percent black cotton soil respectively. It shows that upon size reduction, the effect of temperature increased while that of percent black cotton soil reduced. This is because some of the large pore spaces created during combustion of rice husk collapsed during size reduction and were occupied by the finer materials. Hence the total volume of the aggregates was lower than that of the fired blocks.

4.2.4 Saturated Hydraulic Conductivity

The analysis of saturated hydraulic conductivity data generally showed a statistically significant difference in the means. It gave an F-value of 379.82 with the corresponding R^2 and RSME as 0.99 and 0.0003 cm s^{-1} respectively. The overall mean of saturated hydraulic conductivity was 0.00446 cm s^{-1}. The effect of each of the factors was as presented in Table 4.9. Generally, all the factors had significant effect on the mean saturated hydraulic conductivity of the aggregates as well as the interaction between temperature and percent black cotton soil. The interactions between temperature and time; percent black cotton soil and time were not significant at 5% level of significance. The interaction between temperature and ratio black cotton soil of was significant since the rice husks added also contributed some heat energy due to flaming combustion.

Table 4.9: ANOVA for Saturated Hydraulic Conductivity

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TEMPERATURE	3	0.00076376	0.00025459	2942.83	<0.0001
TIME	2	0.00000500	0.00000250	28.88	<0.0001
BCS	3	0.00001630	0.00000543	62.81	<0.0001
TEMPERATURE*TIME	4	0.00000101	0.00000025	2.93	0.0664
TIME*BCS	6	0.00000058	0.00000010	1.13	0.4035
TEMPERATURE*BCS	6	0.00000195	0.00000033	3.77	0.0242

The LSmean of saturated hydraulic conductivity nearly doubled from 0.00335 cm s^{-1} to 0.00606 cm s^{-1} for a temperature change from 700°C to 800°C respectively as shown in Table 4.10.

Table 4.10: Least Square Means of Hydraulic Conductivity for Temperature

Temperature (°C)	Ksat (cm s^{-1})
700	0.00335
750	0.00396
800	0.00606

Figure 4.8 give the graphical representation for the least square means of saturated hydraulic conductivity based on firing temperature and the corresponding Tukey adjustments in Figure 4.9.

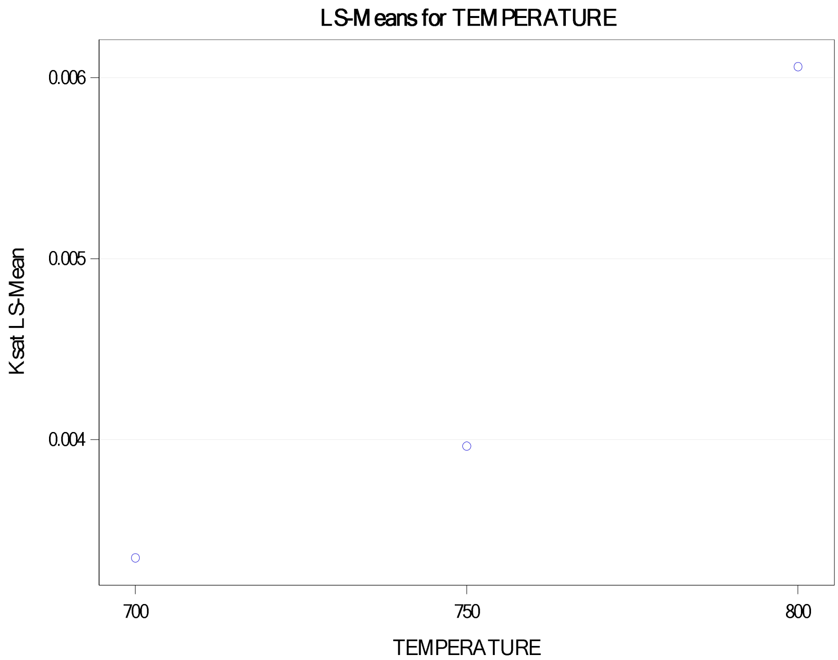

Figure 4.8: Least Square Mean for Temperature

The effect of temperature was significant across all the levels. This meant that an increase in the firing temperature resulted in increased hydraulic conductivity due to reduced adhesive forces on the aggregates.

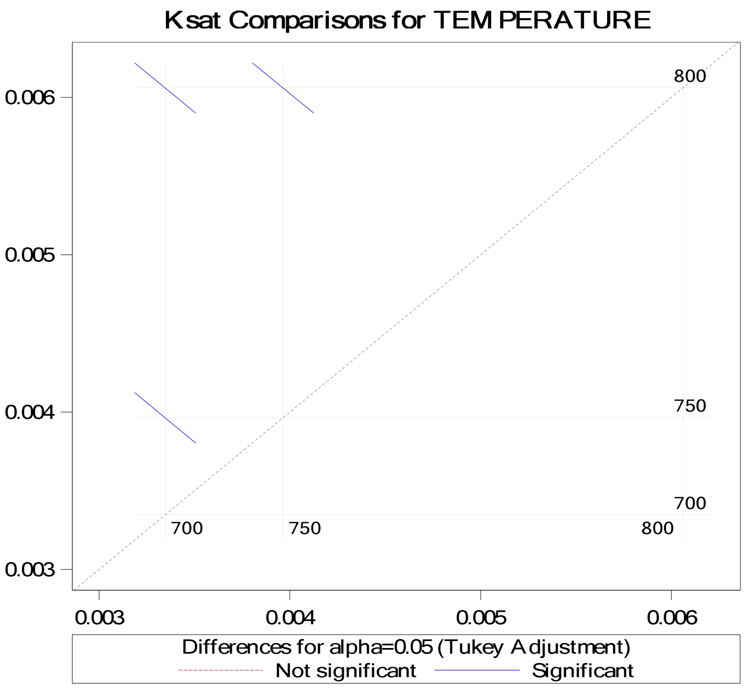

Figure 4.9: The Tukey Adjustment for Temperature

Low values of Ksat hinder drainage and water movement while high values result in accelerated drainage and low water retention. The best soils for agricultural production are the loamy soils which have the following values of saturated hydraulic conductivity estimated by the RETention Curve (RETC) model given in Table 4.11 below.

Table 4.11: Estimated Ksat Values for Selected Soils

Soil Texture	Ksat (cm s^{-1})
Clay Loam	0.00000722
Silt Loam	0.000125
Loam	0.000289
Sandy Loam	0.001228
Loamy Sand	0.004053

From Table 4.10, it is noted that the value of mean saturated hydraulic conductivity corresponding to a firing temperature of 800^{o}C is way above the range for loamy soils.

In terms of the firing time, the ANOVA gave the results as in Table 4.12;

Table 4.12: Least Square Means of Saturated Hydraulic Conductivity for Time

Time (min)	Ksat LSMean (cm s^{-1})
30	0.00393
60	0.00470
90	0.00473

A plot of these values is shown in Figure 4.10. The saturated hydraulic conductivity increased with increase in time for firing. In order to evaluate significance in the LSmeans across the level of time used in the study, Tukey adjustment was done the results presented in Figure 4.11. There was no significant effect on saturated hydraulic conductivity by raising the time from 60 to 90 minutes. However, the means at 60 and 90 minutes are above those of loamy soils. A firing time of 30 minutes is therefore not only sufficient but also the most economical in terms of energy consumption.

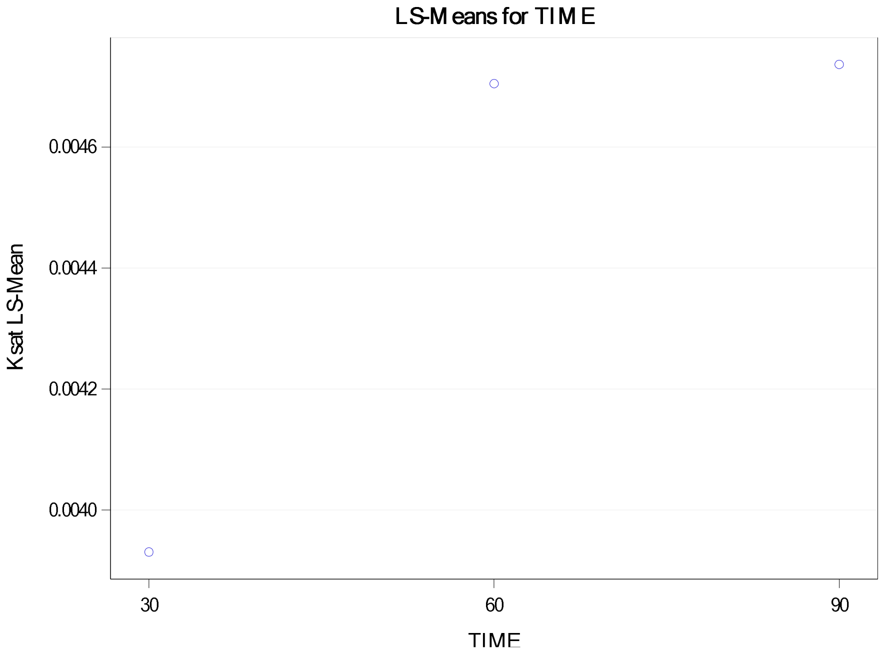

Figure 4.10: Least Square Means for Time

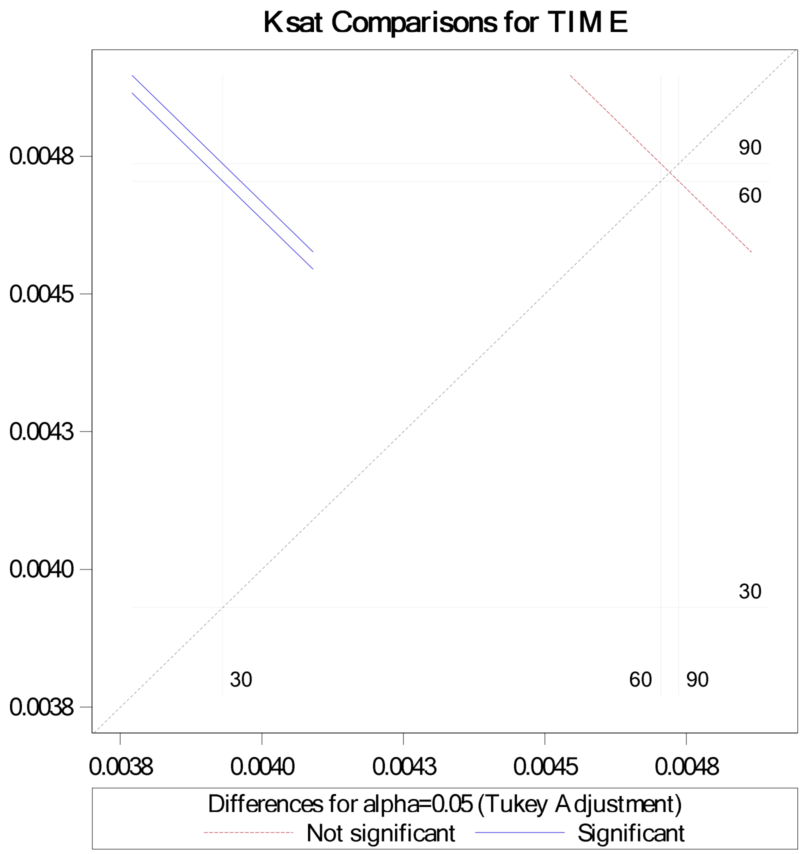

Figure 4.11: The Tukey Adjustment for Time

The least square means for saturated hydraulic conductivity reduced with a decline in percent rice husk as shown in Table 4.13.

Table 4.13: Least Square Means of Saturated Hydraulic Conductivity for Percent BCS

Percent BCS	Ksat (cm s^{-1})
90	0.00521
95	0.00486
97.5	0.00434
100	0.00342

A graphical presentation of these results was as in Figure 4.12. Higher black cotton soil content means more compact aggregates hence the reduced hydraulic conductivity. From this analysis, it shows that 100% black cotton soil gives the lowest hydraulic conductivity. The incorporation of rice husk resulted in larger pore openings between the aggregates resulting in faster movement of water.

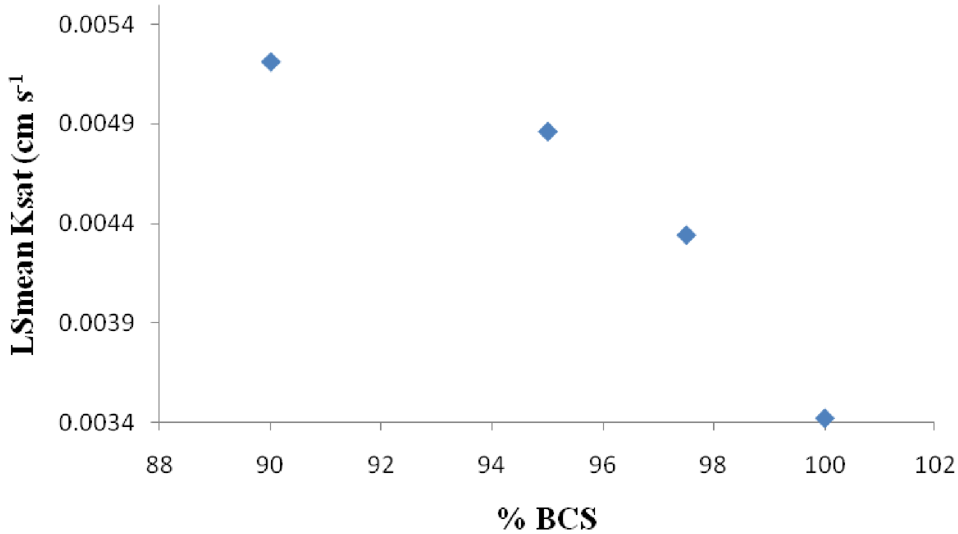

Figure 4.12: Least Square Means for Percent Black Cotton Soil

From the Tukey adjustment shown in Figure 4.13, it was observed that the LSmeans were significantly different across all the level of percent black cotton soil. A deviation from this observation was noted at between 90% and 95% but this could be attributed to errors in measurement of hydraulic conductivity.

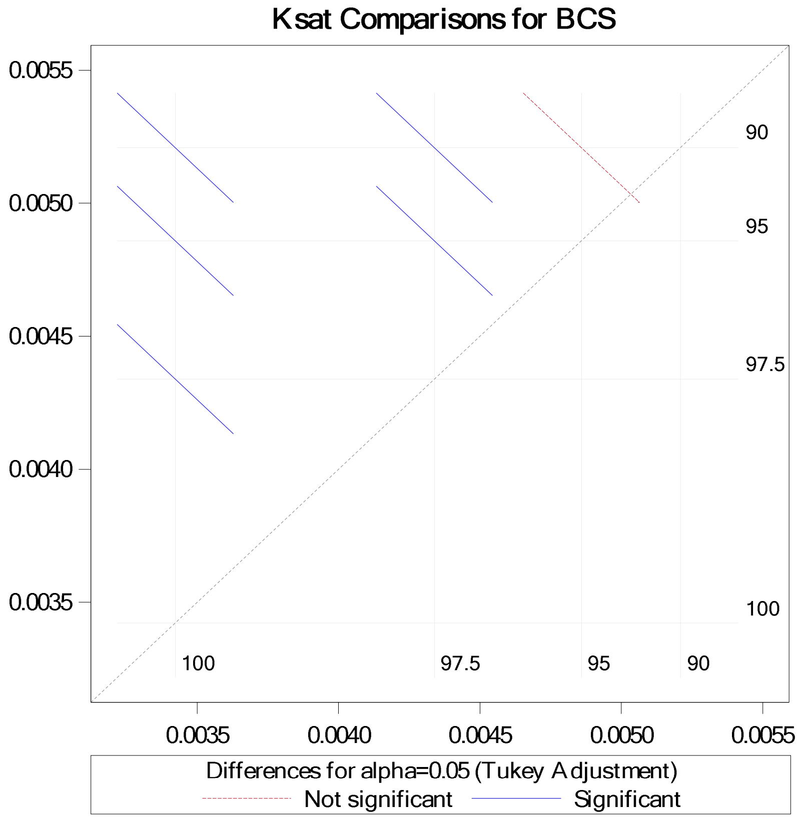

Figure 4.13: The Tukey Adjustment for Percent Black Cotton Soil

In order to obtain the optimal set of preparation conditions, both the results on bulk density and saturated hydraulic conductivity were considered simultaneously together with the possible saving in energy requirement. A temperature rise from 750^{o}C to 800^{o}C did not result in significant change in mean bulk density but raises the hydraulic conductivity by 53%. Hence the higher temperature of 800^{o}C was undesirable since the rate of water movement was high resulting fast drainage. Firing at this temperature was also uneconomical in terms of energy consumption. The lower temperature of 700^{o}C was also undesirable because it resulted in the highest bulk density which could mean incomplete combustion of the organic content. This would mean that aggregates prepared at this temperature were not fully inert.

A firing time of 30 minutes was selected because it was the most economical as well as it gave acceptable results both in terms of bulk density and hydraulic conductivity. However the challenge was in deciding on the best percent black cotton soil. Based on the selected firing temperature and time of 750^{o}C and 30 minutes respectively, these were treated as constants and the results for corresponding bulk density and saturated hydraulic conductivity expressed as in Table 4.14.

Table 4.14: Hydraulic Conductivity and Bulk Density (at 750°C, 30 minutes)

% BCS	Ksat (cm s^{-1})	BD (g cm^{-3})
100	0.002475	1.327
97.5	0.003422	1.113
95	0.003604	1.076
90	0.003854	0.954

By settling for the lowest bulk density, 90% black cotton soil was selected giving a Ksat value of 0.00385 cm s^{-1} which although was the highest, was still within the range of loamy soils.

Pearson's correlation gave coefficients of 0.77, 0.22 and -0.43 for temperature, time and percent black cotton soil respectively. The greater effect of temperature on saturated hydraulic conductivity can be attributed to its direct effect on bulk density of the material which enhances its porosity.

