# Spatio-temporal distribution of temperature in an expansive soil under a low-cost house

**by**

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# DECLARATION

I declare that the work in this dissertation hereby submitted by me for the Master of Science in Agriculture degree at the University of the Free State is my own independent work and has not been previously in its entirety or in part submitted to any other university.

I further cede copyright of the dissertation in favour of the University of the Free State.

Mjanyelwa G. Nokhwezi

Signature:

Date: February 2018
Place: Bloemfontein,
Republic of South Africa.

I dedicate this piece of work to

**Zwelandile L. Mjanyelwa (December, 2016)**

My late brother, how I wish I could bring you back to see this work in person.
This is the reason I missed you by a day.

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# SPATIO-TEMPORAL DISTRIBUTION OF TEMPERATURE IN AN EXPANSIVE SOIL UNDER A LOW-COST HOUSE

by

**NokhwezI G. Mjanyelwa**

## ABSTRACT

Expansive soils are rich in smectite with shrink and swell behaviour in response to changing water contents. These soils are a worldwide problem causing damage to engineering structures, as is the case in Land Type Dc17, east of Bloemfontein. In the built environment, soil temperature is the main driving force behind soil water migration, responsible for volume changes in expansive soils. Little is known on soil temperature underneath houses built on expansive soils and its contribution to structural deterioration. This study was conducted with the goal of characterizing soil temperature underneath a basic house built on an expansive soil and to better understand thermal behaviour of these soils. This was attained through a number of specific objectives: (1) To classify and categorize expansive soils in Land Type Dc17; (2) To assess the effect of soil water content and (3) temperature on thermal properties (thermal conductivity, volumetric heat capacity and thermal diffusivity) of expansive soils; and finally (4) To characterize temperature variation underneath a low-cost house in comparison to bare soil in Botshabelo (Land Type Dc17).

Five soils were selected in the study area and classified through laboratory analyses as Sepane (1210), Bonheim (1210), Swartland (1121), Valsrivier (1120) and Arcadia (1100). The soils had higher contents of $Mg^{2+}$ than $Na^{+}$, thus low hydraulic. Arcadia soil form had high swelling potential, with Sepane, Bonheim, Swartland and Valsrivier having a medium swelling potential.

To study the effect of increasing soil water content on thermal properties, different water content ranges (from moderate to near saturation), were created *in situ* by saturating profile pits and sampling during the desorption period. Generally, with increasing water content, thermal conductivity and diffusivity increased, but decreased as near saturation was reached. Volumetric heat capacity increased with increasing water content to near saturation. The significance of these trends depended on individual soil forms.

The “moist” water range samples were subjected to increasing temperatures (0 to 60°C) to study the effect of temperature on thermal properties. In all the soil forms, these properties decreased from 0 to 10°C and increased with further increase in temperature from 10 to 60°C. The significance of these trends was however depended upon individual soil form.

To characterize temperature variation underneath the house in comparison to bare soil, capacitance probes were installed to a depth of 1 m under the foundation and in bare soil adjacent to the house as a control, and monitored for two years. Over a 24 hour period, there was practically no variation in soil temperature under the house (profile average). In summer and spring, temperature under the house was cooler during day time, while at night it was warmer than bare soil. In winter and autumn the profile temperature under the house was warmer throughout the 24 hour period. Seasonally, temperature of the soil profile under the house fluctuated less and was cooler than bare soil in summer and spring. In winter and autumn, temperature under the house was warmer than in bare soil. For both surface treatments, soil temperature decreased with depth in summer and spring, with cooler temperatures under the house at all depths. In winter and autumn, soil temperatures for both surface treatments increased with depth, with warmer temperatures under the house at all depths.

**Keywords:** Land Type Dc17, expansive soils, thermal properties, soil temperature

# CHAPTER 1. GENERAL INTRODUCTION

The Reconstruction and Development Program (RDP) was introduced in South Africa in 1994, with provision of shelter for necessitous people as a main objective (Nnadozie, 2013). Some of these low-cost houses unfortunately face early degradation. One important contributing factor leading to the degradation of these houses is the fact that they are often built on expansive soils, as is the case in Botshabelo located in the Land Type Dc17 in the Free State Province (Land Type Survey Staff, 2006). Expansive soils are a worldwide geotechnical cause of damage to built structures (Fityus *et al.*, 2004). These soils usually contain montmorillonite clay minerals with shrink and swell potential in reaction to water changes (Brady & Weil, 2002). Continuous changes in soil volume cause structures constructed on this type of soil to move unevenly and crack (Huang & Wu, 2007; Elsharief, 2016).

Generally, the cost of damage caused by expansive soils on engineering structures is higher than damage resulting from natural disasters (Nelson & Miller, 1992). In the city of Saskatchenwan (Canada) alone, the cost of annual maintenance to buried pipelines due to damage by expansive soils is $2 million (Azam *et al*., 2013), in the USA overall damage to structures is as high as $9 billion per year (Soltani & Estabragh, 2015), while in Britain the damages per year amount to £400 million (Driscoll & Crilly, 2000). In the period of 2008 to 2009, the South African government spent approximately R2 billion to repair damage to low-cost houses caused by expansive soils (Diop *et al.*, 2011; Dlamini, 2015).

Although it is changes in soil water content that are responsible for shrinking and swelling of expansive soils, soil temperature may also be involved. Soil temperature plays an important role in soil water migration, since it is the major driving force of evaporation (Hillel, 2004; Jury & Horton, 2004; Weiss & Hays 2005). Soil temperature can be defined as the detection of heat energy which is derived from the transformation of solar energy (Lal & Shukla, 2004; Fan & Liu, 2013). The propagation of this energy throughout the soil profile dependents on fundamental soil thermal properties (Lajos, 2008). Soil thermal properties, including heat capacity, thermal conductivity and thermal diffusivity, are determined by soil physical properties (Abu-Hamdeh, 2003; Alnerfaie & Abu-Hamdeh, 2013; Pramanik & Aggarwal, 2013; Rublo, 2013).

This study was part of a larger pilot project investigating the effect of expansive soils on degradation of low-cost houses in Botshabelo (Land Type Dc17). While another part of the project specifically examined soil water movement in expansive soils in this area (Bester *et al*., 2016), the current study focused on the soil temperature aspect.

The knowledge of soil temperature under houses will provide better estimates of heat flow that can eventually be used to estimate water migration that affects structural deterioration. The main goal of the study was to monitor distribution of temperature over time and depth in an expansive soil under a low-cost house over an extended period. This was achieved with specific objectives allocated to Chapters 2 to 6:

- The objective of the literature review in Chapter 2 was to present a theoretical background on expansive soils, their behaviour in response to water and temperature gradients and how built structures affect soil temperatures.

- The objective of Chapter 3 was to differentiate expansive soil forms in the study area (Land Type Dc17), to characterize the morphological, physical and chemical properties of each soil form.

- The objective of Chapter 4 was to monitor the response of fundamental soil thermal properties (heat capacity, thermal conductivity and thermal diffusivity) to different water contents on the selected expansive soils.

- The objective of Chapter 5 was to monitor the effect of increasing temperature on thermal properties of these expansive soils.

- The objective of Chapter 6 was to characterize the diurnal and seasonal soil temperature underneath a basic house in comparison to bare soil, for the profile average and at different depths over the period of two years.

- Chapter 7 provided a summary of the results from the experiments above, concluding and recommending how the information can be used to guide future research on this topic.

# CHAPTER 2. LITERATURE REVIEW

## 2.1 Introduction

Expansive soils, also called expansive clays, swelling clays or heaving soils, are soils with shrink and swell characteristics due to fluctuations in soil water content (Das & Roy, 2012; Puppala *et al.*, 2013; Shi *et al*., 2014; King, 2015; Soltani & Estabragh, 2015). These soils are commonly known worldwide as a major cause of damage to engineering structures (Nelson & Miller, 1992; Pedarla *et al.*, 2011; Mokhtar & Dehghani, 2012; Azam *et al*., 2013; Puppala *et al.*, 2013). The problem brought about by these soils was first recognized in the 1930's when brick veneer residences gained popularity in the USA (Chen, 1975). At first, structural damage (cracks) to residences was ascribed to substandard construction and settlement of foundations without any correlation to expansive soils. Chen (1975) further elaborated that due to population growth and high demand for houses, concrete slab-on-ground construction, rather than frame dwellings, became more popular and more structural damage was observed. From the observations, engineers were able to associate structural damage to the type of soil supporting the house foundations.

Presently, the cost of damage caused by expansive soils on engineering structures is higher than damage resulting from natural disasters (Nelson & Miller, 1992). In the city of Saskatchenwan (Canada) alone, the cost of annual maintenance to buried pipelines due to damage by expansive soils is $ 2 million (Azam *et al*., 2013), in the USA overall damage to structures is as high as $ 9 billion per year (Soltani & Estabragh, 2015), while in Britain the damages per year amount to £400 million (Driscoll & Crilly, 2000). In the period of 2008 to 2009, the South African government spent approximately R2 billion to repair the damage to low-cost houses caused by expansive soils (Diop *et al*., 2011; Dlamini, 2015).

The rate of water migration in soils is dependent on heat energy, detected as soil temperature and water vapour potential. Soil temperature gradients enhance water migration and in cooler areas of the soil, for example under built structures, condensation will take place, resulting in volume changes in expansive soils, causing deterioration of the structures. It is therefore of importance to understand the main driving force behind the swelling of expansive soils, i.e. soil temperature. Soil temperature is affected by precipitation, soil cover, air temperature and solar radiation, thermal properties of the soil and soil type, as well as depth. These aspects are reviewed in detail by Lehnert (2014). The effect of buildings on soil temperature have been studied for a few decades, however, no results have been published on this aspect specifically on expansive soils.

The first objective of this literature review was to provide a broad overview on the nature of expansive soils. This includes the origin, structure and mechanism of swelling, distribution, swelling potential and soil properties related to the swelling potential of these soils. Since expansive soils are considered problematic, mitigation measures currently employed to minimize damage to structures erected on such soils will also be summarized. The final objective was to consider temperature as the driving force for water migration in soils in general, since very little information is available specifically for expansive soils. This was achieved by first explaining heat transfer processes and how it determines soil temperature regimes, followed by a discussion on thermal properties and the factors affecting them, and ending with a review on soil temperature under buildings.

## 2.2 Origin and identification of expansive soils

Clay minerals that form the structure of expansive soils occur as fibrous particles or in crystalline form, either in sedimentary and altered rocks or soils (Deer *et al.,* 1992). In sedimentary rocks like shale, siltstone and mudstone the clay minerals exist as slate, while in soils they only occur as transported materials (Chen, 1975). In Southern Africa, the formation of expansive soils is the result of weathering of the Karoo Super Group parent material, which is responsible for the shale and varvites of the Dwyka formation, as well as the shale and mud rock of the Ecca and Beaufort Groups (Chen, 1975). Transported expansive soils are the lacustrine, alluvium and colluvium deposits and gulleywash deposits occurring as a black clay (Dlamini, 2015).