4.3 Estimation of the Hydraulic Properties of Expanded Black Cotton Soil

Table 4.15 gives the water retention at various tensions for the aggregates prepared at 750°C for 30 minutes as determined using the pressure membrane apparatus.

Table 4.15: Water Retention

%BCS	Moisture content (%wt)			
	10bar	5 bar	1 bar	1/3 bar
100	12.01	12.92	13.11	34.73
90	13.58	15.13	15.65	49.62

Converting these values into volumetric water content (cm^3cm^{-3}) by multiplying by the respective mean bulk densities resulted in Table 4.16. The pressure heads were also converted from bars to cmH_2O, the units used in Hydrus 1D model.

Table 4.16: Volumetric Water Contents at Varying Pressure Heads

Matric Head (cm)	Water content(cm^3 cm^{-3})	
	100% BCS	90% BCS
336.62	0.410	0.453
1019.74	0.155	0.143
5098.72	0.152	0.138
10197.44	0.142	0.124

For the selected mix ratio of 9:1 for the aggregates, an initial estimate of the hydraulic parameters was determined using the in-built Rosetta Litte Version 1.1 based on the % sand, silt, clay and bulk density as shown in Figure 4.14.

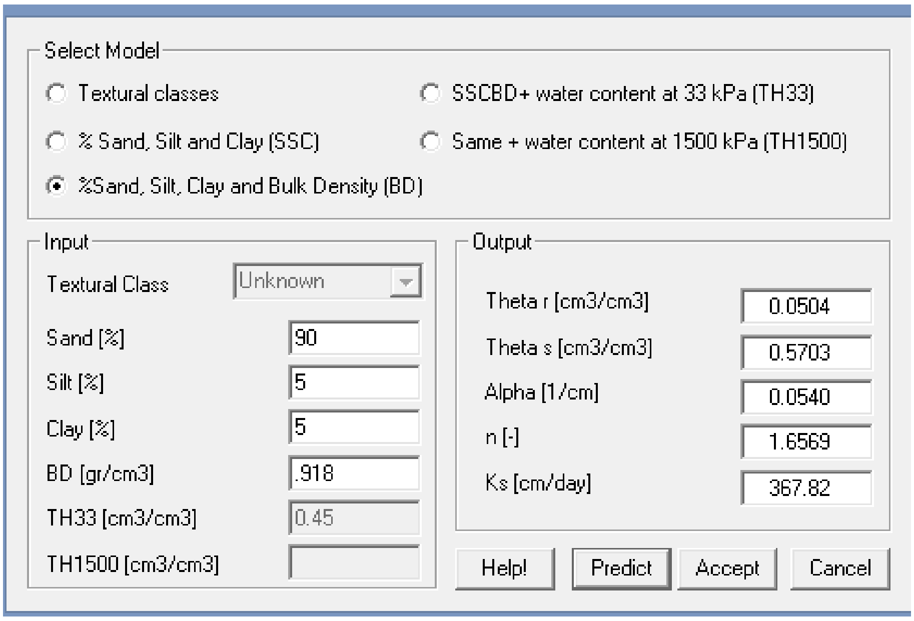

Figure 4.14: Initial estimates of hydraulic parameters

The hydraulic parameters were limited to within the ranges between maximum and minimum values as shown in Figure 4.15. The measured Θ_s and K_s values were used to calibrate the model and only allowed to vary within limited ranges. The expanded black cotton aggregates have secondary porosity which is expected to increase their surface area therefore the Θ_r was higher than the initial estimated value. The value of *n* was not fitted since it affected the shape of the curve.

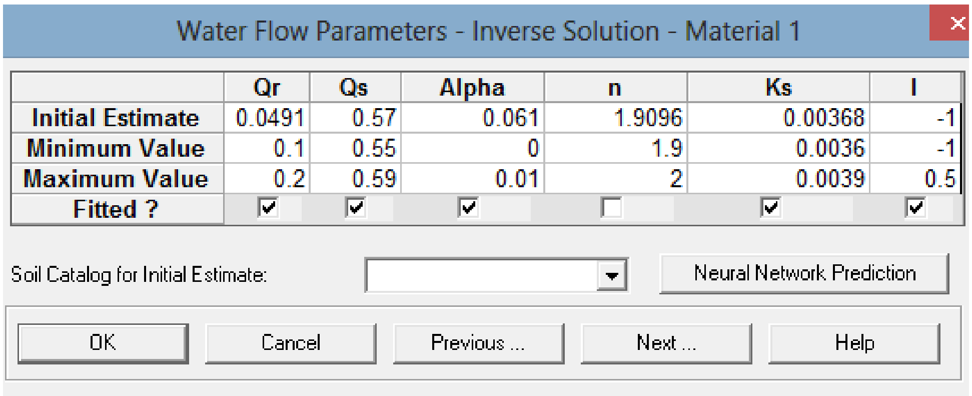

Figure 4.15: Hydraulic Parameters for the Inverse Solution

The Inverse Solution was carried out in the Hydrus 1D model and the data input was as in Figure 4.16 below.

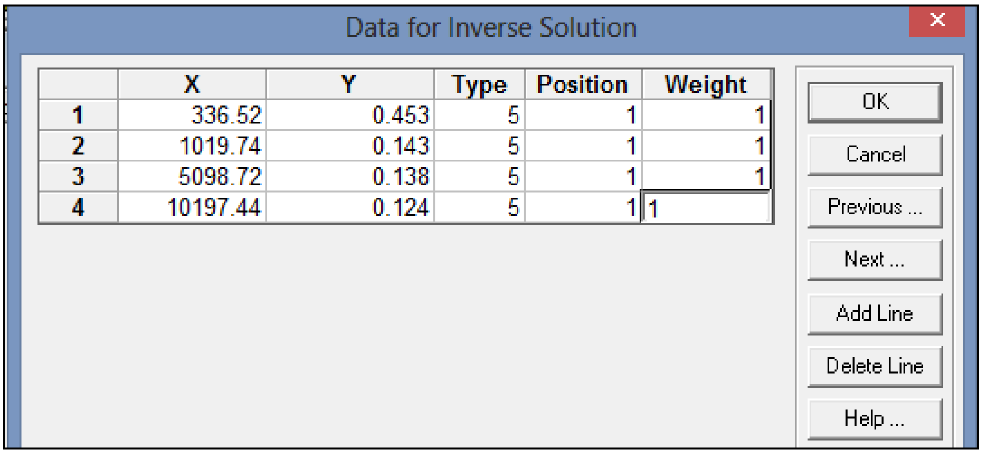

Figure 4.16: Data Input

On execution of the model, the iteration process converged on the second step giving the optimized values of hydraulic parameters. The parameter estimation process based on each iteration step was presented in Table 4.17.

Table 4.17: Results of the Optimization Process

Iteration	0	1	2
Θ_r	0.0491	0.100	0.100
Θ_s	0.57	0.55	0.55
ά	0.061	0.01	0.01
K_s	0.00368	0.00368	0.00368
l	-1.0	-1.0	-1.0

The optimized hydraulic parameters for the expanded black cotton soil aggregates were as summarized in Table 4.18.

Table 4.18: Hydraulic Parameter of Expanded Black Cotton Soil Aggregates

Parameter	Estimate
Residual moisture content (Θ_r)	0.1
Saturated moisture content (Θ_s)	0.55
First coefficient (*ά*)	0.01
Second coefficient (n)	1.91
Saturated conductivity (K_s).	0.00368
Pore connectivity factor (l)	-1.0

Using the van Genuchten – Mualem (1980) equation and substituting the optimized parameter values, *Θ(h), K(h)* and *Se* were computed in HYDRUS 1D. These gave the following graphical results for water retention, unsaturated hydraulic conductivity and the effective saturation as shown in Figures 4.17, 4.18 and 4.19 respectively.

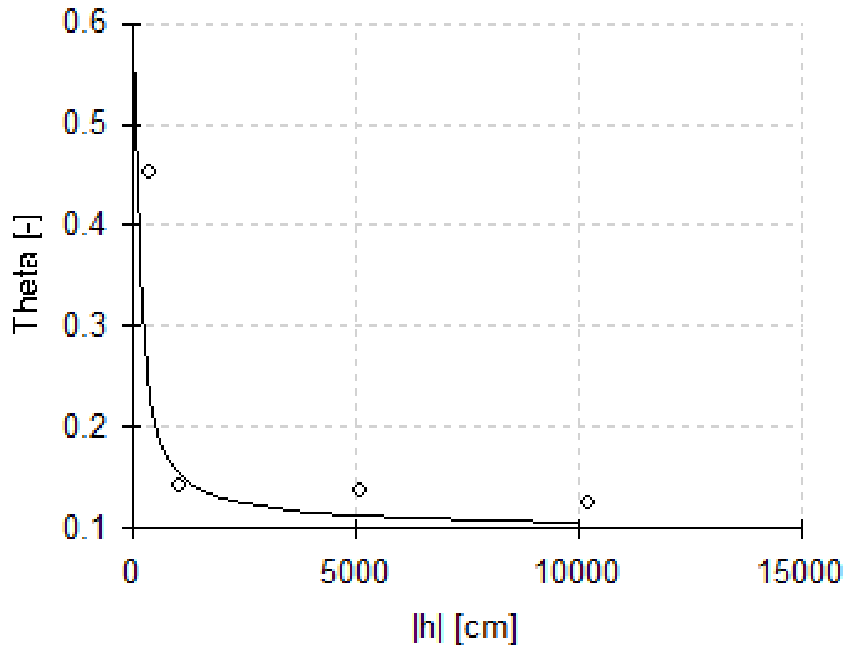

Figure 4.17: Graphical presentation of *Θ(h)*

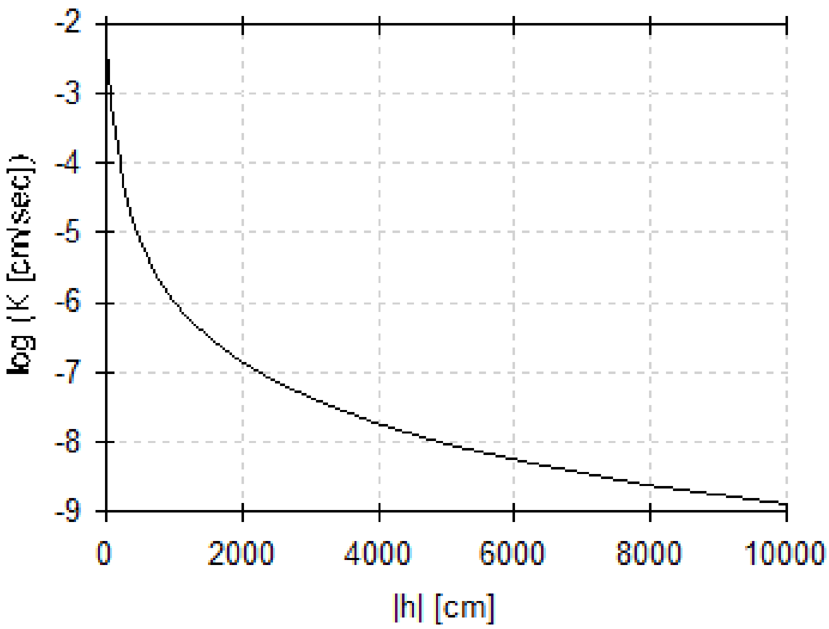

Figure 4.18: Graphical presentation of log *K(h)*

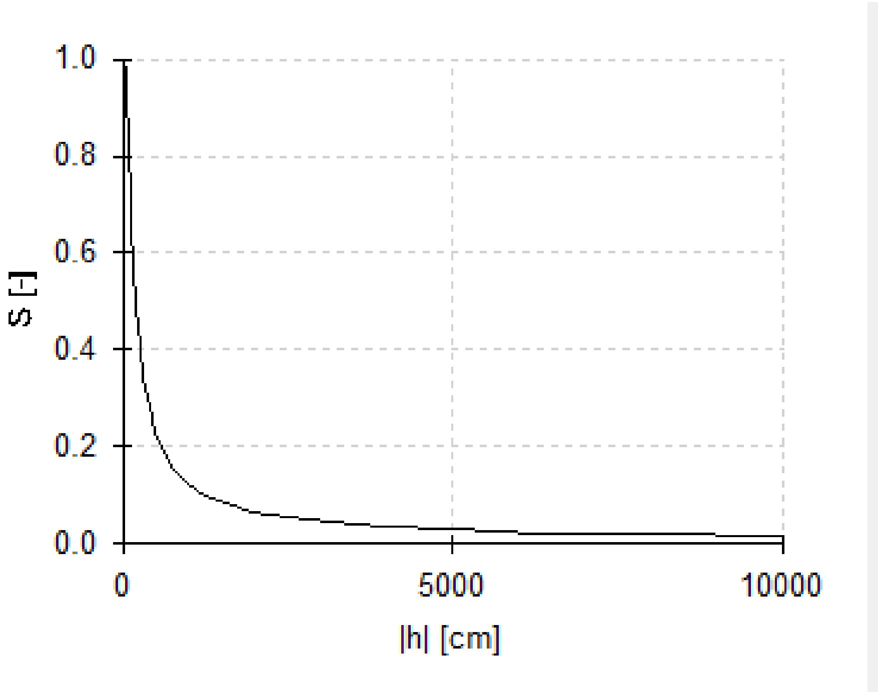

Figure 4.19: Graphical presentation of *Se(h)*

The measured K_s was 0. 00385 cm s^{-1} while the value estimated by the model was 0.00368 cm s^{-1}. This gave a residual error of 0.00017 cm s^{-1}. The variation between *Ks* and the *K* at pressure head of zero as estimated by the model was due to the effect of macropores which saturate after the pressure above zero is applied as explained by Simunek and van Genuchten (1996). Therefore the actual saturation is slightly elevated above that measured at atmospheric pressure. The value of *ά* of soil of similar texture based on Neural Network prediction of Rosetta used as the initial estimate was 0.054 but was predicted by Hydrus 1D as 0.01 for the expanded back cotton soil aggregates.

The estimated *Θ(h)* and *K(h)* for selected values of *h* based on the van Genuchten – Mualem (1980) model were as given in Table 4.19.

Table 4.19: Estimated Hydraulic Properties

Pressure, P (cm)	Log P	Water content ($cm^3\ cm^{-3}$)	Hydraulic conductivity ($cm\ s^{-1}$)
0.0		0.5500	$3.68*10^{-3}$
2.0	0.300	0.5499	$3.47*10^{-3}$
5.6	0.750	0.5491	$3.16*10^{-3}$
15.8	1.200	0.5438	$2.43*10^{-3}$
31.6	1.500	0.5280	$1.59*10^{-3}$
37.6	1.575	0.5203	$1.35*10^{-3}$
63.1	1.800	0.4814	$6.63*10^{-4}$
211.0	2.350	0.3057	$2.35*10^{-5}$
299.0	2.475	0.2574	$6.37*10^{-6}$
355.0	2.550	0.2366	$3.22*10^{-6}$
1000.0	3.000	0.1551	$4.35*10^{-8}$
1190.0	3.075	0.1472	$2.09*10^{-8}$
4730.0	3.675	0.1135	$5.78*10^{-11}$
5620.0	3.750	0.1115	$2.77*10^{-11}$
9440.0	3.975	0.1072	$3.02*10^{-11}$
11200.0	4.050	0.1061	$1.45*10^{-12}$
15800.0	4.200	0.1045	$3.30*10^{-13}$
211000.0	5.325	0.1004	$5.14*10^{-18}$
422000.0	5.625	0.1002	$2.68*10^{-19}$

From these results, the estimated values of water content corresponding to the measured values of pressure heads computed by interpolation as in Table 4.20.

Table 4.20: Estimated and Measured Water Contents at Varying Pressure Head

Pressure Head (cm)	Water content($cm^3\ cm^{-3}$)	
	Estimated	Measured
0.00	0.5500	0.570
336.62	0.2565	0.453
1019.74	0.1543	0.143
5098.72	0.1127	0.138
10197.44	0.1067	0.124

These were used to evaluate the performance of the model by calculating the Goodness of fit (R^2) and the Root Mean Squared Error (RMSE) which were obtained as 0.83 and 0.0895 cm^3cm^{-3} respectively. Figure 4.20 shows the graphical presentation of estimated against measured water contents. These indicated a close relation between the measured and simulated values of water content based on the computed R^2 hence the estimated hydraulic parameters using Hydrus 1D were within acceptable limits for application on the expanded black cotton soil aggregates.

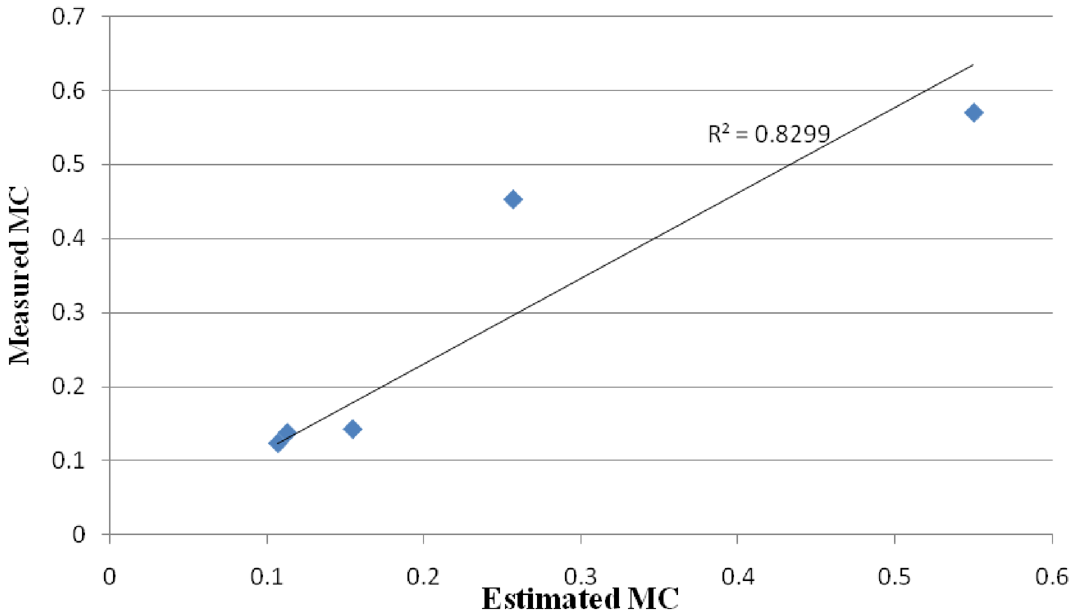

Figure 4.20: Graph of Measured versus Estimated Moisture Contents

4.4 Plant Growth on Expanded Black Cotton Soil

The results shown in Table 4.21 were obtained from the stem diameter (D) and height (H) measurements. Subscripts 0 - 5 indicate the number of weeks elapsed since commencement of data collection.

Table 4.21: Weekly Measurements of Stem Diameter and Height in cm.

Sample	D_0	H_0	D_1	H_2	D_2	H_2	D_3	H_3	D_4	H_4	D_5	H_5
C1	0.19	6.05	0.36	10.07	0.49	16.48	0.67	24.5	0.69	37.5	0.75	55.9
C2	0.28	11.6	0.45	16.02	0.58	22.32	0.67	32.5	0.74	48	0.83	71.1
C3	0.3	11	0.47	15.66	0.57	20.53	0.7	36.5	0.77	51	0.85	68.6
CL1	0.34	10.1	0.48	15.17	0.73	22.34	0.7	34.5	0.84	50	1.01	69.9
CL2	0.24	8.1	0.45	14.46	0.6	19.54	0.68	29.8	0.7	39	0.71	50.8
CL3	0.32	10.7	0.58	16.6	0.64	22.24	0.75	32.2	0.74	41	0.89	61.0
CL4	0.33	11.2	0.5	16.93	0.61	24.04	0.72	36.2	0.81	52	0.94	73.7
M1	0.3	10.8	0.49	15.25	0.6	22.69	0.68	38.1	0.71	54	0.79	71.1
M2	0.27	10.6	0.51	15.31	0.62	20.73	0.72	37.8	0.78	51	0.87	69.9
M3	0.27	10.7	0.47	15.76	0.57	19.01	0.69	34.7	0.73	46	0.76	68.6
M4	0.2	8.8	0.41	12.23	0.6	22.34	0.65	32.2	0.66	46	0.77	63.5
F1	0.35	8.8	0.6	14.89	0.73	24.61	0.78	36.8	0.82	53	0.92	78.7
F2	0.32	9.8	0.48	13.85	0.63	21.02	0.7	34.9	0.74	48	0.83	71.1
F3	0.25	7.7	0.49	13.6	0.66	21.24	0.7	34.5	0.86	55	0.94	78.7

C – coarse aggregates; CL – black cotton soil; M – mixed aggregates; F – fines.

From the results, the percent change in stem height (elongation) and diameter (enlargement) was determined and averaged over the test period as given in tables 4.22 and 4.23 respectively.

Table 4.22: Percent changes in stem height

Sample	Weekly stem elongation rates					Mean weekly growth rate	
	Wk1	Wk2	Wk3	Wk4	Wk5	Per sample	Av. (%)
C1	0.66	0.64	0.49	0.53	0.49	0.56	
C2	0.38	0.39	0.46	0.48	0.48	0.44	
C3	0.42	0.31	0.78	0.40	0.35	0.45	48.3
CL1	0.50	0.47	0.54	0.45	0.40	0.47	
CL2	0.79	0.35	0.53	0.31	0.30	0.45	
CL3	0.55	0.34	0.45	0.27	0.49	0.42	
CL4	0.51	0.42	0.51	0.44	0.42	0.46	45.2
M1	0.41	0.49	0.68	0.42	0.32	0.46	
M2	0.44	0.35	0.82	0.35	0.37	0.47	
M3	0.47	0.21	0.83	0.33	0.49	0.46	
M4	0.39	0.83	0.44	0.43	0.38	0.49	47.2
F1	0.69	0.65	0.50	0.44	0.48	0.55	
F2	0.41	0.52	0.66	0.38	0.48	0.48	
F3	0.77	0.56	0.62	0.59	0.43	0.51	51.4

These results are summarized graphically in Figure 4.21.

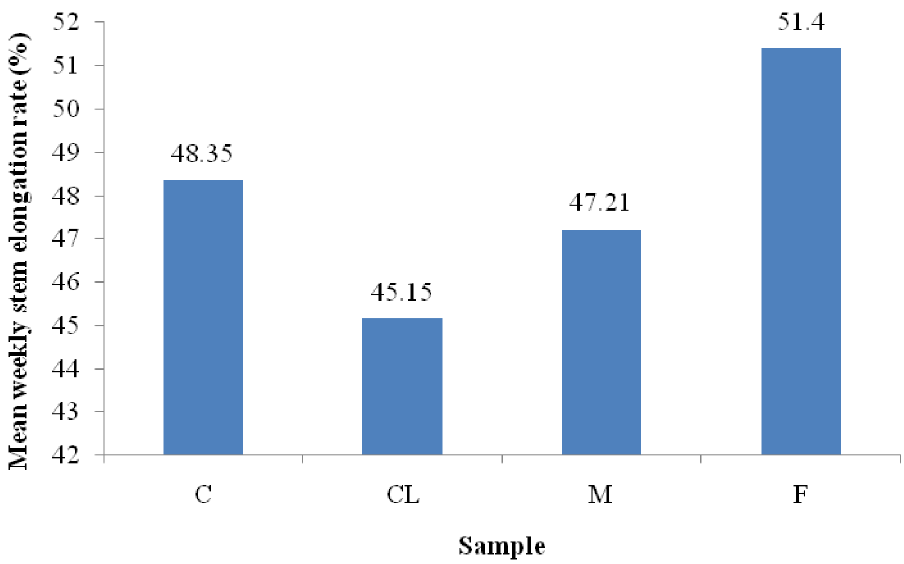

Figure 4.21: Mean weekly stem elongation rates (%) for different samples

The plants grown in fine aggregates of the expanded clay had the highest mean weekly stem elongation rate of 51.4%. This could be attributed to better water holding capacity, nutrient flow and root contact. The black cotton soil had the least stem elongation at an average weekly rate of 45.2% attributed to poor drainage and aeration conditions.

Table 4.23: Changes in stem diameter

Sample	Weekly stem enlargement rates					Mean weekly growth rate	
	Wk1	Wk2	Wk3	Wk4	Wk5	Per sample	(%)
C1	0.89	0.36	0.37	0.03	0.09	0.348	
C2	0.61	0.29	0.16	0.10	0.12	0.255	
C3	0.57	0.21	0.23	0.10	0.10	0.242	28.2
CL1	0.41	0.52	-0.04	0.20	0.20	0.259	
CL2	0.88	0.33	0.13	0.03	0.01	0.277	
CL3	0.81	0.10	0.17	-0.01	0.20	0.255	
CL4	0.52	0.22	0.18	0.13	0.16	0.240	25.8
M1	0.63	0.22	0.13	0.04	0.11	0.230	
M2	0.89	0.22	0.16	0.08	0.12	0.293	
M3	0.74	0.21	0.21	0.06	0.04	0.253	
M4	1.05	0.46	0.08	0.02	0.17	0.356	28.3
F1	0.71	0.22	0.07	0.05	0.12	0.235	
F2	0.50	0.31	0.11	0.06	0.12	0.220	
F3	0.96	0.35	0.06	0.23	0.09	0.338	26.4

This is summarized graphically as;

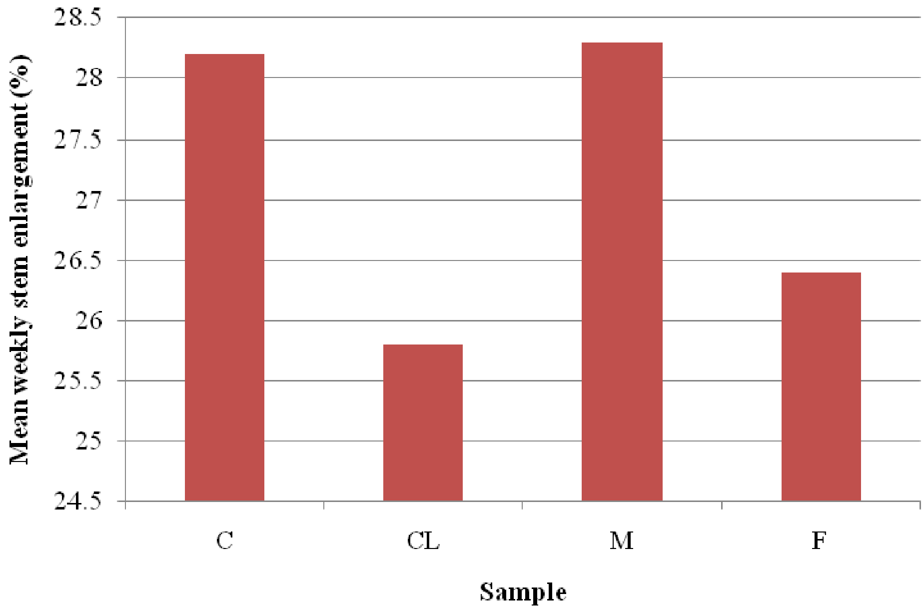

Figure 4.22: Mean weekly stem enlargement rates (%) for different textures

The plants grown in the coarse and mixed size aggregates had higher weekly growth in stem diameter of 28%. This could be attributed to improved water and nutrient flow, better drainage and aeration. The black cotton soil had the least change of 25.8%. This is because clay although has high total available water, the bulk of this water is not readily available for uptake by plant. From week two there is a decline in stem enlargement rate in all the samples due to development of more leaves hence higher evapotranspiration rates. The decline is more pronounced in black cotton soil between weeks three and four after which the crop seems to recover as the roots spread deeper into the soil. The mean values of RLD were as presented in Table 4.24 below;

Table 4.24: Root Length Density

Sample	**Root length density (m m^{-3})**
C	9433
CL	25654
M	18936
F	17019

Since the crops were planted in containers, the RLD was generally high for all the samples. This is because RLD tends to be higher at depths between 0 to 20 cm and decreases down the profile. Under drip irrigation, 70-75% of the total RLD of tomatoes is concentrated in 0 – 15 cm soil layers because of the high irrigation frequencies. Smaller soil volumes also tend to give higher RLD values (Rangjian *et al*., 2017; de Azevedo *et al*., 2011). The containers concentrated the roots within the limited space resulting in increase in RLD. In this study coarse aggregates had the lowest RLD value. The finer aggregates had numerous small pore spaces which encouraged the development of more root hairs. The plants in black cotton soil had the highest RLD hence providing more surface area to be able to extract the nutrient feed. This is response to an assumed water stress due lower readily available water in clays. For the expanded clay, the mixed aggregates had high RLD. Mixing fine and coarse aggregates makes the medium to have proportionate ratio of micro and macro pores hence moderate drainage and water holding capacities. Considering both root and stem development, black cotton soil performed well under the test conditions provided. The unsuitability of this soil type often becomes evident when subjected to extremes of moisture content presented during excess wetness or lack of moisture.

The results for stem growth and root development combined into a single graph gives;

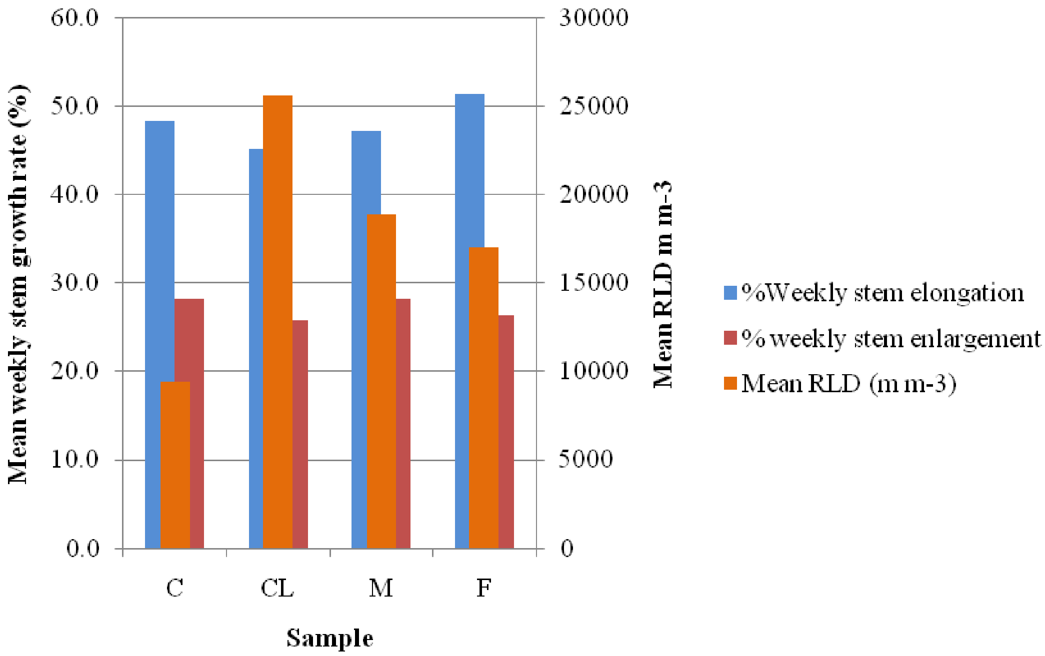

Figure 4.23: Crop growth under different growing sample media

Growing of tomatoes (as is the case with a variety of horticultural crops), the interest is on the shoot rather than the roots and therefore the fine size aggregates was more desirable but the scenario would change if excess water was applied to require fast drainage as may occur if planting is done outside a greenhouse (as in rainfed conditions where the rainfall intensity is not regulated). Where space is limiting in terms of planting pot and aggregate volume as in hydroponics, the coarse aggregates was more appropriate to accommodate the low RLD. For self supporting vegetables such kales or ornamentals such as roses which do not require stacking, stem diameter plays an important role in supporting the foliage and the mixed size aggregates was recommended.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The ratio of black cotton soil to rice husk, firing temperature and time affected the bulk density and saturated hydraulic conductivity of expanded black cotton soil aggregates. The firing temperature, time and percent black cotton soil of 750^{o}C, 30 minutes and 90% respectively resulted in reduced bulk density and improved hydraulic conductivity. Upon size reduction, a mean bulk density of 0.954 g cm^{-3} was obtained compared to 1.43 g cm^{-3} for the black cotton soil. The corresponding saturated hydraulic conductivity obtained was 0.00385 cm s^{-1}, an improvement from 0.0000333 cm s^{-1} for the black cotton soil (estimated by RETC model based on the texture).

The hydraulic parameters estimated by HYDRUS 1D model were 0.1 cm^3 cm^{-3}, 0.55 cm^3 cm^{-3}, 0.01, 1.91, 0.00368 cm s^{-1} and -1 for Θ_r, Θ_s, $\acute{\alpha}$, n, K_s and l respectively. The estimated K_s compared closely to the measured value of 0.003854 cm s^{-1}. The computed R^2 and the RMSE of 0.83 and 0.0895 cm^3 cm^{-3} respectively showed that the model estimations were acceptable.

The texture of expanded black cotton soil, affected both root development and stem growth of the tomato crop which requires good drainage and aeration conditions. The expanded black cotton soil improved the performance of the crop in terms of stem elongation and enlargement for all the aggregate size ranges used. The Root length density was highest in black cotton soil.

5.2 Recommendations

Farmers and agricultural extension officers can be trained on how to prepare to prepare expanded black cotton soil aggregates for adoption as a hydroponic medium to improve agricultural production. The following are recommendations for further studies;

i) Compare the performance of the expanded black cotton soil with other available hydroponic media.
ii) Determine the effect of mixing expanded black cotton soil with other available hydroponic media with the aim of further reducing bulk density while improving water retention.