The climate of a region plays an important role in the formation of expansive soils. Smectite minerals are formed in regions with high amounts of silica, low drainage and rainfall, with conditions that hinders chemical weathering. Weathering processes release bases, and with inadequate rainfall in the area these bases are not leached, leading to the formation of montmorillonite (Al-Rawas & Goosen, 2006).

In the field, expansive soils may be red, yellow-grey or black in colour and sometimes white, light grey or brown (Deer *et al.,* 1992). Expansive soils can be identified by polygonal fissures on the soil surface in dry conditions (Figure 2.1), and a sticky appearance accompanied by slow drainage in wet conditions (Brady & Weil, 2002). A soil paste is made and rolled into a cylinder of 20 mm long and 3 mm in diameter; if it rolls to the mentioned dimensions without breakage then the soil is considered expansive (Lucian, 2006).

In the laboratory, expansive soils can be noticed by high organic matter and cation exchange capacity, low bulk density (1.1 g $cm^{-3}$) and the shrink/swell tests can be done based on the consistency indices.

**Figure 2.1** A cracked expansive soil under dry conditions (Mokhtari & Dehghani, 2011).

## 2.3 Structure of expansive soils

In order to understand expansive soil behaviour, one requires knowledge of the basic structure of these soils that leads to shrinking and swelling. Expansive soils are usually characterized by a clay content of 30% or higher (M'Ndegwa, 2012). The heaving characteristic of these soils mainly manifests near the ground surface where the soil is mostly affected by environmental and seasonal changes (Fredlund & Rahardjo, 1993; Terzaghi *et al.*, 1996). Changes in soil water content, as brought about by environmental and seasonal changes, cause the soil to experience volumetric changes of up to 30% or more (Sudjianto *et al.,* 2011; Das & Roy, 2014). This can be contributed to the presence of certain silicate clay minerals in their mineralogical composition (Brady & Weil 2002).

All silicate clay minerals are fundamentally composed of tetrahedral sheets (T), where four oxygen atoms are coordinated with silicon, and octahedral sheets (O), with six oxygen atoms or hydroxyl groups (OH) coordinated with either aluminium or magnesium (Figure 2.2: Das, 2002; Jury & Horton, 2004). These tetrahedral and octahedral sheets combine in layers to form either 1:1 or 2:1 silicate clay minerals. The 1:1 silicate clay minerals has one tetrahedral sheet linked to one octahedral sheet (T-O), while the latter has one octahedral sheet sandwiched between two tetrahedral sheets (T-O-T) (Brady & Weil, 2002; White, 2006).

The T-O layers of 1:1 silicate clay minerals are strongly attached to one another because the tetrahedral sheet of the upper layer and the octahedral sheet of the adjacent layer share the apical oxygen atom on the tetrahedral sheet producing a strong hydrogen bond (Figure 2.3). The firm bonding of layers gives the T-O silicate clay minerals a non-expanding character since no water or cations can be adsorbed in between the layers. The T-O silicate clay mineral type comprises of kaolinite and nacrite groups.

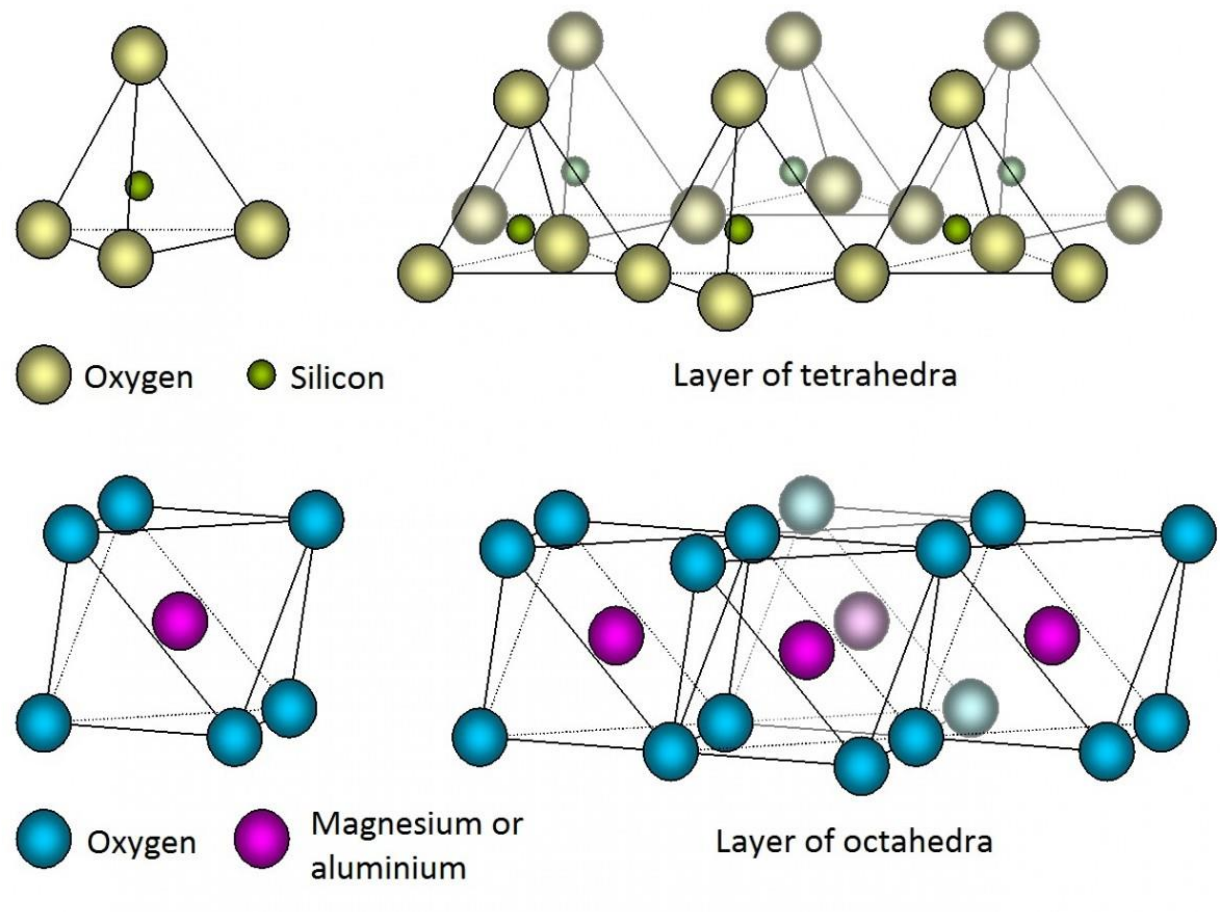


**Figure 2.2** A simple schematic diagram indicating the structure of tetrahedral and octahedral layers (Koening, 2010).

On the other hand, T-O-T layers of 2:1 silicate clay minerals, have oxygen atoms both at the top and bottom initiating the layers (Figure 2.3). The layers are held together by weak Van der Waals forces and the bond can be easily broken by the presence of water. The poor force of attraction is also caused by exchangeable cations resulting from isomorphous substitution when $Mg^{2+}$ substitutes the $Al^{3+}$ ion in the octahedral sheet, or $Al^{3+}$ substitutes the $Si^{4+}$ ion in the tetrahedral sheet (Brady & Weil, 2002). The 2:1 silicate clay minerals consist of three groups, i.e. smectite (montmorillonite and vermiculite), micas (illite) and chlorite. Montmorillonite and vermiculite have the tendency of shrinking during dehydration and swelling under rainy events, hence they are called expansive soils. While the micas and chlorite are non-expanding since they do not shrink nor swell in response to change in water contents. Although mica (illite) belong to the 2:1 group, there is a presence of non-exchangeable potassium ions between the layers that hold them together preventing expansion.

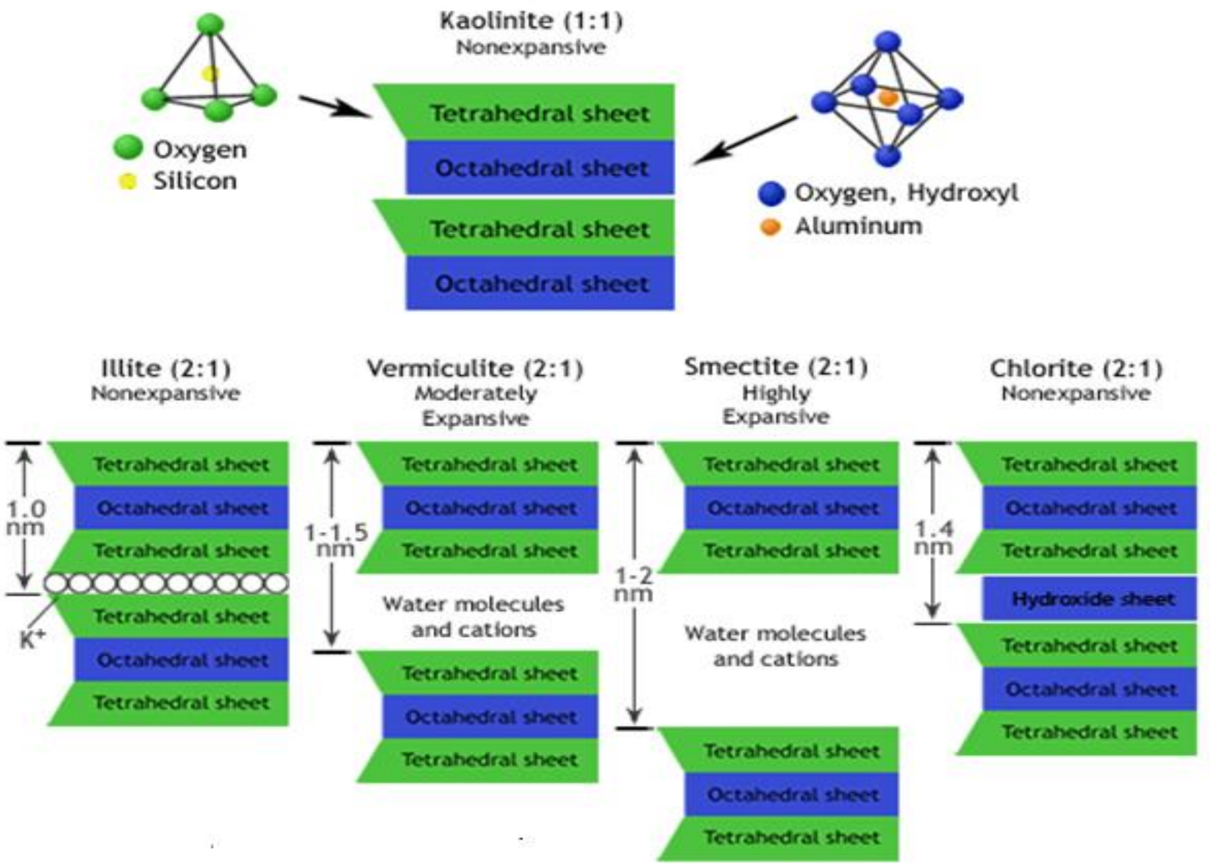


**Figure 2.3** The structure of different silicate clay minerals (Lory, 2016).

**Table 2.1** Summarized clay mineral properties (Brady & Weil, 2002; Jury & Horton, 2004; White, 2006)

| **Silicate** clay mineral | **Type** | **Force of attraction between sheets** | **Expansion** | **Swelling potential** | **CEC [cmol kg$^{-1}$]** |
|---|---|---|---|---|---|
| Kaolinite | 1:1 | Strong | Non-expansive | None | 3 – 15 |
| Montmorillonite | 2:1 | Very weak | Highly-expansive | High | 80 – 150 |
| Vermiculite | 2:1 | Weak | Expansive | High | 100 – 150 |
| Mica (Illite) | 2:1 | Strong | Non-expansive | Low | 20 – 40 |
| Chlorite | 2:1:1 | Moderate to strong | Non-expansive | None | 10 – 40 |

## 2.4 Mechanism of swelling

As it has been mentioned earlier, the shrink/swell behaviour of expansive soils is controlled by the changes in soil water levels. The overall changes of soil water content are brought about by the climatic conditions. For instance, on sunny days high temperatures enhance removal of water from the soil by evaporation as well as transpiration by plants. Chen (1975) indicated that the migration of soil water does not only depend on climatic conditions (temperature) alone, but also on topographic features, soil type and ground water levels. In this review, however, the focus will be on the relationship between soil temperature and soil water with regards to swell and shrink behaviour of expansive soils.

The shrinking and swelling occur in the upper few meters of the soil which is termed the "active zone". This zone could be approximately 3 m depth, depending on the climatic conditions of the area, as well as the presence of tree roots (Jones & Jefferson, 2012). In the United Kingdom, depth of the active zone is between 1.5 and 6 m and in London specifically, between 3 and 4 m (Biddle, 2001). The water migration in this zone is basically controlled by climatic factors (temperature), hence it is sometimes termed the seasonal fluctuation zone (Nelson & Miller, 1992). In hot conditions, water migrates in liquid phase in saturated soils and in the vapour phase in unsaturated soils, from hot to cooler conditions in order to neutralize the thermal gradient (Ao *et al.,* 2016). The vapourized water condenses to liquid water and this changes the soil water content initializing the swelling of expansive soils (Chen (1975). This migration of water from hot to cooler conditions is common under built structures. More detail on the movement of water in saturated and unsaturated soils are further elaborated by Ao *et al.,* (2016).

The arrangement of expansive clays is such that water molecules can be adsorbed between the sheets (Figure 2.3). The attraction between clay minerals and water molecules is influenced by the structure of the latter which has an electrical dipole that enhances their electro-chemical attraction to the sheets. The water quantity adsorbed by the clay minerals depends on the type of mineral. For instance, montmorillonite can imbibe vast amounts of water compared to vermiculite, hence it has a high swelling capacity (Jones & Jefferson, 2012).

## 2.5 Swelling potential

The swelling potential of expansive soils, or volume change as it is sometimes called, is the change in volume of a dry undisturbed or remoulded soil specimen (Holtz, 1959; Seed *et al*., 1962). Swelling potential can be estimated by using direct or indirect measures. Direct measures include swelling pressure and free swell testing, which are done in the laboratory under controlled conditions to mimic environment conditions (Yitagesu, 2006). Indirect measures use soil properties that are mostly used by engineers, such as cation exchange capacity, consistency indices (Atterberg limits), soil texture (clay content), initial water content and bulk density, to estimate swelling potential from standardized classification charts.

With the aid of soil properties, a number of researchers have formulated models to predict swelling potential of expansive soils (Seed *et al*., 1962; Komornik & David, 1969; Vijayvergiya & Ghanzzaly, 1973; Chen, 1975; Komine & Ogata, 1994; Guiras-Skandaji, 1996). Djedid & Oudah (2013) reviewed and tested these models and found that the models are difficult to be generalized to all soil types and provide unacceptable estimates. The conclusion was drawn, however, that the increase of soil properties in the model provides better results.

## 2.6 Factors used to predict swelling potential of expansive soils

Soil properties are fundamental parameters that define a soil's stability, fertility and quality. Numerous investigations have been made globally and in South Africa on the properties of expansive soils. While some studies concentrated on soil properties for agricultural use, others focused on properties for environmental benefit and engineering purposes. Table 2.2 summarizes the properties that are of interest in the current study that have been evaluated in other studies on expansive soils. This is followed by a discussion of the properties often used in the geotechnical engineering field relating to the swelling potential (volume change) of expansive soils.

### 2.6.1 Soil texture

Expansive soils are categorized as clay soils with separates of less than 0.002 mm in diameter. Soil texture may be used to classify the swelling potential of a soil. Seed *et al.* (1962) and Van Der Merwe (1964) recognized that there was a relationship between clay content and plasticity index of a soil. The correlation between the mentioned properties forms a linear regression and may indicate the degree of "activity" of a soil. Clay activity was defined as the ratio of the plasticity index (PI) to the clay (< 0.002 mm) fraction (CF) and could be related to the mineralogy and geotechnical history of the sediment (Equation 2.1).

$$\text{Activity} = \text{PI} / \text{clay fraction} \quad (2.1)$$

According to clay activity, clays can be categorized as:

- Inactive clays – activity < 0.75
- Normal clays – activity 0.75 – 1.25
- Active clays – activity > 1.25

Generally, soils with high activity clays denotes high potential of shrinking and swelling, followed by normal clays and lastly the inactive clays, which pose little threat of damage.

**Table 2.2** Studies on physical and chemical soil properties of expansive soils

| | | | | Particle size distribution | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Country** | **Author** | **Soil form** | **OC** | **Sand** | **Silt** | **Clay** | **$\rho_b$** | **pH** | **CEC** | **R** | **EC** | **AL** |
| South Africa | Nhlabatsi (2011) | Bonheim | + | + | + | + | + | + | + | + | + | - |
| South Africa | Hensley *et al.* (2000) | Bonheim | - | + | + | + | + | - | - | - | - | - |
| South Africa | Botha (2003) | Bonheim | + | + | + | + | - | + | + | + | + | - |
| Lesotho | Van Zijl (2010) | Bonheim | + | + | + | + | - | + | + | - | + | - |
| Turkey | Cumhur (2003) | Mollisols | + | + | + | + | - | + | + | - | + | - |
| Argentina | Barbei *et al.* (2014) | Mollisols | + | - | - | - | - | + | + | - | - | - |
| Turkey | Dengiz *et al.* (2012) | Vertisols | + | + | + | + | + | + | + | - | + | - |
| India | Pal *et al.* (2012) | Vertisols | + | + | + | + | + | + | + | - | - | - |
| Senegal | Boivin *et al.* (2006) | Vertisols | + | + | + | + | - | - | - | - | - | - |
| India | Rajagopal *et al.* (2013) | Vertisols | + | + | + | + | + | + | + | - | + | - |
| South Africa | Van Tol *et al.* (2015) | Swartland | - | - | + | + | + | + | - | - | - | - |
| Lesotho | Van Zijl (2010) | Swartland | + | - | - | + | - | + | + | - | + | - |
| South Africa | Van Zijl (2010) | Swartland | + | + | + | + | - | + | + | - | + | - |
| South Africa | Mavimbela & Van Rensburg (2015) | Swartland | - | + | + | + | + | + | - | - | - | - |

OC: organic carbon; $\rho_b$: bulk density; CEC: cation exchange capacity; R: resistivity; EC: electrical conductivity; AL: Atterberg Limits.

(+) indicates work done and (-) indicates work not carried out on the topic.

### 2.6.2 Soil water content

Expansive soils on their own pose no threat until there are changes in soil water content (Jones & Jefferson, 2012). With an increase in soil water content, a volume change is expected, both vertically and horizontally. Expansive soils do not require complete saturation to have a detrimental effect, a soil water change as low as 1% is enough to enhance the shrink/swell behaviour of these soils (Chen, 1975). The extent to which the soil can swell or shrink is determined by the water distribution and flow in the soil profile which depend mainly on the soil's hydraulic conductivity.

Hydraulic conductivity, normally represented by *K,* is the most significant parameter for water transportation in the soil. It is defined as the ease with which water flows down the soil profile and is expressed in velocity units, m $s^{-1}$ (Hillel, 2004). The law of water flow in porous media was pioneered by Darcy in 1856, indicating that under steady state conditions (media should be uniform and saturated by means of steady water flow) the velocity of water flow in a medium (soil) is directly proportional to the hydraulic gradient.

Thus:

Water flow = hydraulic gradient (2.2)

Expressed by Darcy's equation as:

$$q = K \, \partial h / \partial x \quad (2.3)$$

Where:

q = flux
K = hydraulic conductivity
x = direction of groundwater flow
h = hydraulic head.

Hydraulic conductivity of soils is affected by the amount of water already in the soil profile (saturated or unsaturated), as well as the temperature and viscosity of the liquid (Lal & Shukla, 2004). In unsaturated soils hydraulic conductivity is low, since the water pathway decreases with decrease in water content and it increases with increase in water content (Hillel. 2004). Hydraulic conductivity indicates the ability of a soil to swell. Hence, dry expansive soils have a high hydraulic conductivity, implying a higher swelling potential than already wet soils.

### 2.6.3 Bulk density

Soil bulk density is basically the ratio of the mass of an oven-dry soil sample to its volume. Soil bulk density can be used to convert gravimetric soil water to volumetric soil water content (Blake & Hartge, 1986). Bulk density values can also be used when calculating soil porosity and in models predicting soil processes (Chaudhari *et al.* 2013). Bulk density of a soil depends on its structure and composition, hence it varies with soil type (Table 2.3). According to Chaudhari *et al.* (2013) and Schoonover & Crim (2015) bulk density is correlated to soil texture, porosity and organic matter. Fine textured soils have high porosity because of high organic matter content, which in turn results in low bulk density (Hillel, 2004; Schoonover & Crim, 2015).

**Table 2.3** Pore space percentage and bulk density of different soil textural classes (Hillel, 2004)

| Texture class | Bulk density (g cm$^{-3}$) | Porosity % |
|---|---|---|
| Sandy soil | 1.6 | 40 |
| Loam | 1.4 | 47 |
| Silt loam | 1.3 | 50 |
| Clay | 1.1 | 58 |

The relationship between bulk density and organic matter was emphasized by Chaudhari *et al.* (2013). The conclusion was drawn that the higher the organic matter the lower the bulk density, as indicated by high correlation coefficients between the two parameters in their studies.

Soil bulk density is not affected by organic matter alone, but by soil water content as well. At low water contents, soil resists being compacted and the bulk density is found to be low. In the presence of water soil particles tend to clot and be compacted, increasing the bulk density. But with a steady increase of water the soil reaches an optimum water content and beyond this point the bulk density start to decrease, since water is no longer occupying the air voids alone, but replaces the soil particles as well. So, with an increase in water content beyond optimum water content, the bulk density of a soil decreases (Krzic *et al.,* 2003; Hillel, 2004). On expansive soils, bulk density affects the overall swelling potential of a soil. With an increase in dry bulk density and decrease in soil water content, the soil swelling potential increases (Zumrawi, 2013). Mokhtari & Dehghani (2012) further discussed that the particles are closely packed in high bulk densities empowering repulsion forces between the particles, resulting in high swelling potential.