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APPENDICES

APPENDIX 1: RESULTS FROM SAS

1.0 General Information

Class Level Information		
Class	**Levels**	**Values**
Temperature	3	700, 750, 800
Time	3	30, 60, 90
BCS	4	90, 95, 97.5,100

Number of Observations Read	36
Number of Observations Used	36

1.1 Results for Bulk Density before Firing

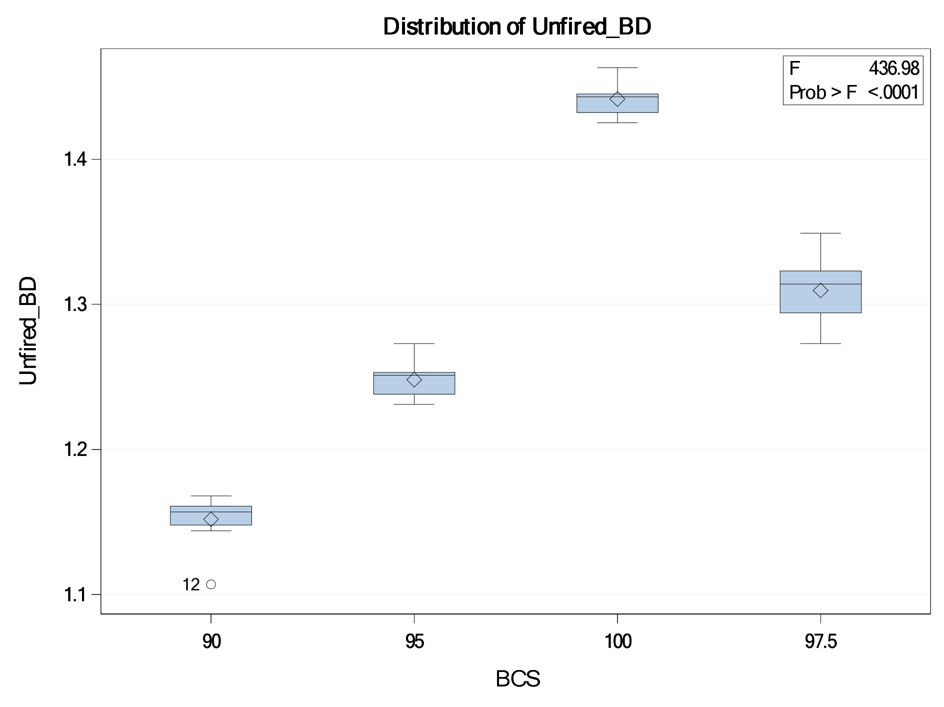
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	0.39714253	0.13238084	436.98	<.0001
Error	32	0.00969422	0.00030294		
Corrected Total	35	0.40683675			

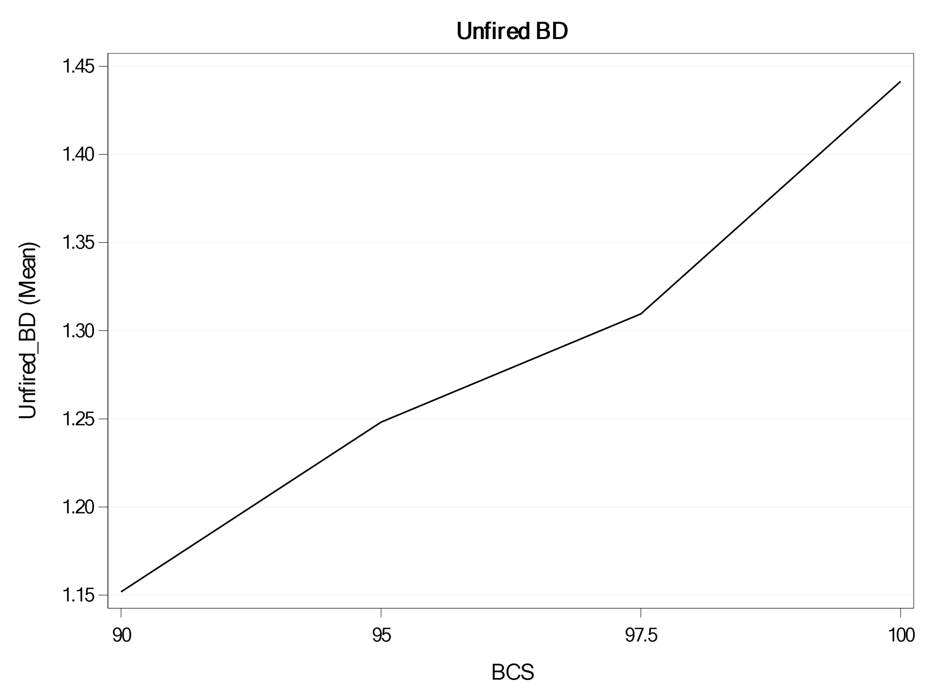
R-Square	Coeff Var	Root MSE	Unfired_BD Mean
0.976172	1.351605	0.017405	1.287750

Source	DF	Type I SS	Mean Square	F Value	Pr > F
BCS	3	0.39714253	0.13238084	436.98	<.0001

Source	DF	Type I SS	Mean Square	F Value	Pr > F
BCS	3	0.39714253	0.13238084	436.98	<.0001

Level of		Unfired_BD	
BCS	n	Mean	Std Dev
90	9	1.15188889	0.01855023
95	9	1.24811111	0.01320459
100	9	1.44144444	0.01275844
97.5	9	1.30955556	0.02303319





Pearson Correlation Coefficients for change in Bulk Density

Factor	Correlation coefficient
Temperature	-0.05073
Time	0.04501
BCS	-0.88110

Results Table

Obs	BCS	Unfired_BD	predicted
1	100	1.443	1.44144
2	97.5	1.323	1.30956
3	95	1.253	1.24811
4	90	1.161	1.15189
5	100	1.434	1.44144
6	97.5	1.294	1.30956
7	95	1.253	1.24811
8	90	1.168	1.15189
9	100	1.43	1.44144
10	97.5	1.325	1.30956
11	95	1.251	1.24811
12	90	1.107	1.15189
13	100	1.443	1.44144
14	97.5	1.29	1.30956
15	95	1.233	1.24811
16	90	1.144	1.15189
17	100	1.463	1.44144
18	97.5	1.314	1.30956
19	95	1.231	1.24811
20	90	1.161	1.15189
21	100	1.432	1.44144
22	97.5	1.321	1.30956
23	95	1.238	1.24811
24	90	1.148	1.15189
25	100	1.425	1.44144
26	97.5	1.297	1.30956
27	95	1.257	1.24811
28	90	1.157	1.15189
29	100	1.445	1.44144
30	97.5	1.349	1.30956
31	95	1.273	1.24811
32	90	1.155	1.15189
33	100	1.458	1.44144
34	97.5	1.273	1.30956
35	95	1.244	1.24811
36	90	1.166	1.15189

1.2 Results for Bulk Density after Firing (Before Size Reduction)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	24	46.39170050	1.93298752	4018.34	<.0001
Error	12	0.00577250	0.00048104		
Uncorrected Total	36	46.39747300			

R-Square	Coeff Var	Root MSE	Fired_BD Mean
0.990567	1.944816	0.021933	1.127750

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Temperature	3	45.78644342	15.26214781	31727.3	<.0001
Time	2	0.00067817	0.00033908	0.70	0.5135
BCS	3	0.60187408	0.20062469	417.06	<.0001
Temperature*Time	4	0.00055017	0.00013754	0.29	0.8815
Time*BCS	6	0.00068317	0.00011386	0.24	0.9559
Temperature*BCS	6	0.00147150	0.00024525	0.51	0.7900

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Temperature	2	0.00092117	0.00046058	0.96	0.4113
Time	2	0.00067817	0.00033908	0.70	0.5135
BCS	3	0.60187408	0.20062469	417.06	<.0001
Temperature*Time	4	0.00055017	0.00013754	0.29	0.8815
Time*BCS	6	0.00068317	0.00011386	0.24	0.9559
Temperature*BCS	6	0.00147150	0.00024525	0.51	0.7900

Pearson Correlation Coefficients for Bulk Density of Fired Blocks

Factor	Correlation coefficient
Temperature	0.02635
Time	-0.01931
BCS	0.94055

Results Table

Obs	Temperature	Time	BCS	Fired_BD	predicted	residual	cookd
1	700	30	100	1.327	1.32569	0.001306	0.00089
2	700	30	97.5	1.139	1.13736	0.001639	0.00140
3	700	30	95	1.096	1.10258	-0.006583	0.02252
4	700	30	90	0.974	0.97036	0.003639	0.00688
5	700	60	100	1.321	1.31978	0.001222	0.00078
6	700	60	97.5	1.12	1.14078	-0.020778	0.22437
7	700	60	95	1.089	1.08767	0.001333	0.00092
8	700	60	90	0.976	0.95778	0.018222	0.17257
9	700	90	100	1.316	1.31853	-0.002528	0.00332
10	700	90	97.5	1.148	1.12886	0.019139	0.19037
11	700	90	95	1.089	1.08375	0.005250	0.01432
12	700	90	90	0.919	0.94086	-0.021861	0.24837
13	750	30	100	1.327	1.32086	0.006139	0.01959
14	750	30	97.5	1.113	1.11653	-0.003528	0.00647
15	750	30	95	1.076	1.07308	0.002917	0.00442
16	750	30	90	0.954	0.95953	-0.005528	0.01588
17	750	60	100	1.347	1.33469	0.012306	0.07870
18	750	60	97.5	1.133	1.13969	-0.006694	0.02329
19	750	60	95	1.07	1.07792	-0.007917	0.03257
20	750	60	90	0.969	0.96669	0.002306	0.00276
21	750	90	100	1.314	1.33244	-0.018444	0.17680
22	750	90	97.5	1.137	1.12678	0.010222	0.05431
23	750	90	95	1.078	1.07300	0.005000	0.01299
24	750	90	90	0.952	0.94878	0.003222	0.00540
25	800	30	100	1.31	1.31744	-0.007444	0.02880
26	800	30	97.5	1.129	1.12711	0.001889	0.00185
27	800	30	95	1.111	1.10733	0.003667	0.00699
28	800	30	90	0.984	0.98211	0.001889	0.00185
29	800	60	100	1.314	1.32753	-0.013528	0.09511
30	800	60	97.5	1.174	1.14653	0.027472	0.39223
31	800	60	95	1.115	1.10842	0.006583	0.02252
32	800	60	90	0.965	0.98553	-0.020528	0.21900
33	800	90	100	1.342	1.32103	0.020972	0.22858
34	800	90	97.5	1.1	1.12936	-0.029361	0.44803
35	800	90	95	1.089	1.09925	-0.010250	0.05460
36	800	90	90	0.982	0.96336	0.018639	0.18055

1.3 Results for Change in Bulk Density Upon Firing

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	24	6082.887706	253.453654	2556.49	<.0001
Error	12	1.189694	0.099141		
Uncorrected Total	36	6084.077400			

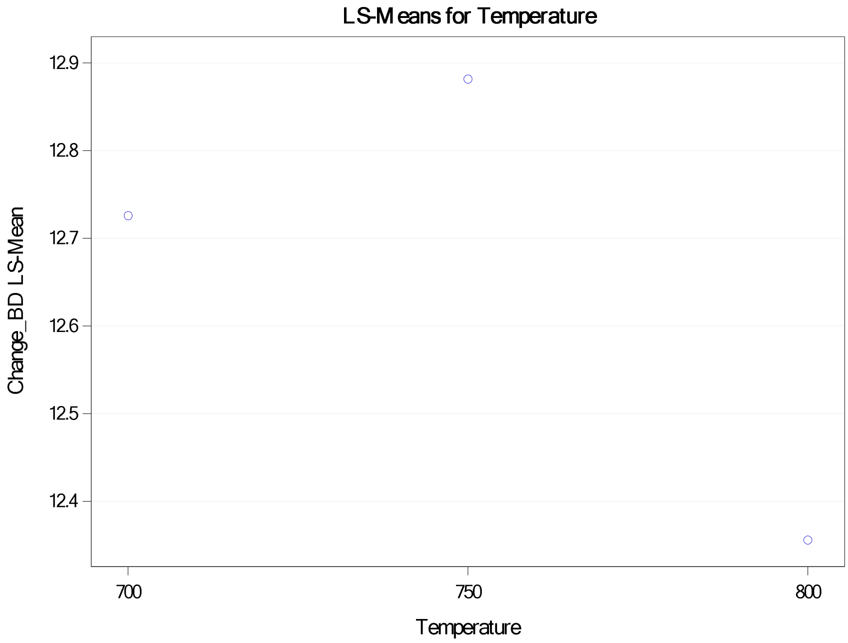
R-Square	Coeff Var	Root MSE	Change_BD Mean
0.996273	2.488193	0.314867	12.65444

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Temperature	3	5766.609450	1922.203150	19388.5	<.0001
Time	2	0.834906	0.417453	4.21	0.0412
BCS	3	311.949711	103.983237	1048.84	<.0001
Temperature*Time	4	0.806594	0.201649	2.03	0.1534
Time*BCS	6	0.809206	0.134868	1.36	0.3054
Temperature*BCS	6	1.877839	0.312973	3.16	0.0427

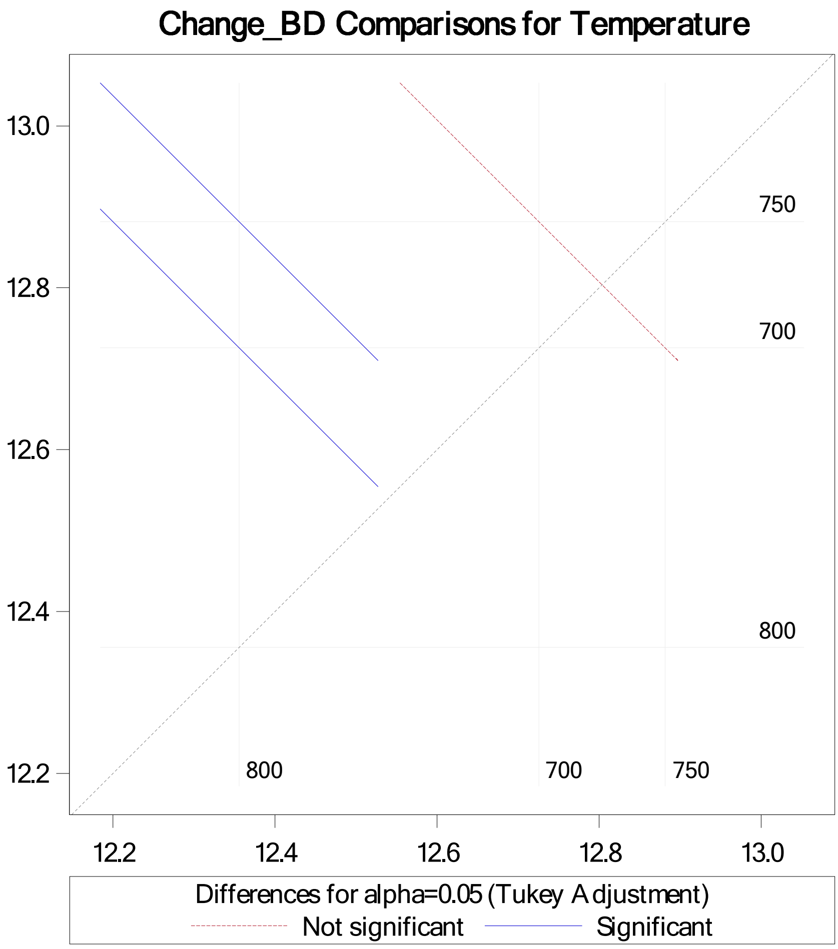
Source	DF	Type III SS	Mean Square	F Value	Pr > F
Temperature	2	1.7507389	0.8753694	8.83	0.0044
Time	2	0.8349056	0.4174528	4.21	0.0412
BCS	3	311.9497111	103.9832370	1048.84	<.0001
Temperature*Time	4	0.8065944	0.2016486	2.03	0.1534
Time*BCS	6	0.8092056	0.1348676	1.36	0.3054
Temperature*BCS	6	1.8778389	0.3129731	3.16	0.0427

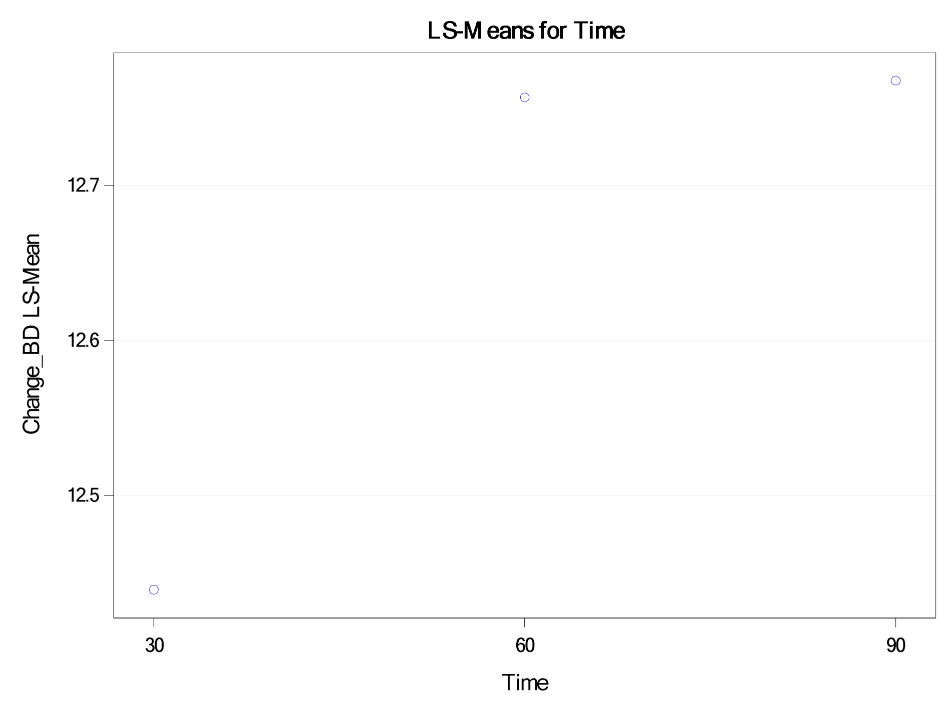
Pearson Correlation Analysis

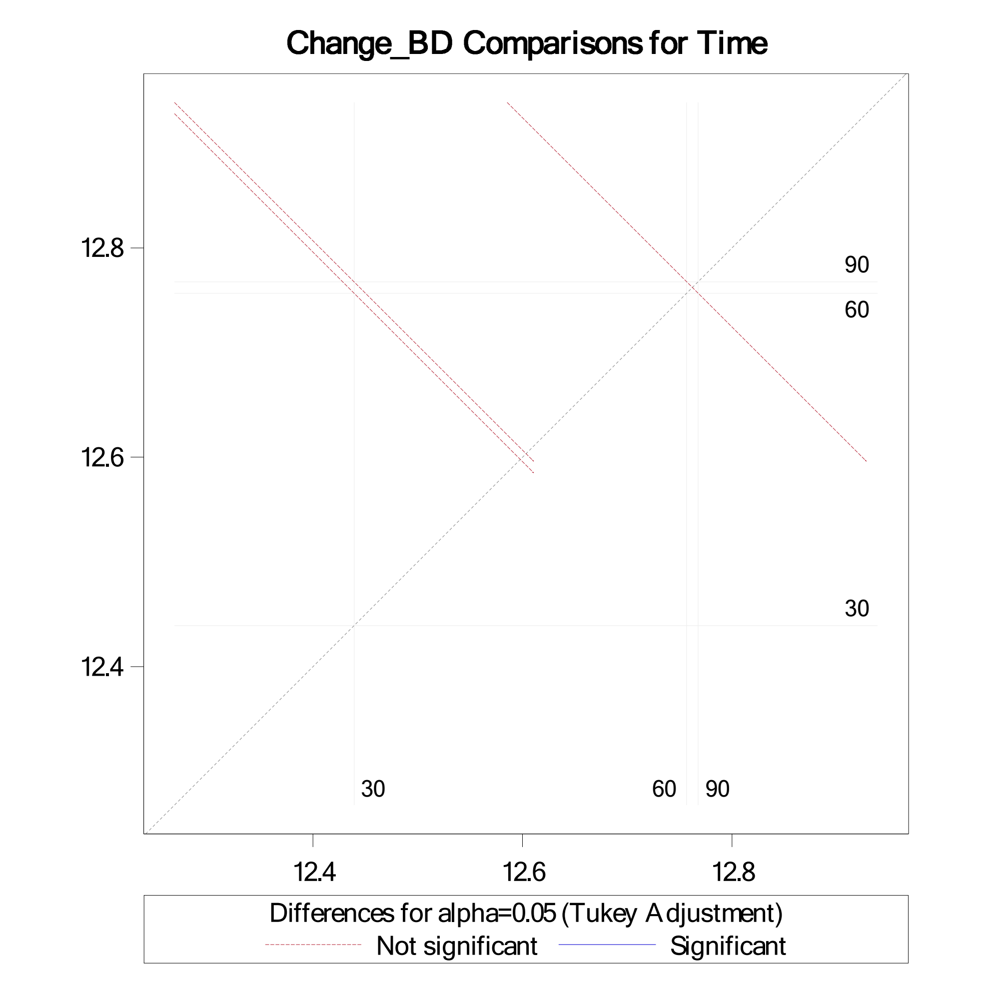
Factor	Coefficient
Temperature	-0.05073
Time	0.04501
BCS	-0.88110