### 2.6.4 Cation Exchange Capacity (CEC)

The CEC of soil is described as its capacity to exchange cations in the exchange sites of the colloids and is measured in moles per unit mass of the soil (Sposito, 1989; Brady & Weil, 2002). This soil parameter does not depend only on clay content, but also on the clay type. The CEC value gives an indication of the mineral composition of soils. High CEC values indicate expansive clay minerals, while a lower CEC indicates the presence of non-expansive clay minerals (Table 2.4; Puppala *et al.*, 2016). In geotechnical engineering, CEC is regarded as the factor that influences swelling characteristics of expansive soils. Swelling potential of expansive soils increases with an increase in the cations on the colloidal surfaces (Al-Rawas & Goseen, 2006; Christidis, 1998). This phenomenon can be further explained by the diffuse double layer theory (DDL).

**Table 2.4** Approximate CEC values of selected clay minerals (Brady & Weil, 2002)

| Clay minerals | CEC (mEq 100g$^{-1}$) |
|---|---|
| Kaolinite | 3 – 15 |
| Illite | 15 – 40 |
| Montmorillonite | 80 – 100 |
| Chlorite | 20 – 40 |

The DDL, or electrostatic double layer as it is sometimes called, is the interrelation among the mineral clay surface (clay particle), the cations and water around the cations, as well as the solution surrounding the clay particle. In dry conditions, the clay particle is dry and negatively charged as indicated by the Guoy-Chapman's theory – negative charges are assumed to be uniform and distributed evenly over the clay surface. However, once a solution is introduced, the cations from the solution are adsorbed by the clay surface, replacing weakly attached cations, forming the DDL (Hillel, 2004). The thickness of the DDL, that enhances the swelling potential, depends on the valence of the cations and their concentration in the solution (Baser, 2009). Monovalent ($Na^{+}$) cations are replaced by divalent ($Ca^{2+}$) ones, and divalent by trivalent ($Al^{3+}$) cations. With an increase in cation valency in the solution, the DDL compresses, resulting in a decrease of swelling potential. A high concentration of cations in the solution occupies the idling negative charges on the clay surface leading to minimal repulsion between clay particles, promoting the reduction of swelling in expansive soil.

### 2.6.5 Atterberg limits

Atterberg limits, including liquid limit, plastic limit and plastic index, are the basic measures of critical soil water contents used to characterize soil plasticity and are assessed from a soil paste in the laboratory. These limits were established by Atterberg in 1911 in an attempt to determine the shrink/swell potential and classify the soils (Jefferson & Rogers, 1998; Lucian, 2006) and are therefore generally called Atterberg limits.

Liquid limit (LL) is a critical water content that changes soil from the solid state to plastic state, plastic limit (PL) is a critical water content at which the soil changes from plastic state to a semi-solid state, while the plastic index (PI) is the numerical difference between LL and PL as shown in Figure 2.4

(Andrade *et al.*, 2011). The shrinkage limit (SL) is the water content between the semi-solid and solid phase, beyond this point any further water reduction cannot cause soil volume change.

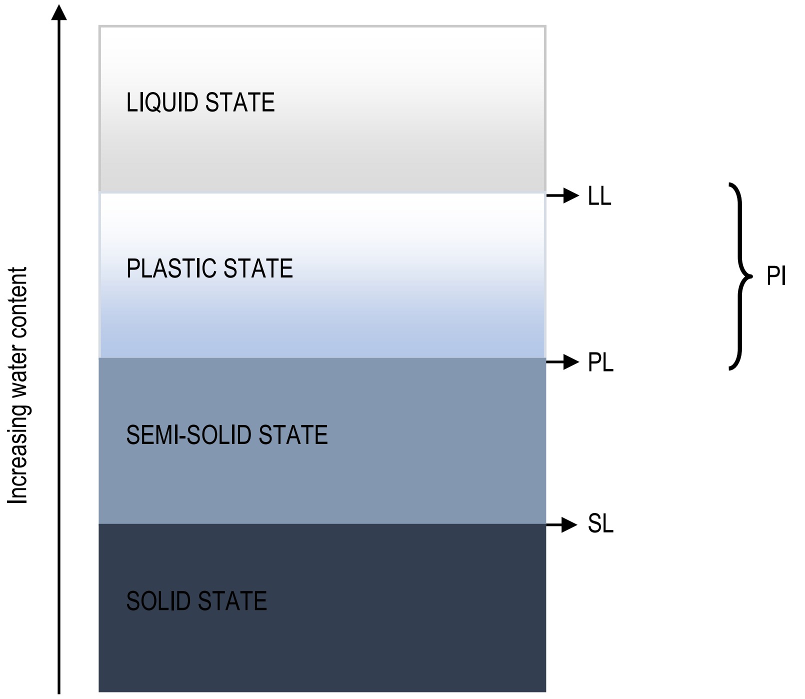


**Figure 2.4** Schematic diagram showing Atterberg limits in response to soil water changes. LL – liquid limit, PL – plastic limit, PI – plasticity index and SL – shrinkage limit (Jefferson & Rogers, 1998).

Holtz & Gibbs (1956) used Atterberg limits to categorize swell potential of soils. Categories range from low to very high swelling according to the LL, PI and SL percentages (Table 2.5).

**Table 2.5** Swell potential of soils using plasticity (Holtz & Gibbs, 1956)

| Classification of swelling | LL % | PI % | SL % |
|---|---|---|---|
| Low | 20-35 | <18 | >15 |
| Medium | 35-50 | 15-28 | 10-15 |
| High | 50-70 | 25-41 | 7-12 |
| Very high | >70 | >35 | <11 |

Clay soils with lower LL and PI-values are classified as having low shrink/swell potential, while clay soils with high LL and PI-values have the potential of shrinking and swelling. Al-Rawas & Goseen (2006) noted that consistency indices should not be used on their own to quantify swelling potential of expansive soils, as they can be misleading when used alone (the values of a single parameter are not sufficient enough to classify the soil). More supporting geotechnical, geological and mineralogical data should be collated and used concurrently with consistency indices for quantifying swelling potential.

## 2.7 Expansive soils in South Africa

Expansive soils are widely distributed in South Africa and originate from basic igneous rocks or argillaceous sedimentary rocks as mentioned earlier. The basic igneous rock units where expansive soils originate from include the norite from the Bushveld Igneous Complex, the Karoo Super Group's dolerite, the diabase and andesite from the Ventersdorp and Pretoria Groups. The argillaceous rock of the Karoo Super Group is the most prominent group associated with expansive soils. The group consists of the shales and mud rocks of the Dwyka, Ecca and Beaufort which weathers to expansive soils. Table 2.6 shows occurrence of the expansive in different parts of South Africa.

**Table 2.6** Occurrence of expansive soils in South Africa (Diop *et al*., 2011)

| **Type of expansive soils** | **Places** |
|---|---|
| Soils from igneous rock | Limpopo |
| | Some areas of Johannesburg |
| Black "turf" soils | Onderstepoort to Rustenburg |
| | Northwards towards Thabazimbi |
| Andesite and diabase soils | Pretoria and Lyderburg |
| Mudstone / Shale soils | Western parts of Northern Cape |
| | Northern largest pars of Free State |
| | Northern parts of Eastern Cape |
| | Northern eastern part of Western Cape |
| Dolerite rock soils | Occur in the interior parts of South Africa |

Figure 2.5 shows the map indicating the distribution of expansive soils in the entire country. According to South African soil classification, the expansive soils in South Africa are of the Arcadia, Bonheim, Valsrivier, Swartland, Sterkspruit, Milkwood, Rensburg, Shortlands soil forms, but the study will focus on expansive soils specifically from the Land Type Dc17.

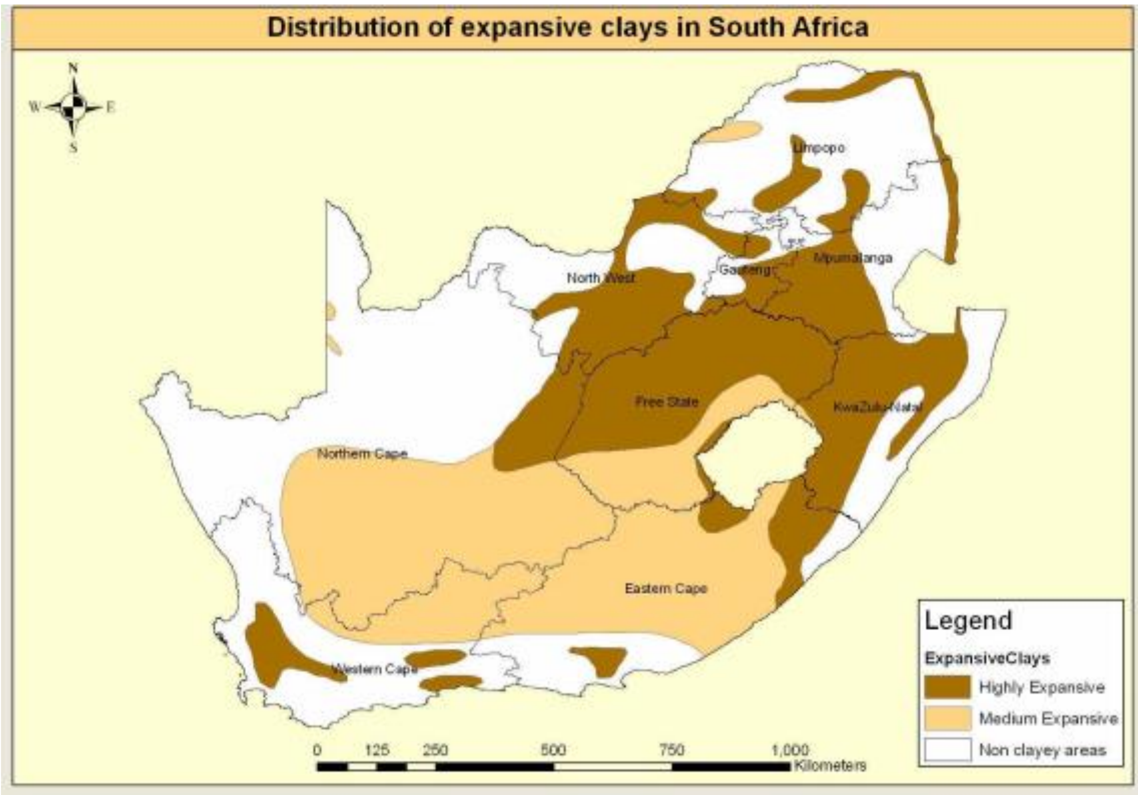


**Figure 2.5** A map showing distribution of expansive soils in South Africa (Diop, 2011).

## 2.8 Expansive soils in Land Type Dc17

The current study was undertaken in an area that resorts under Land Type Dc17 and the focus in this literature review will be on five of the most prominent expansive soils found in this area. A land type represents an area shown at 1:2500 000 scales with a noticeable uniformity regarding terrain form, soil pattern and climate (Van der Watt & Van Rooyen, 1995). The "Dc" symbol denotes that duplex soils with a high clay content of the smectite group is a dominant soil pattern in the area, whereas 17 is the number differentiating this land unit from other Dc land units in South Africa (Woyessa *et al*., 2006). Land Type Dc17 in the Free State province of South Africa occupies 239 080 ha and 190 786 ha thereof is mainly occupied by different expansive soils. The area is characterized by low rainfall and this decreases leaching of mineral clay particles and hampers weathering of active smectite into low active mineral clay (Al-Rawas & Goosen, 2006). Table 2.7 illustrates how these soils are distributed in Land Type Dc17 in the Free State Province.

Duplex soils with prismacutanic and pedocutanic diagnostic horizons are dominant in this area with addition of vertic, melanic and red structured diagnostic horizons (Tekle, 2005; Woyessa *et al.*, 2006). Approximately 15% of the area has shallow soils covered by rocks with slopes greater than 4% located on crest, scarp and hill side terrain units, while the remaining area has slopes of less than 4% and is located on crest, hillside, foot slope and valley bottom (Tekle, 2005).

**Table 2.7** Distribution of expansive soils in Land Type Dc17 (Land type survey staff, 2006))

| Soil form[1] | Depth (mm) | MB[2] | ha | % ha | Terrain type[3] | Slope shape[4] | Clay % |
|---|---|---|---|---|---|---|---|
| Mw, Bo | 250 – 350 | 2 | 4017 | 1.7 | 1,3 | Z-Y,X | 35 – 50 |
| Sw, Se | 100 – 250 | 2 | 3873 | 1.6 | 1,3 | Z-Y,X | 15 – 20 |
| Sw | 100 – 250 | 0 | 67994 | 28.4 | 1(1),3(1),4,5 | Z-Y,Z,X-Z | 15 – 30 |
| Va | 100 – 300 | 0 | 44086 | 18.4 | 1(1),3(1),4,5 | Z-Y,Z,X-Z | 15 – 30 |
| Mw | 300 – 600 | 0 | 32563 | 13.6 | 3(1),4,5 | Z-Y,Z,X-Z | 40 – 55 |
| Bo | 250 – 400 | 0 | 15492 | 6.5 | 3(1),4,5 | Z-Y,Z,X-Z | 40 – 55 |
| Es | 200 – 300 | 0 | 7818 | 3.3 | 3(1),4,5 | Z-Y,Z,X-Z | 12 – 25 |
| Se | 100 – 300 | 0 | 7651 | 3.2 | 1(1),3(1) | Z-Y | 15 – 30 |
| Ar | 400 – 900 | 0 | 7292 | 3.1 | 3(1),4,5 | Z-Y,Z,X-Z | 40 – 60 |

[1]Soil form = Mw-Milkwood, Bo-Bonheim, Sw-Swartland, Se-Sepane, Va-Valsrivier, Es-Estcourt, Ar-Arcadia.

[2]MB (mechanical limitations) = 0-no mechanical limitations, 2- large stones and boulders, unploughable.

[3]Terrain morphological units = 1-crest, 3-midslope, 4-footslope and 5-valley bottom.

[4]Slope shape = X-concave, Y-convex, Z-straight and combination of the letters means the soil form is found in both slope shapes.

The soils selected for the current study are Sepane, Swartland, Valsrivier, Arcadia and Bonheim soil forms, as classified according to the Soil Classification Working Group (1991). Classifications of these soils according to the USDA soil classification, as well as the World Reference Base are given in Table 2.8. The table also provides summarized information on the global distribution of these soils, as well as their parent materials.

South Africa makes use of its own classification system because of its peculiar geology. The WRB classifies 73 soil forms of South Africa into 14 soil groups using nomenclature that is internationally familiar, but based on the South African system's diagnostic horizons key (Fey, 2012). The selected expansive soils fall under the soil groups vertic, melanic and duplex soils. According to South African classification this implies top soil horizons that are vertic, melanic and orthic, with the sub-soils mostly as pedocutanic. The aforementioned diagnostic horizons will be described below in detail using South African soil classification according to the Soil Classification Working Group (1991).

**Table 2.8** Summarized classification, parent material and global magnitude of expansive soils

| SA Classification | USDA Classification | WRB Classification | Parent material and environment | Magnitude |
|---|---|---|---|---|
| Swartland | Alfisols<br>CEC – 9.0 *cmol* $kg^{-1}$<br>pH - 6 | Luvisols | Wide variety of parent material, unconsolidated, strongly leached and fine textured material. | 435 million ha globally |
| Sepane | Alfisols<br>CEC – 9.0 *cmol* $kg^{-1}$<br>pH - 6 | Solonetz | Mostly clayey alluvial and colluvial deposits. | 130 million ha globally |
| Valsrivier | Alfisols<br>CEC – 9.0 *cmol* $kg^{-1}$<br>pH - 6 | Luvisols | Wide variety of parent material, unconsolidated, strongly leached and fine textured material. | 435 million ha globally |
| Bonheim | Mollisols<br>CEC – 18.7 *cmol* $kg^{-1}$<br>pH – 6.51 | Chernozems | Mostly aeolian and re-washed aeolian sediments. In regions with continental climate. | 230 million ha globally |
| Arcadia | Vertisols<br>CEC – 35.6 *cmol* $kg^{-1}$<br>pH – 6.72 | Vertisols | Sediments with high proportion of swelling clays or weathering rocks with characteristics of swelling clays. | 335 million ha globally and 150 million for cropland |

### 2.8.1 Vertic A horizon

Vertic A has a strongly developed blocky structure with regularly occurring slickensides in some part of the horizon. It has high clay content with smectitic clay minerals dominating. Soils with vertic A horizons can crack to 50 cm down and 1 cm wide when dry. It is derived from weathering of basic rock and usually forms in low lands. Soils are mostly black with stickiness and plastic response to wet conditions. Plastic index is greater than 32% and linear shrinkage above 12%.

### 2.8.2 Melanic A horizon

This diagnostic horizon is dark coloured and well developed, but has weak structure with parent materials as rocks or sediments. These are mature soils formed under a sub-humid climate. Unlike vertic A, this horizon lacks slickensides and has a vermiculitic clay mineral (Brady & Weil, 2012). Melanic A does not have very high organic matter to qualify as an organic A horizon, but has enough not to qualify as orthic A. Soils with Melanic A are non-sticky, have a plasticity index of less than 32% and linear shrinkage less than 18%. This master horizon has a higher proportion of water available for plants, since it has lower clay content than vertic horizons and the infiltration rate is high, an ideal soil for crop production.

### 2.8.3 Orthic A horizon

The orthic A horizon does not qualify to be humic, vertic, melanic or organic according to South African taxonomy, but has organic matter as indicated by its dark colour. This horizon requires specific macro- and microbiological conditions to develop under warm climates. Soils with orthic A horizons dominate in South Africa. Soil forms classified with orthic A have different characteristics, for example Hutton has a weakly structured top soil and no water logging, while Katspruit has a water logging character and Pinegrove has coarse texture and is also subjected to water logging.

### 2.8.4 Pedocutanic B horizon

This horizon can only be found underlying an orthic or mellanic A, or an E horizon and does not qualify as a G horizon, prismacutanic, plinthic or red structured B sub-horizon. A pedocutanic B horizon has a cutanic character and is enriched with clay, apparently by illuviation. It has angular or sub-angular blocky structure with moderate to strong degree of development.

## 2.9 Mitigation of the effects of expansive soils on built structures

A number of techniques have been developed over the last few decades to mitigate the effect of shrinking and swelling of expansive soils on built structures and research in this regard is still ongoing. It is advisable to include soil engineers when development of an area is considered as this will grant the opportunity to implement suitable mitigation for a given development. As indicated by Houston *et al.* (2011), some chemical stabilizers (lime) are unproductive for pre-treatment of expansive soils for houses, but advised for the use of specific foundations (pier/pile, raft or beam). If the land is meant for pavements, however, lime is commonly used worldwide to suppress the expansive soil problem. This literature will provide only a brief explanation of control measures for expansive soils. For more detailed information on various techniques refer to articles and reviews by Chen (1975), Al-Rawas & Goseen (2006), Ahmadi *et al.* (2012), Jones & Jetterson (2012), Soltani & Estabragh (2015) and Elsharief (2016) amongst others.

### 2.9.1 Foundation types

Pioneering in foundation techniques to accommodate the shrinking and swelling behaviour of expansive soils dates back to 1947. The implementation of specific foundations for built structures in the 1960's (USA) was a success and the positive results were documented by Jennings & Kerrich (1963) (cited by Chen, 1975). The naming of foundation types varies from country to country although the designs are the same, for example raft foundation is termed slab-on-ground in the USA. Recommended foundations for expansive soils include pier and beam or pile and beam, raft or stiffened raft foundation and modified continuous perimeter footings or deep trench foundation (Figure 2.6 a, b and c; Chen, 1975; Elsharief, 2016; Jones & Jefferson, 2016).

(a)

(b)

(c)

**Figure 2.6** Different foundation types used on expansive soils: (a) pier and beam foundation, (b) stiffened raft foundation, and (c) continuous perimeter footing foundation.

Pier and beam foundations isolate the structure from the swelling soil by resisting the uplift forces of the soil. This foundation is quite reliable for expansive soils with high swelling potential, but it has a complex design and requires a specialist contractor (Chen, 1975; Elsharief, 2016). Stiffened raft foundation consists of a stiffened concrete slab with cross beams for additional stiffness to provide a solid foundation inhibiting structural settlement. This foundation is favourable in areas where soils have a moderate amount of movement and has a less complex layout than the pier and beam. A modified continuous perimeter footing foundation is basically constructed on soils with low swelling potential and requires no specialist equipment (Jones & Jefferson, 2016).

### 2.9.2 Cyclic wetting and drying

Expansive soil behaviour is controlled by its dry density and water content, amongst other factors. The swelling potential increases with the increase in dry bulk density and decrease in soil water content. Mokhtari & Dehghani (2012) elaborated that at higher dry densities, particles are closely packed allowing greater repulsion forces between the particles, causing high swelling potential. In recent years, water is used to effectively mitigate expansiveness of soils (Al-Homoud *et al.*, 1995; Jones & Jefferson, 2016). Results indicate that expansive clay soils exhibited signs of permanent deformation when exposed to consecutive wetting and drying, accompanied by significant decrease in swell percentage. This technique, termed cyclic drying and wetting, was proposed to be used as a mitigation procedure in arid and semi-arid areas (Soltani & Estabragh, 2015). The procedure involves water application to the soil to reach full swelling capacity, the soil is then allowed to dry to its initial water content. The procedure should be repeated four to five times since Ring (1966) noted that at first attempt the swell-shrinkage tests cannot exhibit the swelling behaviour and only can be determined after four to five cycles.

The swell potential of expansive soils will continue to decrease with repeated cycles and will reach a steady value from four cycles (Al-Homoud *et al.*, 1995; Rahimi & Barootkoob, 2002). This method was put into practice in an irrigation project to reduce damage to channel linings in Iran and it gave positive results, since the project ran for five years without any damage to the linings (Ahmadi *et al.,* 2012). This procedure was also evaluated by Dif & Bluemel (1991), Tripany (2002) and Soltani & Estabragh (2013, 2015) with positive results that the swelling potential of expansive soils is reduced by repeated wetting and drying of the soil.