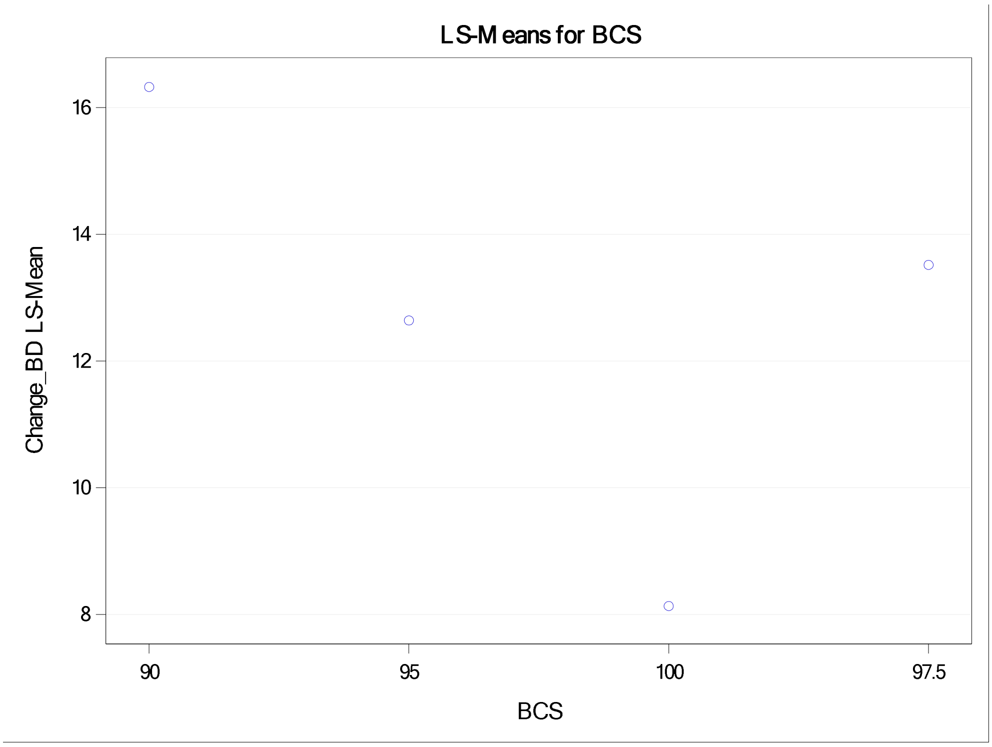


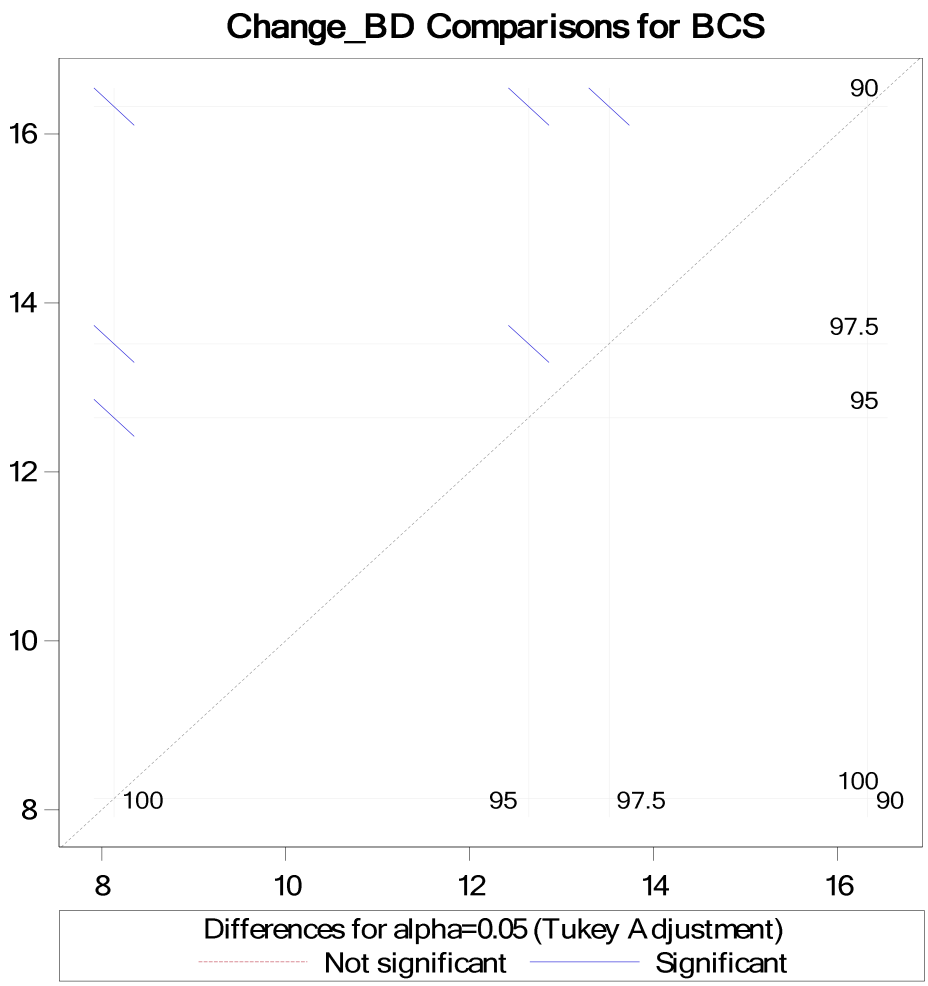
Least squares means adjustment for multiple comparisons: Tukey




LS-Means for Time
Change_BD LS-Mean
12.7
12.6
12.5
30
60
90
Time


Change_BD Comparisons for Time
12.8
12.6
12.4
90
60
30
30
60
90
12.4
12.6
12.8
Differences for alpha=0.05 (Tukey Adjustment)
Not significant
Significant


LS-Means for BCS
Change_BD LS-Mean
16
14
12
10
8
90
95
100
97.5
BCS


Change_BD Comparisons for BCS
90
97.5
95
100
95
97.5
100
90
16
14
12
10
8
8
10
12
14
16
Differences for alpha=0.05 (Tukey Adjustment)
Not significant
Significant

Results Table

Obs	Temperature	Time	BCS	Change_BD	predicted	residual
1	700	30	100	8.04	8.0169	0.02306
2	700	30	97.5	13.91	13.7203	0.18972
3	700	30	95	12.53	12.6414	-0.11139
4	700	30	90	16.11	16.2114	-0.10139
5	700	60	100	7.88	8.0103	-0.13028
6	700	60	97.5	13.45	13.3403	0.10972
7	700	60	95	13.09	12.9614	0.12861
8	700	60	90	16.44	16.5481	-0.10806
9	700	90	100	7.97	7.8628	0.10722
10	700	90	97.5	13.36	13.6594	-0.29944
11	700	90	95	12.95	12.9672	-0.01722
12	700	90	90	16.98	16.7706	0.20944
13	750	30	100	8.04	8.0953	-0.05528
14	750	30	97.5	13.72	13.9253	-0.20528
15	750	30	95	12.73	12.6664	0.06361
16	750	30	90	16.61	16.4131	0.19694
17	750	60	100	7.93	8.0761	-0.14611
18	750	60	97.5	13.77	13.5328	0.23722
19	750	60	95	13.08	12.9739	0.10611
20	750	60	90	16.54	16.7372	-0.19722
21	750	90	100	8.24	8.0386	0.20139
22	750	90	97.5	13.93	13.9619	-0.03194
23	750	90	95	12.92	13.0897	-0.16972
24	750	90	90	17.07	17.0697	0.00028
25	800	30	100	8.07	8.0378	0.03222
26	800	30	97.5	12.95	12.9344	0.01556
27	800	30	95	11.61	11.5622	0.04778
28	800	30	90	14.95	15.0456	-0.09556
29	800	60	100	9.07	8.7936	0.27639
30	800	60	97.5	12.97	13.3169	-0.34694
31	800	60	95	12.41	12.6447	-0.23472
32	800	60	90	16.45	16.1447	0.30528
33	800	90	100	7.96	8.2686	-0.30861
34	800	90	97.5	13.59	13.2586	0.33139
35	800	90	95	12.46	12.2731	0.18694
36	800	90	90	15.78	15.9897	-0.20972

1.4 Results for Saturated Moisture Content (Fired Blocks)

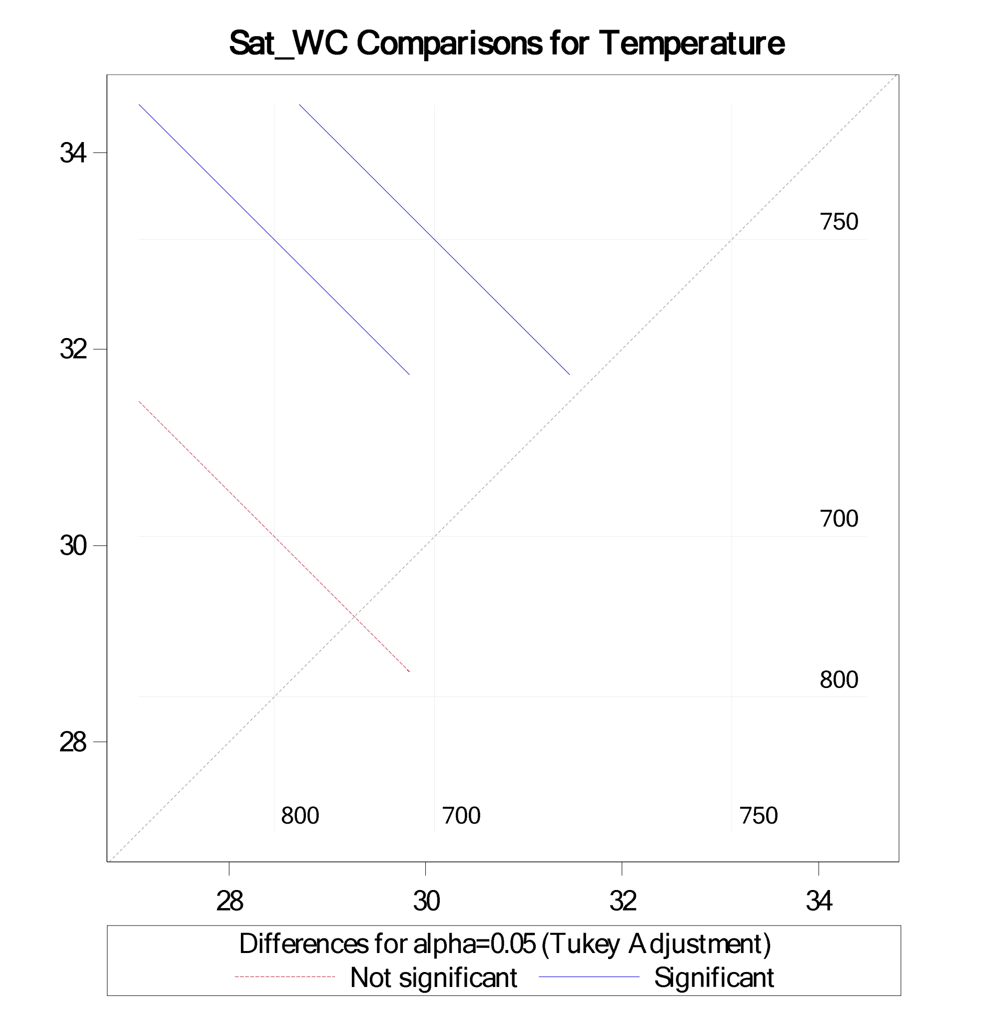
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	24	36858.16979	1535.75707	240.02	<.0001
Error	12	76.78121	6.39843		
Uncorrected Total	36	36934.95100			

R-Square	Coeff Var	Root MSE	Sat_WC Mean
0.976900	8.278405	2.529513	30.55556

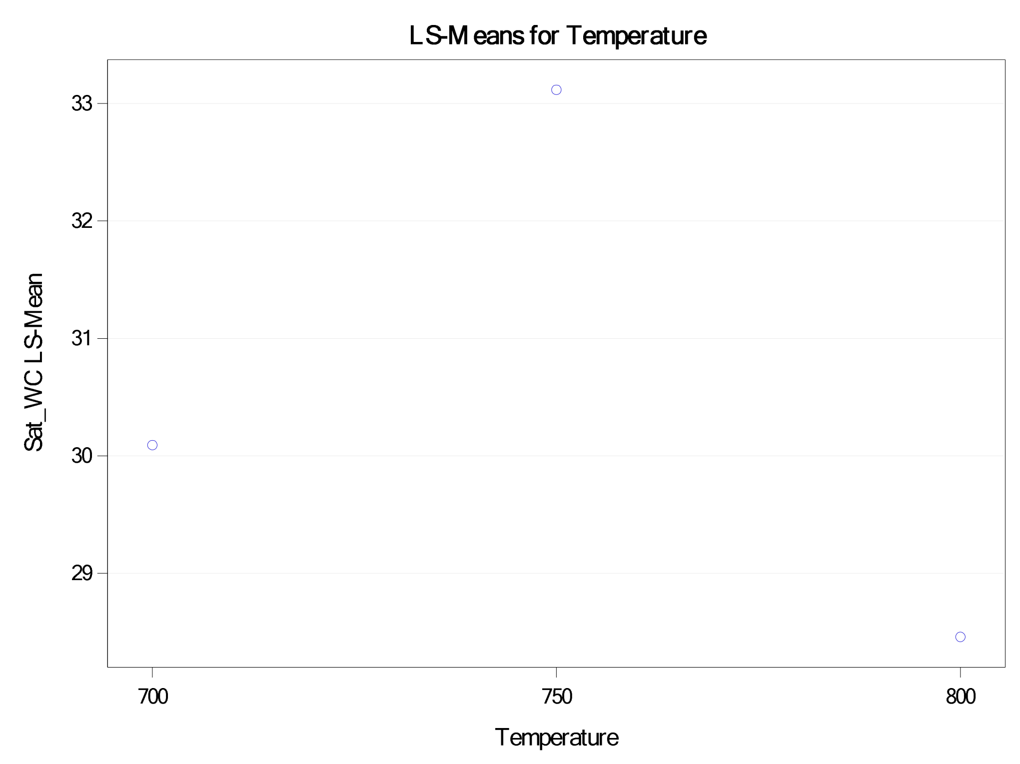
Source	DF	Type I SS	Mean Square	F Value	Pr > F
Temperature	3	33745.09185	11248.36395	1757.99	<.0001
Time	2	72.82144	36.41072	5.69	0.0183
BCS	3	2895.46758	965.15586	150.84	<.0001
Temperature*Time	4	84.13361	21.03340	3.29	0.0488
Time*BCS	6	20.29847	3.38308	0.53	0.7766
Temperature*BCS	6	40.35684	6.72614	1.05	0.4410

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Temperature	2	133.980739	66.990369	10.47	0.0023
Time	2	72.821439	36.410719	5.69	0.0183
BCS	3	2895.467578	965.155859	150.84	<.0001
Temperature*Time	4	84.133611	21.033403	3.29	0.0488
Time*BCS	6	20.298472	3.383079	0.53	0.7766
Temperature*BCS	6	40.356839	6.726140	1.05	0.4410

Temperature	Sat_WC LSMEAN	LSMEAN Number
700	30.0916667	1
750	33.1158333	2
800	28.4591667	3

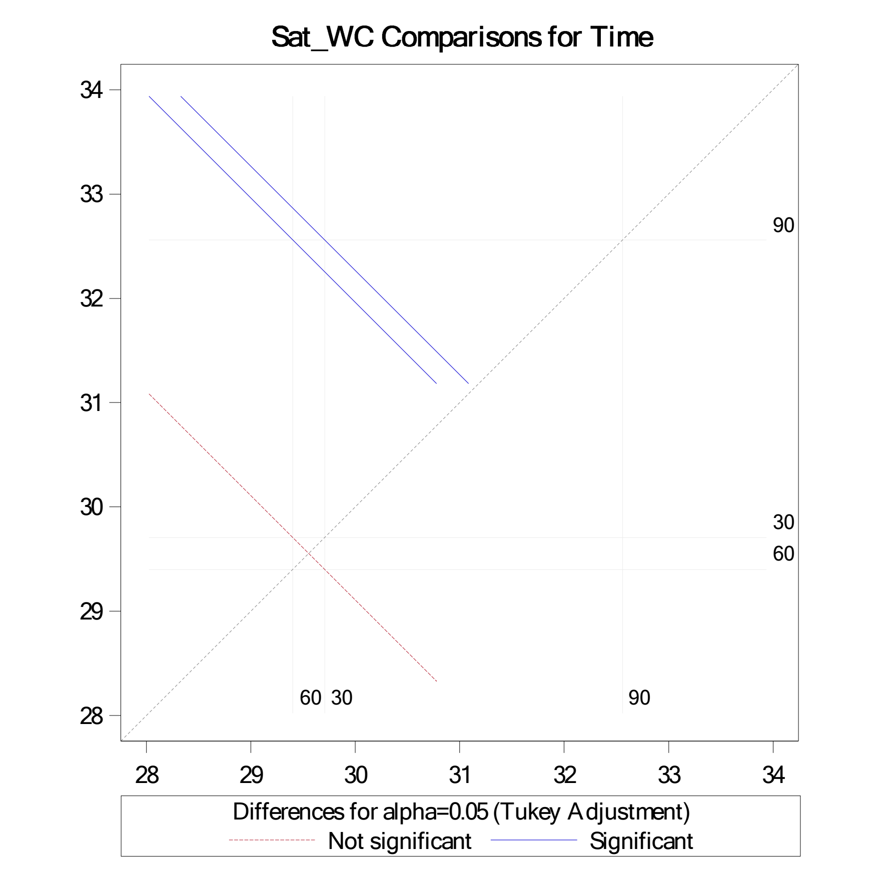


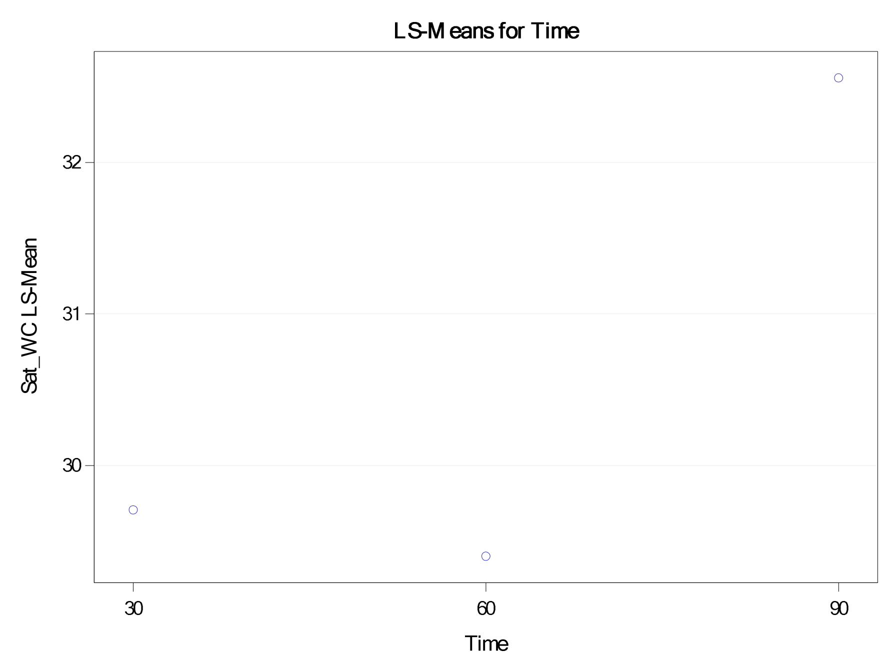
Sat_WC Comparisons for Temperature
34
32
30
28
750
700
800
800
700
750
28
30
32
34
Differences for alpha=0.05 (Tukey Adjustment)
Not significant
Significant



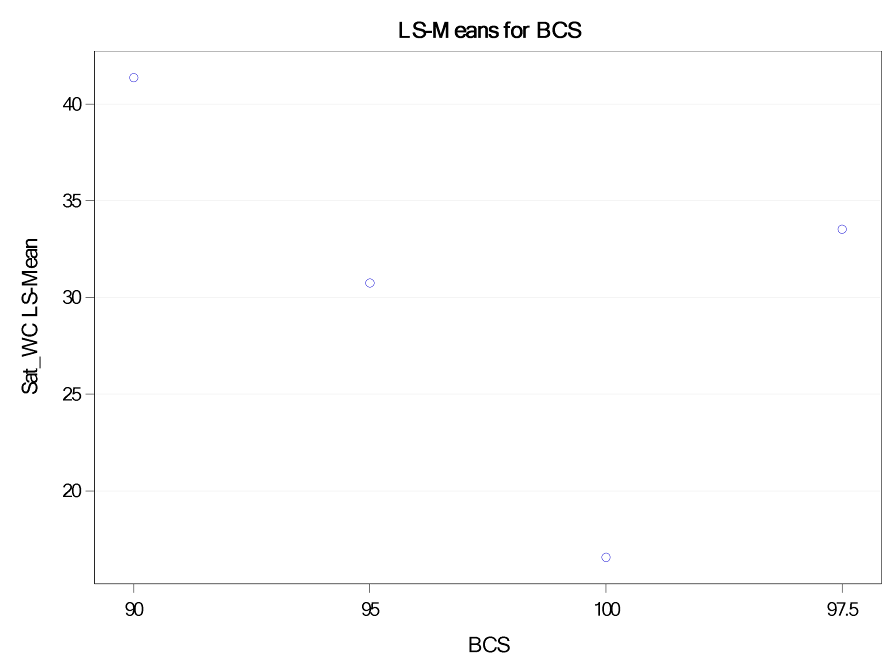
LS-Means for Temperature
Sat_WC LS-Mean
33
32
31
30
29
700
750
800
Temperature

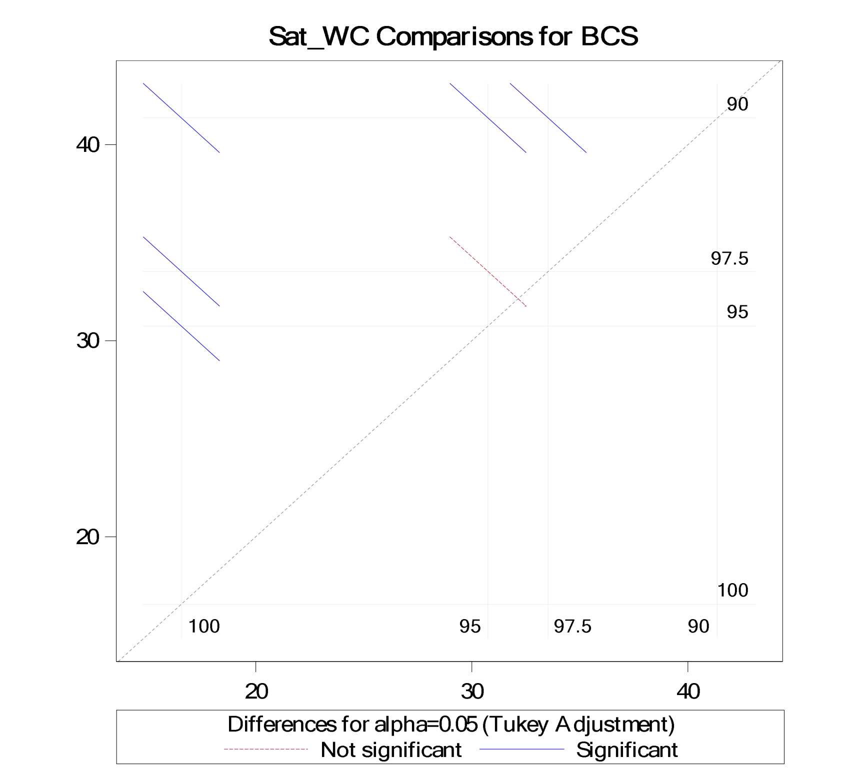
Time	Sat_WC LSMEAN	LSMEAN Number
30	29.7066667	1
60	29.4008333	2
90	32.5591667	3





BCS	Sat_WC LSMEAN	LSMEAN Number
90	41.3733333	1
95	30.7511111	2
100	16.5633333	3
97.5	33.5344444	4





Results Table

Obs	Temperature	Time	BCS	Sat_WC	predicted
1	700	30	100	15.96	15.2789
2	700	30	97.5	31.42	32.1011
3	700	30	95	27.89	27.3744
4	700	30	90	40.15	40.6656
5	700	60	100	16.87	18.5889
6	700	60	97.5	36.06	35.1011
7	700	60	95	31.68	30.5578
8	700	60	90	40.72	41.0822
9	700	90	100	16.42	15.3822
10	700	90	97.5	32.51	32.7878
11	700	90	95	28.67	30.3078
12	700	90	90	42.75	41.8722
13	750	30	100	16.64	18.0264
14	750	30	97.5	35.9	36.3753
15	750	30	95	33.47	32.2053
16	750	30	90	47.15	46.5531
17	750	60	100	16.36	14.9064
18	750	60	97.5	32.93	32.9453
19	750	60	95	30	28.9586
20	750	60	90	38.06	40.5397
21	750	90	100	20.26	20.3272
22	750	90	97.5	39.75	39.2594
23	750	90	95	35.03	37.3361
24	750	90	90	51.84	49.9572
25	800	30	100	14.84	14.1347
26	800	30	97.5	30.76	29.6036
27	800	30	95	25.94	27.7203
28	800	30	90	36.36	36.4414
29	800	60	100	15.79	15.5247
30	800	60	97.5	29.74	30.6836
31	800	60	95	26.82	28.9836
32	800	60	90	37.78	34.9381
33	800	90	100	15.93	16.9006
34	800	90	97.5	32.74	32.9528
35	800	90	95	37.26	33.3161
36	800	90	90	37.55	40.3106

Correlation Analysis for Saturated Water Content of the Blocks

Factor	Correlation
Temperature	-0.06936
Time	0.12119
BCS	-0.82048

1.5 Results for Bulk Density after Size Reduction

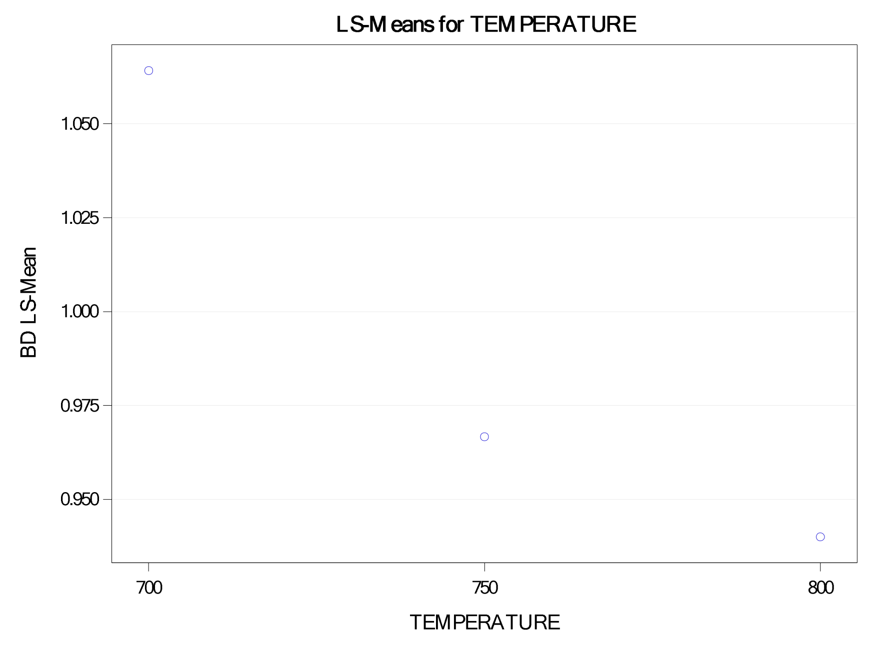
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	24	35.64806111	1.48533588	1929.24	<.0001
Error	12	0.00923889	0.00076991		
Uncorrected Total	36	35.65730000			

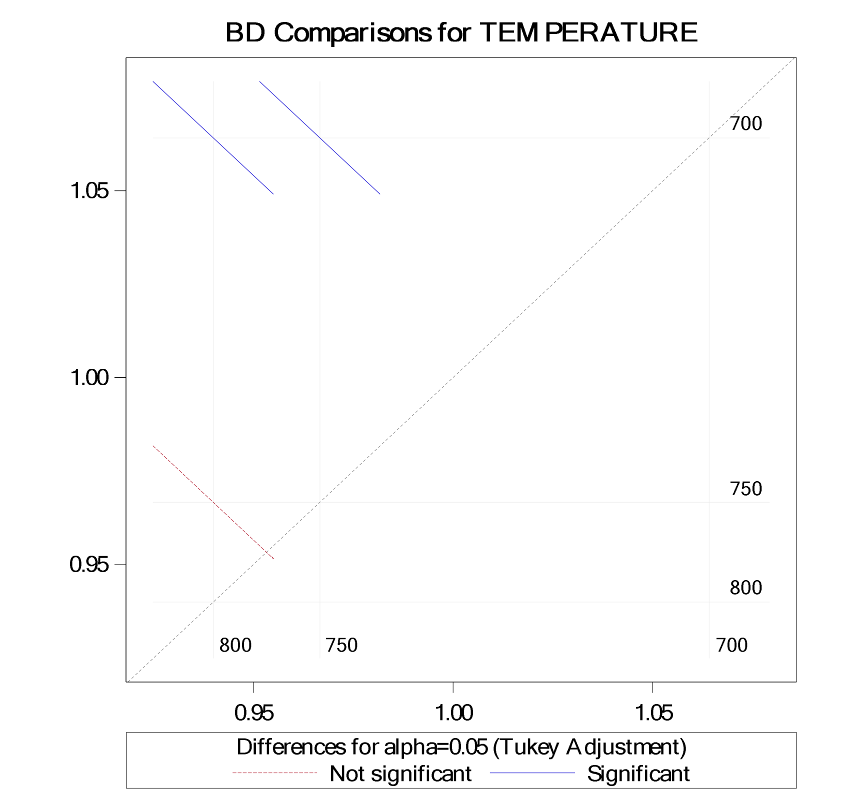
R-Square	Coeff Var	Root MSE	BD Mean
0.973894	2.801962	0.027747	0.990278

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TEMPERATURE	3	35.40594167	11.80198056	15329.1	<.0001
TIME	2	0.00202222	0.00101111	1.31	0.3050
BCS	3	0.21269722	0.07089907	92.09	<.0001
TEMPERATURE*TIME	4	0.01756111	0.00439028	5.70	0.0083
TIME*BCS	6	0.00584444	0.00097407	1.27	0.3421
TEMPERATURE*BCS	6	0.00399444	0.00066574	0.86	0.5471

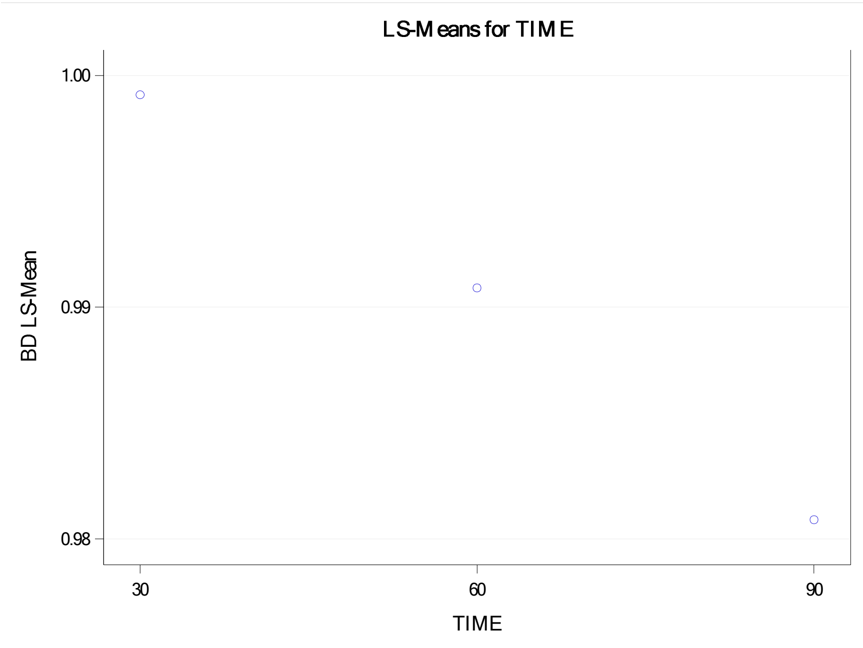
Source	DF	Type III SS	Mean Square	F Value	Pr > F
TEMPERATURE	2	0.10253889	0.05126944	66.59	<.0001
TIME	2	0.00202222	0.00101111	1.31	0.3050
BCS	3	0.21269722	0.07089907	92.09	<.0001
TEMPERATURE*TIME	4	0.01756111	0.00439028	5.70	0.0083
TIME*BCS	6	0.00584444	0.00097407	1.27	0.3421
TEMPERATURE*BCS	6	0.00399444	0.00066574	0.86	0.5471