### 2.9.3 Chemical stabilization of expansive soils

Application of chemical mixtures, such as lime, cement or fly ash is a common technique for stabilizing shrink-swell behaviour of expansive soils, as it improves the soil's performance. It involves simply mixing the additives into the soil in the presence of water. This triggers chemical reactions such as cation exhange, pazzolanic reaction and flocculation to occur which in turn improves the soil's structure and swelling potential. Soil stabilizing materials are commonly selected based on the value of the structure to be erected, the client's economic consideration and the soil's mineralogical composition (Mokhtari & Dehghani, 2012; Muthyala *et al.,* 2012).

Application of lime ($CaCO_3$) to expansive soils in the presence of water enhances cation exchange, since the cations on the mineral surfaces and the cations from the lime exchange (Sivapullaiah, 1996). The monovalent ions are replaced by the divalent $Ca^{2+}$ cations from the lime and this reduces repulsion forces between layers. Attraction between the layers forces the particles to clod and the process is called flocculation. Flocculation improves the soil's structure and decreases the swelling potential. Furthermore, the silica and aluminium from the layers react with calcium from lime forming cementations, calcium silicates and calcium aluminate hydrate, in a process called pozzolanic reaction as indicated below:

$$Ca^{2+} + 2(OH)^{-}(\text{lime}) + SiO_2\,(\text{clay silicate}) \rightarrow \text{hydrated calcium silicate}$$
$$Ca^{2+} + 2(OH)^{-}(\text{lime}) + Al_2O_3\,(\text{clay alumina}) \rightarrow \text{hydrated aluminate silicate}$$

The pozzolanic reaction forms a gel that binds clay particles together and hence the strength of the expansive soil increases (Hadi *et al.,* 2008).

## 2.10 Modes of heat transfer in soil

As mentioned earlier, soil temperature is the driving force behind the soil water migration that leads to structural deterioration in expansive soils. Soil temperature varies in response to changes in thermal processes, as well as meteorological and subsurface variables (Hillel, 2004; Florides & Kalogirou, 2005). The effects of these events are propagated into the soil profile by a complex series of processes, i.e. radiation, convection and conduction (Hillel, 2004; Jury & Horton, 2004; Lal & Shukla, 2004).

Radiation is described by Cengel (2008) as the energy emitted by matter in the form of electromagnetic waves (or photons). This process differs from convection and conduction as it does not require any medium and is regarded as the fastest way the sun's energy reaches the earth (Lal & Shukla, 2004. The soil surface becomes warmer as a result of incoming radiation energy from the sun and this results in heat accumulation which is channeled down the soil profile (Akinremi, 2010). Convection is defined as the mode of heat transfer in liquids and is generally not considered a major process in soils. It may only be of significance if the flow velocity is great or the fluid temperature differs from the nearby soil (Hillel, 2004). Lastly, conduction is defined as heat transfer by collision of molecules in a body and is caused by fast movement of molecules in response to high temperature and mainly occurs in solid materials. It is considered as most responsible for subsurface heat transfer and associated soil temperature (Hillel, 2004; Jury & Horton, 2004; Lal & Shukla, 2004). Heat energy from the sun is absorbed by the soil surface through the process of conduction and is propagated down the soil profile, the calculations on how much heat or temperature – as a detector of heat, varies with space and time is based on thermal properties of the soil (Abu-Hamdeh, 2003). The thermal properties, namely, the volumetric heat capacity ($C_v$), thermal conductivity ($K_t$) and thermal diffusivity (D), together are responsible for the partitioning of energy down the profile.

## 2.11 Soil thermal properties

Soil thermal properties influence the partitioning of energy in the soil profile (Lajos, 2008) and are used in soil heat as well as water flux. Thermal properties are strongly influenced by physical properties such as bulk density, water content, particle size distribution, mineralogical composition and structural arrangement (Abu-Hamdeh, 2003; Pramanik & Aggarwal, 2013; Rublo, 2013). Although thermal properties are coupled with soil temperature, they are more related to the transmission of heat throughout the soil by the processes of convection, conduction and radiation.

### 2.11.1 Heat capacity

Volumetric heat capacity (*C,* J $m^{-3}$ $K^{-1}$) of a soil is defined as its ability to store energy while undergoing a temperature change (Hillel, 2004; Lajos, 2008). Heat capacity of a soil is influenced by factors that are inherent to the soil (mineralogical composition and texture) and those that can be managed, i.e. bulk density, organic matter and water content (Abu-Hamdeh, 2003; Hillel, 2004).

In soils, the value of heat capacity is assumed by the summation of the constituents' (organic matter, mineral matter, water and air) heat capacities weighted volume fractions as:

$$C_{(soil)} = \Sigma (f_{si}C_{si} + f_wC_w + f_aC_a) \quad (2.6)$$

Where:

*f* = volume fractions of constituents
*s* = solid
*w* = water and
*a* = air
*i* = denotes components in a solid phase, such as organic matter and minerals.

Studies showed that heat capacities of different soil minerals differ insignificantly (Kersten, 1949; Bowers & Hanks, 1962 as cited by Jury & Horton, 2004; Hillel, 2004), therefore De Vries (1963) used not only the averages for soil minerals, but exact values for organic matter and water. Since heat capacity of air was found to be small, it was completely excluded from the equation:

$$C_{(soil)} = f_m C_m + f_o C_o + f_w C_w \quad (2.7)$$

Here *m,o* and *w* denotes minerals, organic matter and water, respectively. The equation for heat capacity is then simplified by De Vries (1963) as:

$$C_{(soil)} = 0.48 f_m + 0.60 f_o + 1.0 f_w \quad (2.8)$$

**2.11.2 Thermal conductivity**

Thermal conductivity ($\lambda$, W $m^{-1}$ $K^{-1}$) is the amount of heat passing through a unit area of the conducting body in a unit time under a temperature gradient (Jury & Horton, 2004; Cengel, 2008). This property depends on bulk density, water content and size of soil particles. De Vries (1963) expressed soil thermal conductivity as:

$$\lambda = \Sigma f_n \Theta_n \lambda_n / \Sigma f_n \Theta_n \quad (2.9)$$

Where:

$f_n$ = constituents weighting factor,

$\Theta_n$ = volumetric fractions of the media constituents and

$\lambda_n$ = the thermal conductivity of the constituents.

Since soil is a medium composed of the solid (*s*), liquid (*w*) and gas (*a*) phases, Campbell *et al.* (1988) proposed to modify the De Vries (1963) model to:

$$\lambda = (f_s \Theta_s \lambda_s + f_w \Theta_w \lambda_w + f_a \Theta_a \lambda_a) / (f_s \Theta_s + f_w \Theta_w + f_a \Theta_a) \quad (2.10)$$

**2.11.3 Thermal diffusivity**

Thermal diffusivity (*D,* $m^2$ $s^{-1}$) is the ratio of thermal conductivity to the product of specific heat capacity and bulk density that occurs under steady state conditions (Hillel, 2004; Cengel, 2008):

$$D = \lambda / c\rho \quad (2.11)$$

Here *D* is thermal diffusivity, $\lambda$ is thermal conductivity, *c* is the specific heat capacity of the porous media and $\rho$ is the density of the media. The equation can be simplified as:

$$D = \lambda / C_{(soil)} \quad (2.12)$$

Apart from the equations above, formulated to predict thermal properties using soil components (indirect measurements), there are direct measurements using probe devices. Volumetric heat capacity and thermal diffusivity can be measured using a dual probe comprising of a thermocouple and a heating part. Thermal conductivity can be measured using a single probe consisting of a temperature sensor and a heater fused to a thin metal wire. The mechanisms of these probes are further described by Hanson *et al.* (2002).

## 2.12 Factors affecting thermal properties

Thermal properties of a soil depend on inherent soil factors and externally managed factors (Abu-Hamdeh, 2003; Usowicz *et al.,* 2010). Inherent factors include mineralogical composition and the organic soil component, while externally managed factors are soil water content, bulk density and temperature (Hanson *et al*, 2002; Abu-Hamdeh, 2003).

Smith & Byers (1938, cited by Jury & Horton, 2002) found that thermal conductivities of minerals are of the same “order of magnitude”, hence different thermal conductivities of different soils can rather be explained by its correlation to porosity and packing of the soil particles. Thermal conductivity of soils decreases as particle size decrease, hence clay soils have lower thermal conductivity than sand. This phenomenon can be explained by the fact that with decrease in particle size at a given water content, the contact surface between particles reduces, resulting in lower conductivity (Abu-Hamdeh & Reeder, 2000; Jury & Horton, 2002). An increase in soil water content, however, works more to the sandy soil’s advantage, as an increase in the water film around the already larger particles enhances surface contact between particles and that causes higher thermal conductivity in sands (Misra *et al.*, 1995; Abu-Hamdeh, 2003; Rubio, 2013). An increase in bulk density of soils automatically decreases porosity and enhances thermal contact between the soil particles (Hanson *et al.*, 2002; Lal & Shukla, 2004).

At a given bulk density, heat capacity of soils tend to increase with an increase in soil water content, regardless of the soil texture (Abu-Hamdeh, 2003; Abu-Hamdeh and Reeder, 2000). Furthermore, with a continuous increase in water content, heat capacity of sand increases less rapidly than in clay soils. The increase of heat capacity in clay soils is due to the adsorption of water by negative charges on particle surfaces, giving clay soils a higher heat capacity than sandy soils. Pramanik & Aggarwal (2013) stated that at a given water content, the heat capacity of soils increases with every unit increase in bulk density, this is due to the fact that soil compaction improves particle contact and reduces porosity.

It has also been observed that under controlled bulk density and soil water content, thermal conductivities increase with increasing temperatures for various types of soil. Farouki (1981) and Sakaguchi *et al*. (2007) found an increase in thermal conductivity and diffusivity with every unit of temperature increase in a wide range of soils. This was attributed to water migration and particle contact being improved by increasing temperatures. Furthermore, Kersten (1949) and Mengistu *et al.* (2017) added that the effect of temperature on thermal properties depend on the amount of soil water present. When soil temperature is increased from below freezing point to thawing, the properties decrease (Farouki, 1981; Kersten, 1949). This response is more distinct for heat capacity than for thermal conductivity. The phenomenon was explained by the fact that ice has higher thermal conductivity and volumetric heat capacity than water. Pavlova (1970) stated that there is always an unfrozen water film around soil particles, even at temperatures as low as -40°C. This water is then believed to have an impact in improving the thermal contact between the soil skeleton and the frozen water.

In expansive soils, thermal properties as a function of soil water content and bulk density behave differently. As stated above, thermal conductivity of non-expansive soils increases with an increase in soil water content. For expansive soils, however, studies on thermal properties explained that thermal conductivity increases slowly with an increase in soil water content, but ultimately decreases as the soil starts to swell (Ross & Bridge, 1987; Ardiansyah *et al.,* 2008). This can be explained by the void ratio. If the void ratio is constant, like in non-expansive soils, an increase in soil water replaces the air in the voids, hence an increase in thermal conductivity, since thermal conductivity of air is lower than thermal conductivity of water. For expansive soils, however, the void ratio increases with further addition of water resulting in a decrease in solid volume and a subsequent decrease in thermal conductivity (Ardiansyah *et al.,* 2008). Heat capacity increases linearly with an increase in soil water content, but the rate of increase declines with swelling, whereas in non-expansive soils the increase remains linear (Ross & Bridge, 1987).