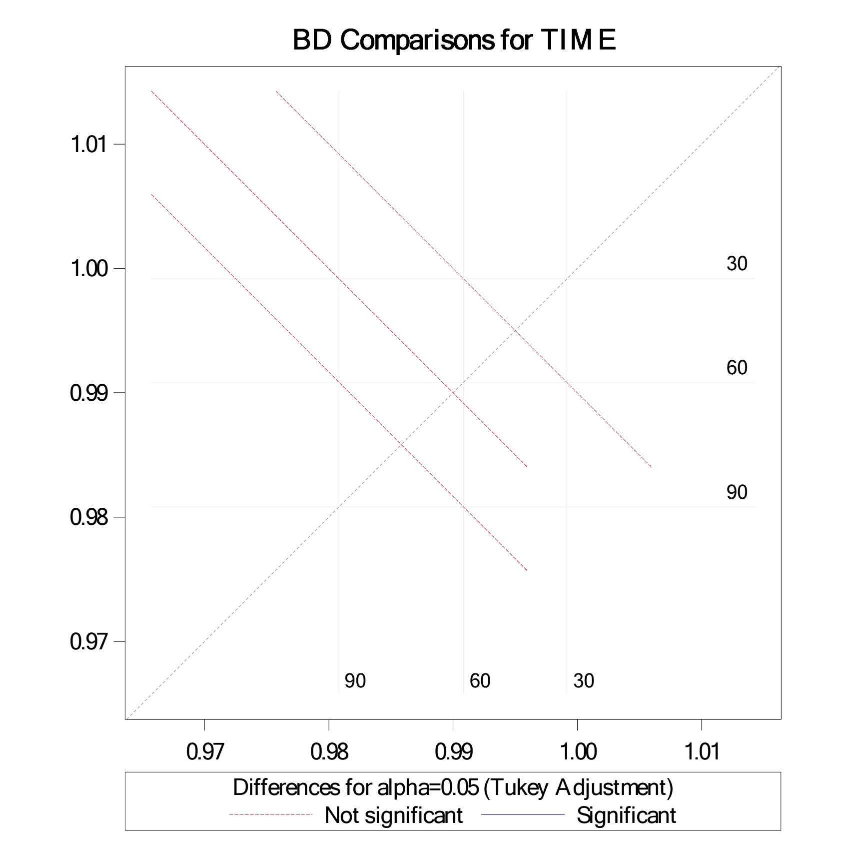
TEMPERATURE	BD LSMEAN	LSMEAN Number
700	1.06416667	1
750	0.96666667	2
800	0.94000000	3



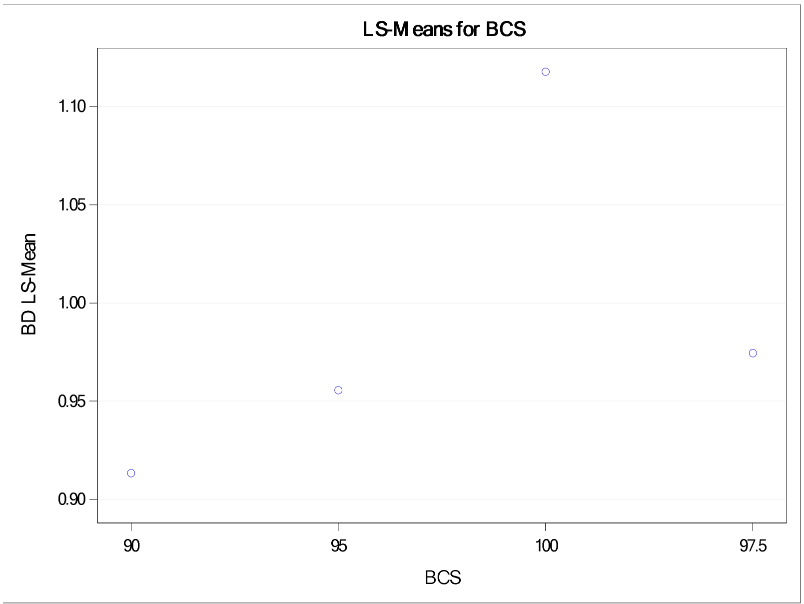


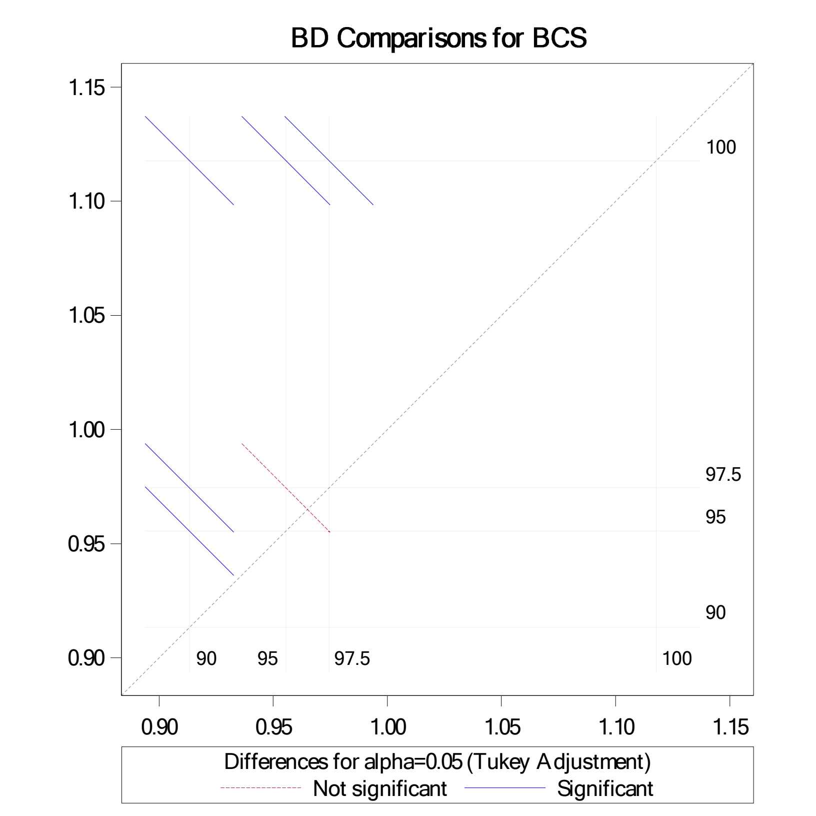
TIME	BD LSMEAN	LSMEAN Number
30	0.99916667	1
60	0.99083333	2
90	0.98083333	3





BCS	BD LSMEAN	LSMEAN Number
90	0.91333333	1
95	0.95555556	2
100	1.11777778	3
97.5	0.97444444	4





Results Table

Obs	TEMPERATURE	TIME	BCS	BD	predicted	lclm	uclm
1	700	30	100	1.19	1.16583	1.11647	1.21520
2	700	30	97.5	1.06	1.07250	1.02314	1.12186
3	700	30	95	0.98	1.00139	0.95203	1.05075
4	700	30	90	0.97	0.96028	0.91092	1.00964
5	700	60	100	1.19	1.19333	1.14397	1.24270
6	700	60	97.5	1.06	1.06000	1.01064	1.10936
7	700	60	95	1.06	1.05889	1.00953	1.10825
8	700	60	90	1.02	1.01778	0.96842	1.06714
9	700	90	100	1.17	1.19083	1.14147	1.24020
10	700	90	97.5	1.07	1.05750	1.00814	1.10686
11	700	90	95	1.04	1.01972	0.97036	1.06908
12	700	90	90	0.96	0.97194	0.92258	1.02131
13	750	30	100	1.16	1.14250	1.09314	1.19186
14	750	30	97.5	0.98	0.99583	0.94647	1.04520
15	750	30	95	0.97	0.97139	0.92203	1.02075
16	750	30	90	0.94	0.94028	0.89092	0.98964
17	750	60	100	1.08	1.08750	1.03814	1.13686
18	750	60	97.5	0.92	0.90083	0.85147	0.95020
19	750	60	95	0.94	0.94639	0.89703	0.99575
20	750	60	90	0.91	0.91528	0.86592	0.96464
21	750	90	100	1.06	1.07000	1.02064	1.11936
22	750	90	97.5	0.88	0.88333	0.83397	0.93270
23	750	90	95	0.9	0.89222	0.84286	0.94158
24	750	90	90	0.86	0.85444	0.80508	0.90381
25	800	30	100	1.02	1.06167	1.01230	1.11103
26	800	30	97.5	0.98	0.95167	0.90230	1.00103
27	800	30	95	0.91	0.88722	0.83786	0.93658
28	800	30	90	0.83	0.83944	0.79008	0.88881
29	800	60	100	1.06	1.04917	0.99980	1.09853
30	800	60	97.5	0.88	0.89917	0.84980	0.94853
31	800	60	95	0.91	0.90472	0.85536	0.95408
32	800	60	90	0.86	0.85694	0.80758	0.90631
33	800	90	100	1.13	1.09917	1.04980	1.14853
34	800	90	97.5	0.94	0.94917	0.89980	0.99853
35	800	90	95	0.89	0.91806	0.86869	0.96742
36	800	90	90	0.87	0.86361	0.81425	0.91297

Correlation Analysis for Bulk Density after size reduction

Factor	Bulk density
Temperature	-0.5113
Time	-0.0755
BCS	0.6701

1.6 Results For Saturated Hydraulic Conductivity

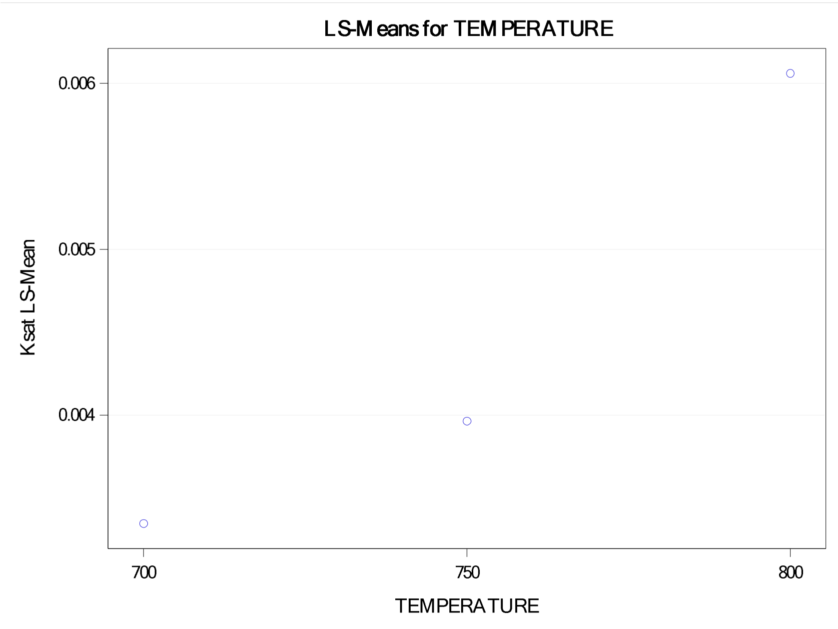
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	24	0.00078861	0.00003286	379.82	<.0001
Error	12	0.00000104	0.00000009		
Uncorrected Total	36	0.00078965			

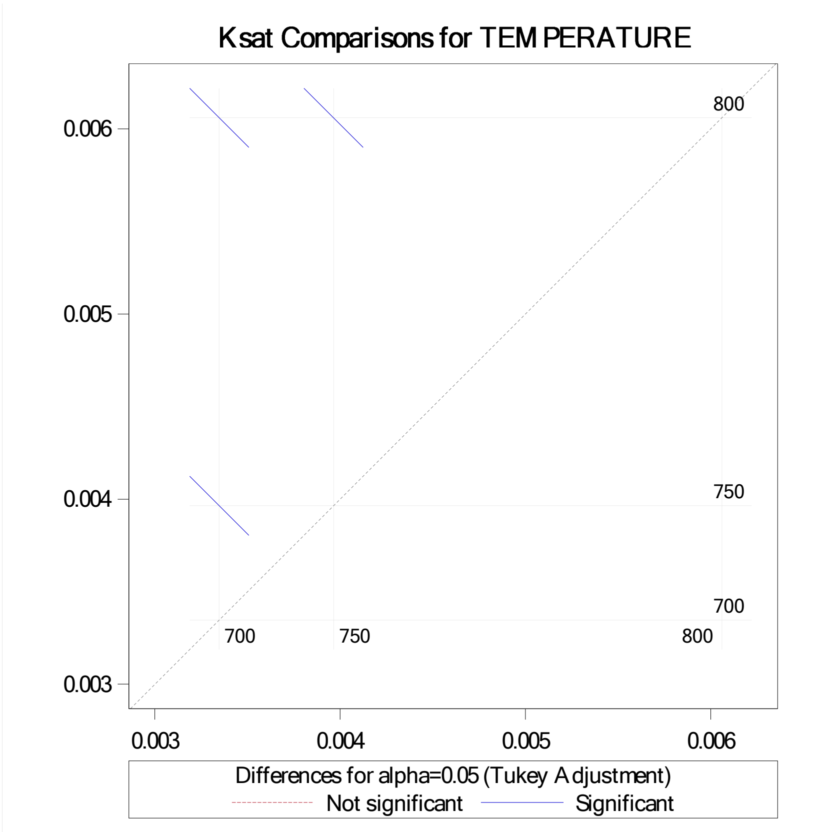
R-Square	Coeff Var	Root MSE	Ksat Mean
0.986051	6.598808	0.000294	0.004457

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TEMPERATURE	3	0.00076376	0.00025459	2942.83	<.0001
TIME	2	0.00000500	0.00000250	28.88	<.0001
BCS	3	0.00001630	0.00000543	62.81	<.0001
TEMPERATURE*TIME	4	0.00000101	0.00000025	2.93	0.0664
TIME*BCS	6	0.00000058	0.00000010	1.13	0.4035
TEMPERATURE*BCS	6	0.00000195	0.00000033	3.77	0.0242

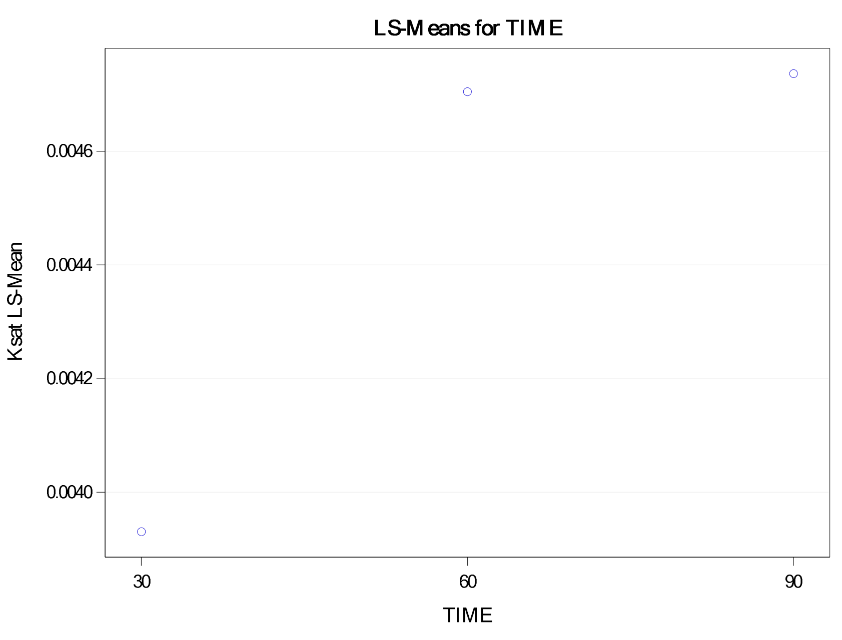
Source	DF	Type III SS	Mean Square	F Value	Pr > F
TEMPERATURE	2	0.00004854	0.00002427	280.53	<.0001
TIME	2	0.00000500	0.00000250	28.88	<.0001
BCS	3	0.00001630	0.00000543	62.81	<.0001
TEMPERATURE*TIME	4	0.00000101	0.00000025	2.93	0.0664
TIME*BCS	6	0.00000058	0.00000010	1.13	0.4035
TEMPERATURE*BCS	6	0.00000195	0.00000033	3.77	0.0242

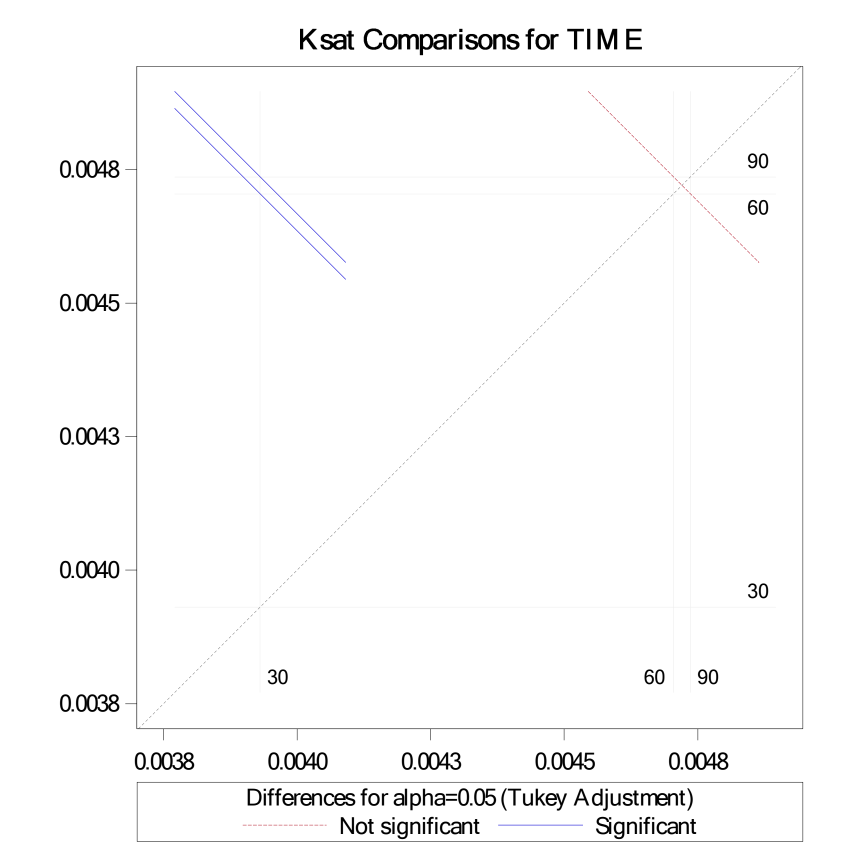
TEMPERATURE	Ksat LSMEAN	LSMEAN Number
700	0.00334717	1
750	0.00396442	2
800	0.00606025	3



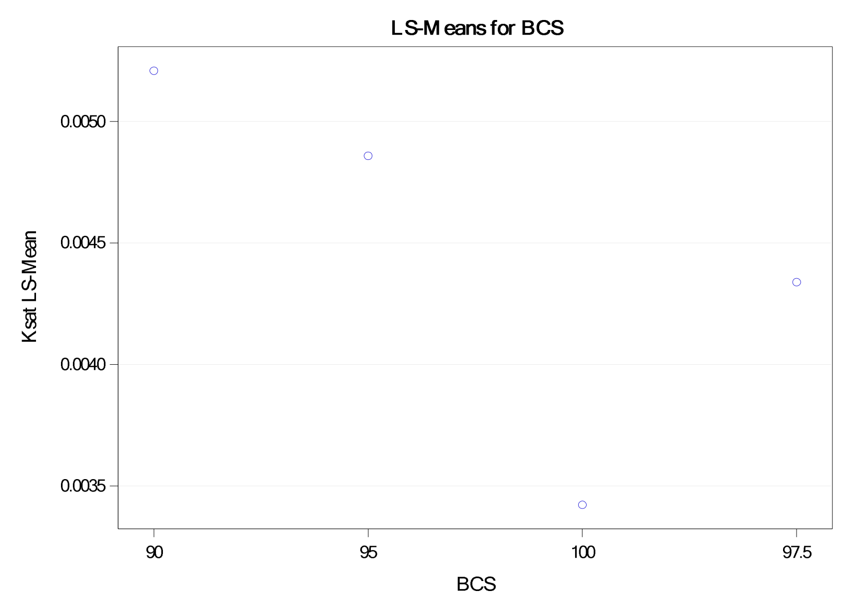


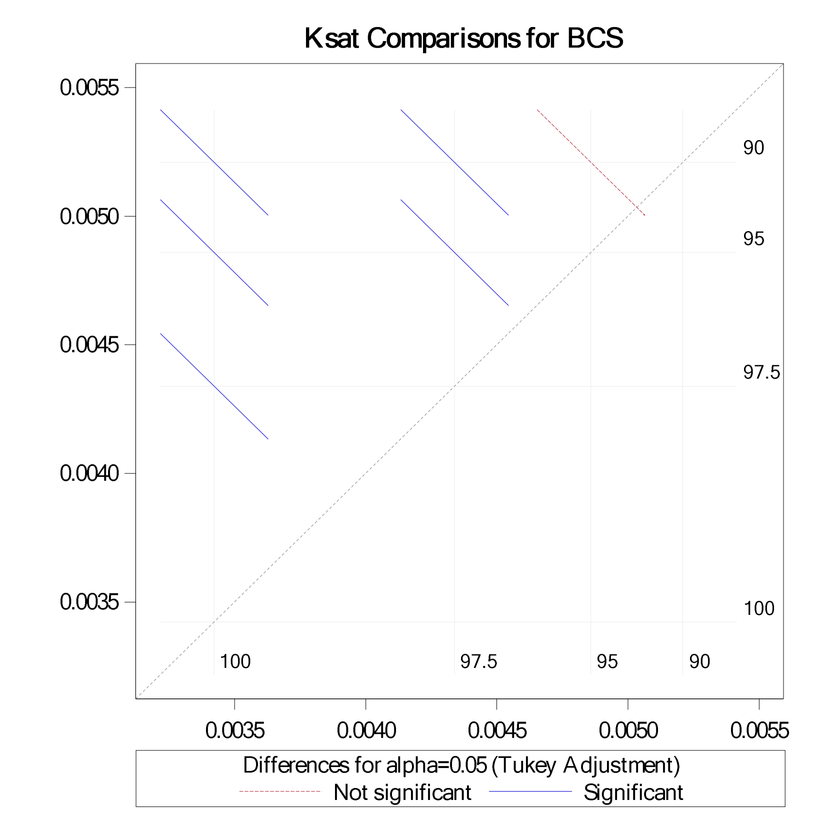
TIME	Ksat LSMEAN	LSMEAN Number
30	0.00393075	1
60	0.00470467	2
90	0.00473642	3





BCS	Ksat LSMEAN	LSMEAN Number
90	0.00520900	1
95	0.00485878	2
100	0.00342244	3
97.5	0.00433889	4





Results Table

Obs	TEMPERATURE	TIME	BCS	Ksat	predicted
1	700	30	100	0.002267	.002399667
2	700	30	97.5	0.003227	.003299222
3	700	30	95	0.003509	.003313667
4	700	30	90	0.003584	.003574444
5	700	60	100	0.002328	.002218000
6	700	60	97.5	0.003546	.003463556
7	700	60	95	0.003627	.003806000
8	700	60	90	0.004123	.004136444
9	700	90	100	0.002464	.002441333
10	700	90	97.5	0.003529	.003539222
11	700	90	95	0.003746	.003762333
12	700	90	90	0.004216	.004212111
13	750	30	100	0.002475	.002763417
14	750	30	97.5	0.003422	.003437306
15	750	30	95	0.003604	.003573083
16	750	30	90	0.003854	.003581194
17	750	60	100	0.003405	.003254250
18	750	60	97.5	0.004244	.004274139
19	750	60	95	0.004599	.004737917
20	750	60	90	0.004834	.004815694
21	750	90	100	0.003546	.003408333
22	750	90	97.5	0.004326	.004280556
23	750	90	95	0.004733	.004625000
24	750	90	90	0.004531	.004822111
25	800	30	100	0.004687	.004265917
26	800	30	97.5	0.004985	.004897472
27	800	30	95	0.005544	.005770250
28	800	30	90	0.006011	.006293361
29	800	60	100	0.004695	.004955750
30	800	60	97.5	0.005881	.005933306
31	800	60	95	0.007452	.007134083
32	800	60	90	0.007722	.007726861
33	800	90	100	0.004935	.005095333
34	800	90	97.5	0.00589	.005925222
35	800	90	95	0.006915	.007006667
36	800	90	90	0.008006	.007718778

Correlation Analysis for Saturated Hydraulic Conductivity

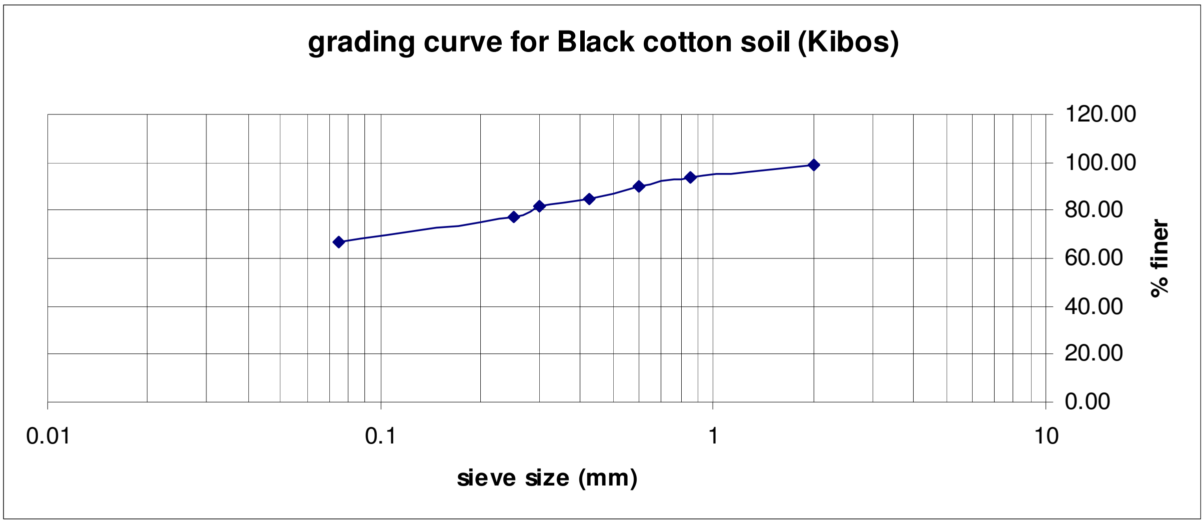
Factor	Correlation
Temperature	0.7703
Time	0.2288
BCS	-0.4340

APPENDIX 2: SOIL LAB ANALYSIS
2.1: Textural Analysis of Black Cotton Soil Samples

	EGERTON UNIVERSITY DEPARTMENT OF AGRICULTURAL ENGINEERING SOIL MECHANICS LABORATORY	Sample: Kibos BCS
		Sample No.: 1
		Date collected:
		Date analyzed
		Analysis done by: Nyakach

SOIL TEST REPORT

SIEVE ANALYSIS							
Sieve no.	Sieve size (mm)	Weight of sieve (g)	Retained soil+sieve (g)	Soil retained (g)	% soil retained	Cum. % retained	% finer
3/8	9.5						
4	4.75						
10	2	438	445	7.0	0.69	0.69	99.31
20	0.85	440	498	58.0	5.68	6.37	93.63
30	0.6	342	380	38.0	3.72	10.09	89.91
40	0.425	328	380	52.0	5.09	15.18	84.82
50	0.3	453	483	30.0	2.94	18.12	81.88
60	0.25	348	397	49.0	4.80	22.92	77.08
200	0.075	285	394	109.0	10.68	33.59	66.41
Pan	0	346	1024	678.0	66.41	100.00	0.00
				1021			



Total weight of sample used = 1021g

Weight of sand retained by sieve number 200 = 342g

Measured % sand in sample = 33.53 (mainly fine sand)

Calculated % sand = 33.59%

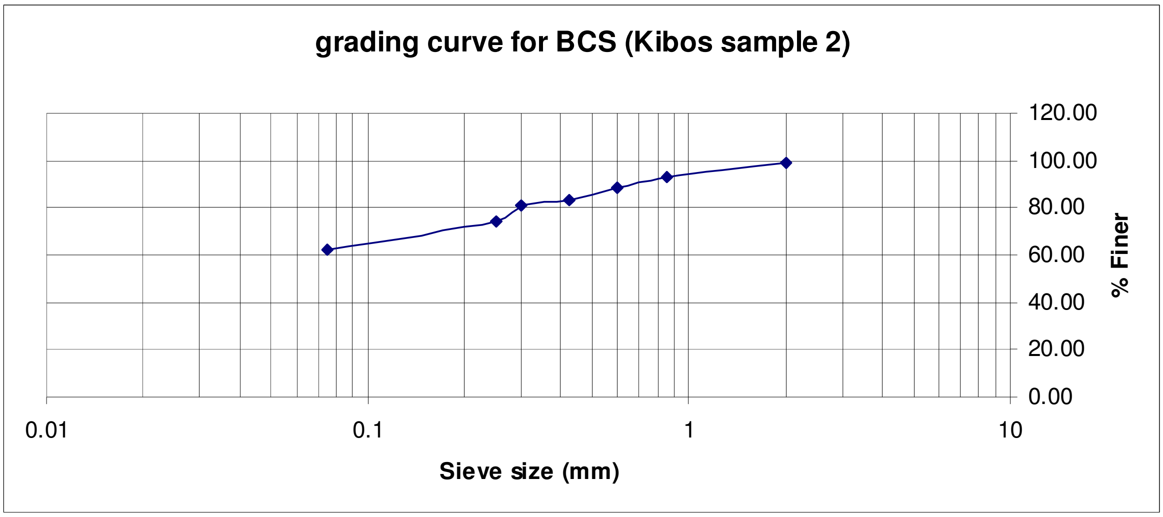
Mean % sand = 33.56

	EGERTON UNIVERSITY DEPARTMENT OF AGRICULTURAL ENGINEERING SOIL MECHANICS LABORATORY	Sample: Kibos BCS Sample No.: 2 Date collected: Date analyzed Analysis done by: Nyakach

SOIL TEST REPORT

SIEVE ANALYSIS

Sieve no.	Sieve size (mm)	Weight of sieve (g)	Retained soil+sieve (g)	Soil retained (g)	% soil retained	Cum. % retained	% finer
3/8	9.5						
4	4.75						
10	2	438	453	15	1.32	1.32	98.68
20	0.85	440	508	68	6.00	7.33	92.67
30	0.6	342	388	46	4.06	11.39	88.61
40	0.425	328	392	64	5.65	17.03	82.97
50	0.3	453	473	20	1.77	18.80	81.20
60	0.25	348	423	75	6.62	25.42	74.58
200	0.075	285	425	140	12.36	37.78	62.22
Pan	0	346		705	62.22	100.00	0.00
				1133			



Total weight of sample used = 1133g

Weight of sand retained by sieve number 200 = 429g

Measured % sand in sample = 37.86 (mainly fine sand)

Calculated % sand = 37.78%

Mean % sand = 37.82

Mean % sand = (33.56 + 37.82)/2 = 35.69%

2.2 Chemical Analysis

Chemical test	Sample	
	Black cotton soil	**Expanded black cotton soil**
pH_{water}	6.7	6.7
Total nitrogen (N) %	0.1	0.0
Phosphorus (P) ppm	66	107
Potassium (k) ppm	582	485
Calcium (Ca)ppm	5988	128
Magnesium (Mg) ppm	526	4.4
Organic carbon (C) %	1.3	0.9

APPENDIX 3: PICTORIALS

a) Dry black cotton soil

b) Mixing the soil

c) Moulding the blocks

d) Sun drying

e) Drying in an oven

f) Firing in an electric furnace

g) Fired blocks

h) Saturating the block for sat.WC

i)) Size reduction

j) Sieving

k) Permeability test set up

l) Pressure membrane apparatus

m) The greenhouse under construction

n)) The crop (at planting) o) after establishment

p) The cropping layout showing part of the greenhouse

q) Staking the plants r) Crop at 12 weeks

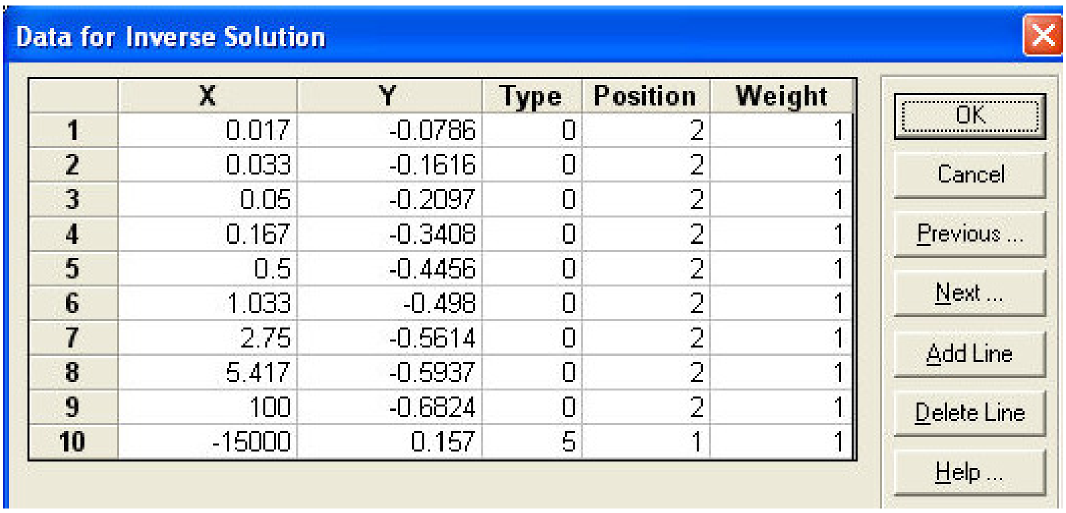
s) Uprooting the plants t) The cleaned roots for RLD

u) Vertical (bag) hydroponic system v) Horizontal (trough) hydroponic system
(Photos taken at *Hydroponics Kenya*)

APPENDIX 4: Data for Inverse Solution in Hydrus 1D (Pre-Processing Menu)

(Source: HYDRUS 1D – User Guide)

Details about the definition of the objective function are given below.



Data for Inverse Solution

	X	Y	Type	Position	Weight
1	0.017	-0.0786	0	2	1
2	0.033	-0.1616	0	2	1
3	0.05	-0.2097	0	2	1
4	0.167	-0.3408	0	2	1
5	0.5	-0.4456	0	2	1
6	1.033	-0.498	0	2	1
7	2.75	-0.5614	0	2	1
8	5.417	-0.5937	0	2	1
9	100	-0.6824	0	2	1
10	-15000	0.157	5	1	1

The following information can be included in the objective function:

Type:

= 0: Cumulative boundary flux across a specified boundary (solute flux when water flow is not simulated)

= 1: Pressure head measurements at certain observation point(s)

= 2: Water content measurements at certain observation point(s)

= 3: Boundary flux across a specified boundary (solute flux when water flow is not simulated)

= 4: Concentration (temperature) measurements at certain observation point(s)

= 5: $h(\theta)$ measurement

= 6: $K(h)$ measurement

= 7: Prior knowledge of the parameter α

= 8: Prior knowledge of the parameter n

= 9: Prior knowledge of the parameter θ_r

= 10: Prior knowledge of the parameter θ_s

= 11: Prior knowledge of the parameter K_s

= 12: Pressure head at location *HO*(*i*) at print time *iPos*(*i*).

= 13: Water content at location *HO*(*i*) at print time *iPos*(*i*).

= 14: Concentration at location *HO*(*i*) at print time *iPos*(*i*).

= 15: Kinetically sorbed concentration at location *HO*(*i*) at print time *iPos*(*i*).

Depending upon the value of the parameter *Type,* the first column contains the following information:

X:

= time for *Type* = 0, 1, 2, 3, 4

= pressure head for *Type* = 5, 6

= dummy parameter for *Type* = 7, 8, 9, 10, 11

= depth (negative) for *Type* = 12, 13, 14, 15

Depending upon the value of parameter *Type,* the second column contains the following information:

Y:

= observation data

= average water content of the entire flow domain when *Type* = 2 and *Position* = 0.

= total solute amount in the entire flow domain when *Type* = 4 and *Position* = 0.

Depending upon the value of parameter *Type*, the fourth column contains the following information:

Position

= position of the observation node for *Type* = 1, 2, 4

= code for the specified boundary for *Type* = 0, 3

= material number for *Type* = 5, 6, 7, 8, 9, 10, 11

= Print time for *Type* = 12, 13, 14, 15

When *iType*(*i*)=2 then *iPos*(*i*)=0 represents the average water content of the entire transport domain.

When *iType*(*i*)=2 then *iPos*(*i*)=-*iLay* represents the average water content of subregion *iLay*.

***Weight* -** weight associated with a particular data point.