## 2.13 Soil temperature regimes

Soil temperature regimes can be defined as temperature distribution along the soil profile along with continuous changes over time (Fan & Liu, 2003). A number of indices are used to characterize soil temperature regimes and all are based on soil horizon temperatures measured at different temporal and spatial intervals. Van Wyk & De Vries (1963) described soil temperature regimes by sine waves that vary around average temperature due to climatic events. Temperature of the soil could be considered as constant with depth under stable meteorological conditions, due to heat conservation assumption. Under normal conditions, the diurnal temperature wave amplitude is greatest at the soil surface and decreases with depth. Maximum soil temperatures are reached after noon, but will be lagging with depth (Holmes *et al*., 2008). The lagging of temperature with depth leads to diurnal and seasonal cycles.

### 2.13.1 Diurnal soil temperature regime

Soil temperature differences between day and night, brought about by the earth’s daily rotation, are referred to as the diurnal soil temperature cycle (Lal & Shukla, 2004; Abbas & Abbas, 2009). During a 24 hour day the earth receives (solar radiation) and losses (terrestrial radiation) heat, the imbalance between the two leads to cooling and warming of the surface. At day time, solar radiation exceeds terrestrial radiation and the surface becomes warmer, but at night time the opposite is true. Solar radiation absorbed by the earth's surface is converted to soil heat, where the response of atoms to the heat applied is equivalent to soil temperature.

Atmospheric temperature, thermo-physical soil properties and solar radiation are the factors that determine daily soil temperature changes (Fan & Liu, 2003). As much as daily soil temperature is affected by several factors as mentioned, Chen (1988) reported soil water content and depth to be more influential. In day light, the soil surface is warmer and the warmth decreases with depth. Diurnal temperature fluctuations are also greater at the surface, decreasing with depth (Fan & Liu, 2003). Thermal conductivity of the upper soil layers is lower due to the effect of less compaction and low water content (Ao *et al.,* 2016). This inhibits downward penetration of solar energy, leading to decreasing soil temperature with soil depth.

### 2.13.2 Seasonal soil temperature regime

As the earth completes its annual revolution around the sun, the angle of radiation varies seasonally amongst the hemispheres. During the Southern Hemisphere winter, the Northern Hemisphere receives more radiation and in the Southern Hemisphere summer, the Northern Hemisphere experiences less solar energy, leading to drastic drop of temperatures (Dwyer *et al.*, 2012). These seasonal temperature changes also affect soil temperature and this is clearly observed through soil depth. During summer, the temperatures decrease with depth and in winter the opposite is true (Guan, 2011. The temperature variation down the soil profile are perceived, however, in transitional seasons. At a definite layer of soil, the temperature is at its highest in autumn decreasing upward and downward from the warm layer. Contrarily, the same layer is coolest in spring and is in between the upper and lower warm layers.

## 2.14 Temperature and water movement under built structures

Under structures evaporation is retarded, the water content decreases naturally (by gravity flow) with depth as opposed to uncovered soils where temperature influences evaporation leading to a decrease in soil water content at the sub-surface. Although evaporation is limited directly beneath a structure, the peripheral zones (edges) experience evaporation during warm seasons and therefore have a lower water content than the soil in the center of the structure (Figure 2.11). The effect of temperature at the center of a foundation is less evident than at the edges (Nelson & Miller, 1992; Rantala & Leivo, 2003).

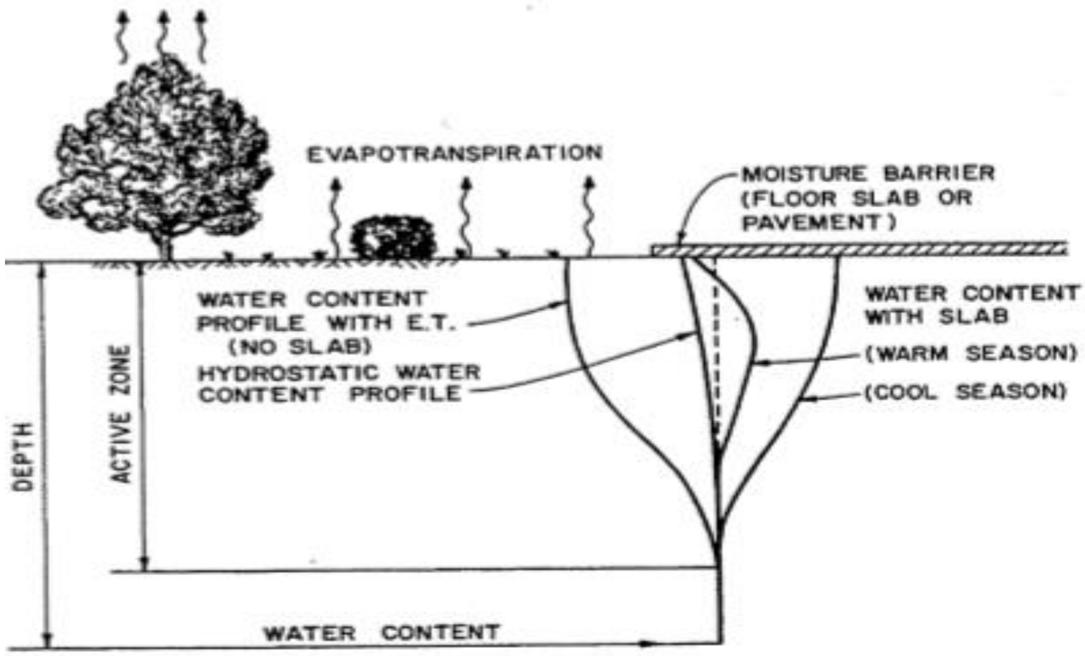


**Figure 2.11** Water content curves in an active zone under a structure and bare conditions (Nelson & Miller, 1992).

It could be expected that since there is water accumulation under built structures due to condensation of water vapour, the temperature should be lower than in bare soils. On the contrary, that depends on the type of structure investigated and meteorological events (Guan, 2011). Wu *et al.* (2014) in the study of comparing the effect of ground cover on soil temperature, reported higher temperatures under a concrete slab than in bare soil through out the study period of two years. On the contrary, Doll *et al.* (1985) found higher temperatures in bare soil during the day but at night, the temperatures under the concrete were warmer. The difference was explained by the direct sunlight exposure of bare soil. A large proportion of radiation energy is used in evaporating soil moisture, which is not applicable to the concrete surfaces (Dong, 1987). Also of importance are the thermal properties of the surfaces. Building materials (concrete, roofing, asphalt) have a higher thermal conductivity and diffusivity, and lower heat capacity than soils (Ministry of construction, 1993; Wu *et al.,* 2014). The high thermal conductivity and low heat capacity in concrete slabs or pavers allow the materials to respond more rapidly to warming than bare soil and propagate the heat to the soils underneath.

Regarding buildings, bare soil temperatures are higher only in warmer months, while during cold seasons temperatures under buildings exceed that in bare soils (Dawson & Fisher, 1963; Parker *et al*., 2016). This is an indication that the type of structure plays a role in soil temperature. Due to the presence of foundation walls, the thermal environment underneath the building is regulated by the response of the foundation walls to meteorological events. In summer, walls receive heat and transmit it to the soil at the center of building, while in winter heat loss at the center of a building is delayed and the soil temperature is out of phase with that at the edges. Parker *et al.* (2016) found that soil temperatures close to the outside walls fluctuate more than in the center of the building, indicating lower energy losses or gains in the center of the building. Therefore, soil temperature under buildings is primarily determined by heat conducted by foundation walls from the bare soil. Overall, soil temperature changes mainly depend on the surface cover and seasonal changes.

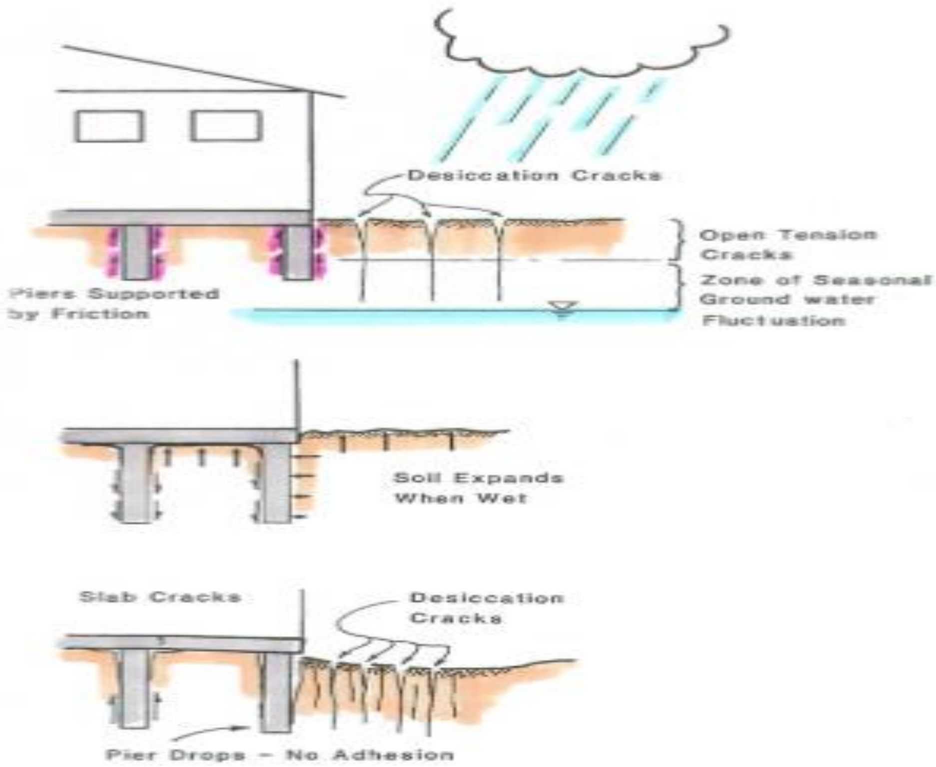


**Figure 2.12** Response of foundation piers to alternating shrinking and swelling of expansive soil due to temperature and water changes (Rogers *et al.*, 1994).

As stated previously, damage to structures on expansive soils manifests with changes in soil water content. Expansive soils do not only heave when exposed to free water, but also in the presence of water vapour moving with temperature gradients in the soil (Chen, 1975). During evaporation water migrates from higher to lower temperatures in the form of vapour to maintain the same thermal energy between the two zones, the cooler areas are under plant canopies or under built structures (Chen, 1975; Ao *et al.,* 2016). Once the vapour has reached the cooler area, it condenses and water content at that particular area increases. This provides an adequate amount of water to facilitate heaving and temperature changes beneath structures (Chen, 1975; Ao *et al.*, 2016).

In most cases, structural deformation starts at the edges of a building due to temperature and water content changes. Expansive soils at the edges of built structures are exposed to evaporation and precipitation and in response they shrink and swell (Figure 2.12). During rainy days, desiccated soils in semi-arid regions absorb water and swell, while on sunny days they shrink due to evaporation. The alternating swelling and shrinking puts strain on foundation piers and eventually leads to cracks and sinks, and ultimately the entire structure starts to deteriorate (Rogers *et al.*, 1994).

## 2.15 Conclusion

Expansive soils are deposits of clay minerals with the tendency of swelling when wet and shrinking during dry seasons. These soils are distributed all over the world in the arid and semi-arid regions. Expansive soils are comparable to natural hazards and cause extensive damage to structures. Expansive soils present significant geotechnical and structural engineering challenges the world over, with costs associated with expansive behaviour estimated to run into several billions annually in individual countries. The swelling potential of expansive soils mainly depends upon the properties of the soil and environmental factors. Control of the swell-shrink behaviour can be accomplished in several ways, for example, by replacing existing expansive soil with non-expansive soil, stabilization through cyclic wetting and drying, improve the expansive soils by chemical stabilization and construction of suitable foundations. Although changes in soil water content is responsible for volume changes in these soils, temperature is the main driving force for soil water migration. Soil temperature variation and distribution is an important indicator of how heat is captured and released. Better understanding of the heat source-sink interaction under different soils could be enriched by accurate knowledge of soil temperature regimes. With the knowledge, water migration may be anticipated and the damage of expansive soils managed.

From the literature it was observed that there is a gap in knowledge about soil temperature in general let alone soils under built structures; houses founded on expansive soils. The question is to what extent (in °C) does temperature under houses differ from bare soils? Under houses it should be complicated as water movement is restricted by the structure forcing it to move literally to the peripheral area of the built structure. The phenomena is of importance yet not much is known about the temperature regimes under houses.

# CHAPTER 3. PHYSICO-CHEMICAL PROPERTIES OF SELECTED EXPANSIVE SOILS IN LAND TYPE DC17

## 3.1 Introduction

A land-type, as indicated by Van der Watt & Van Rooyen (1995), is a piece of land with unique terrain form (topography), soil pattern and climate that isolate it from other land-types. In the case of Land Type Dc17 the entire area is dominated by margalitic soils with melanic and vertic A horizons and duplex soils with orthic A horizons, that are classified as expansive soils (ARC, 2006; Botha *et al*., 2007).

Expansive soils are known as soils with a shrink and swell nature in response to changes in soil water content (Nelson & Miller, 1992; Lucian, 2011; Diop *et al.,* 2011; Mokhtari & Dehghani, 2012; Li *et al.,* 2014; Mohan & Ramesh, 2014; King, 2015; Soltani & Estabragh, 2015). These soils inherited the shrink/swell behaviour from the smectite mineral group with one octahedral between two tetrahedral sheets (Chen, 1975; Brady & Weil; 2002). During wet conditions the clay minerals adsorb water between the sheets and expand, while under dry conditions the clay minerals shrink. Expansive soils are found in arid and semi-arid regions around the world and are characterized by fissures on the surface when dry, while they are sticky with low drainage in wet seasons (Diop *et al*., 2011; Soltani & Estabragh, 2015). Expansive soils are notorious for being problematic by causing tremendous damage to infrastructure globally. With knowledge of their properties, the behaviour of expansive soils can be better understood since understanding is the first step in managing and solving the problem.

A number of studies have been undertaken in South Africa and globally on expansive soils as mentioned in Chapter 2. Most of these studies have focused on soil pedology, soil classification, as well as soil health. However, some soil parameters, such as consistency indices, bulk density and gravimetric water content, are rarely available in soil survey databases due to the high costs and time involved in attaining them. Consistency indices and bulk density are important parameters in engineering and conversion of gravimetric to volumetric water content, calculation of soil porosity and an indication of soil compaction that affects hydraulic properties (Blake & Hartge, 1986, Bagheri *et al*., 2011; Ahmadi *et al.,* 2012). To fill the gap in the soil survey database, consistency indices and bulk density are mostly predicted using other available soil properties, i.e. cation exchange capacity, organic matter and clay content (Ahmadi *et al.,* 2012). This study will give opportunity to provide more information on a wide range of expansive soils in land type Dc17 to be readily available in the database.

The study was conducted to determine selected physical and chemical properties of the Sepane, Swartland, Valsrivier, Arcadia and Bonheim soil forms that dominate Land Type Dc17. The main focus was the classification of the aforementioned soil types with respect to morphological, physical and chemical properties of each individual soil form.

## 3.2 Materials and Methods

### 3.2.1 Site location

The study was conducted on Land Type Dc17 located east of Bloemfontein in the Free State Province of South Africa. This land type occupies an area of 239 080 ha and 85% of the area (203 739 ha) is mainly clay soils of different types (ARC, 2006). It is described as a semi-arid region with average annual rainfall of 573 mm, average maximum and minimum temperatures of 24.8˚C and 7.5˚C, respectively (Botha *et al*., 2003). Duplex soils with prismacutanic and pedocutanic diagnostic B horizons are dominant, underlying vertic and melanic A horizons (Tekle, 2005). The Land Type Dc17 covers three towns, i.e. Dewetsdorp, Thaba-Nchu and Botshabelo (Figure 3.1).

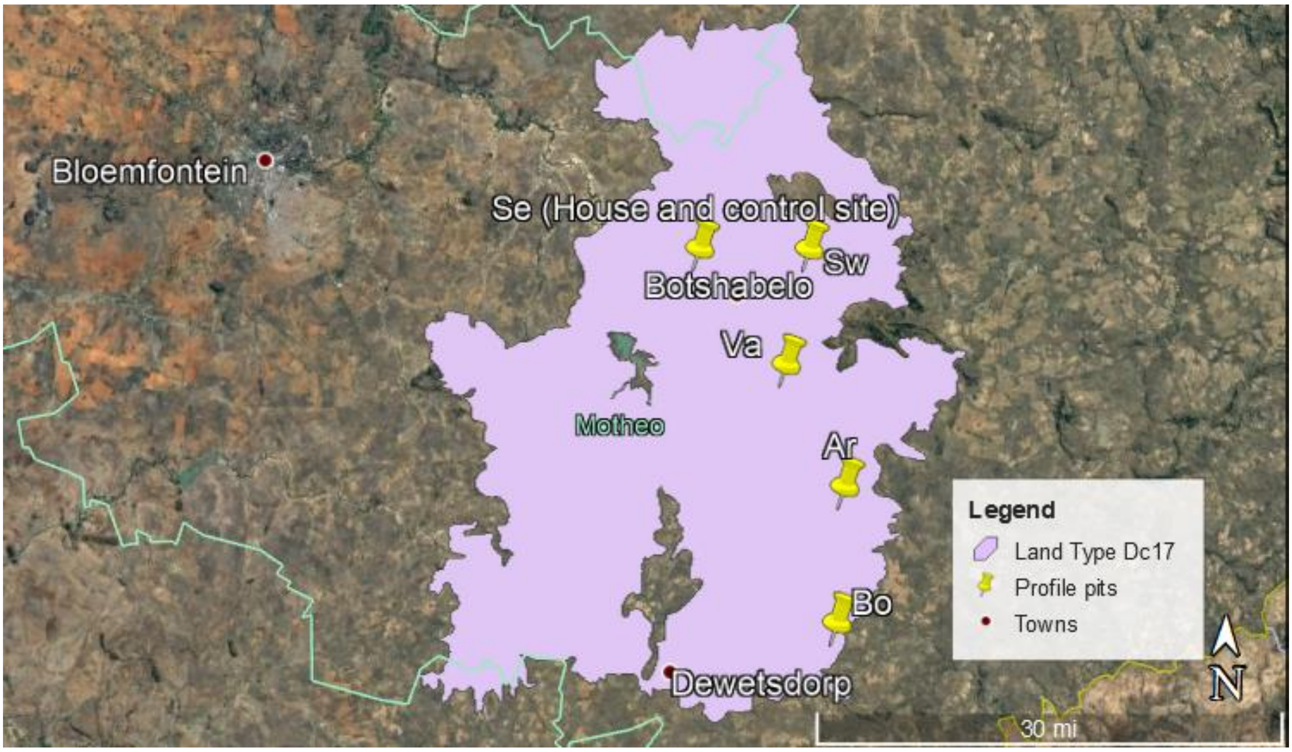


**Figure 3.1** Land Type Dc17 showing the location of the selected expansive soils: Se – Sepane, Sw – Swartland, Va – Valsrivier, Ar – Arcadia and Bo – Bonheim (Google maps, 2017).

Five expansive soil forms across the land type area were selected for this study, namely Arcadia, Bonheim, Swartland and Valsrivier in a natural veld, and Sepane situated in a residential area next to a house. The profile pits (randomly scattered in the land type) were excavated for soil classification in accordance with the guidelines of Soil Classification: A Taxonomic System for South Africa (Soil Classification Working Group, 1991).

### 3.2.2 Methodology for soil analyses

Soil specimens representing the above mentioned soil forms were taken from the demarcated master horizons of each profile pit using a scoop. The collected samples were dried at 105˚C for one week. Each specimen was ground with mortar and pestle and screened through a 2 mm sieve before any analysis commenced.

***Particle size analysis***

Particle size distribution for each soil form was determined using the pipette method as described by the Non-Affiliated Soil Analysis Work Committee (1990). The weighed 30 g oven dried samples were dispersed by adding 50 ml Calgon and stirred using an electric stirrer to separate particles (Figure 3.2a). The suspended clay+silt fraction was sieved through a 53 µm aperture sieve into a 1000 $cm^3$ cylinder and covered to settle. Soil fractions with particle size greater than 0.05 mm were transferred from the sieve to a glass beaker and oven-dried. The dried samples from the beaker were then quantified for sand fractions by shaking for 5 minutes through a set of sieves using a mechanical shaker. The clay+silt suspension in the cylinder was then stirred vigorously with a metal rod, pipetted three times into small suspension beakers. The first sample, taken immediately, included all particle sizes, the second sample was extracted at 10 cm depth after 5 minutes for silt+clay, while the third extraction was at 7 cm after 7 hours for clay. The pipetted suspensions were oven dried and weighed for coarse silt, fine silt and clay contents. The percentage values of each class were calculated as a percentage of the total mass of the sample.

***Soil bulk density***

Soil bulk density was determined on dry basis using the core sampler method (Blake & Hartge, 1986). The weight of the PVC ring (which was 75 mm height and 105 mm in diameter) was first subtracted from the core samples. Each core was calculated as the ratio of the mass of the dried core sample to its total volume. Bulk density *pd* was then expressed as:

$$\rho d = \frac{Ms}{Vs} \quad (3.1)$$

Where,

$M_s$ = Mass of wet soil

$V_s$ = Volume of core sampler = $\pi * (\frac{d}{2})^2 * h$

d = Diameter of pipe

h = Height of pipe

***Consistency limits (Atterberg limits)***

The consistency limits, which are liquid limit (LL), plasticity limit (PL) and plasticity index (PI), were determined by standard procedures from Standard Methods of Testing Road Construction Materials (1986).

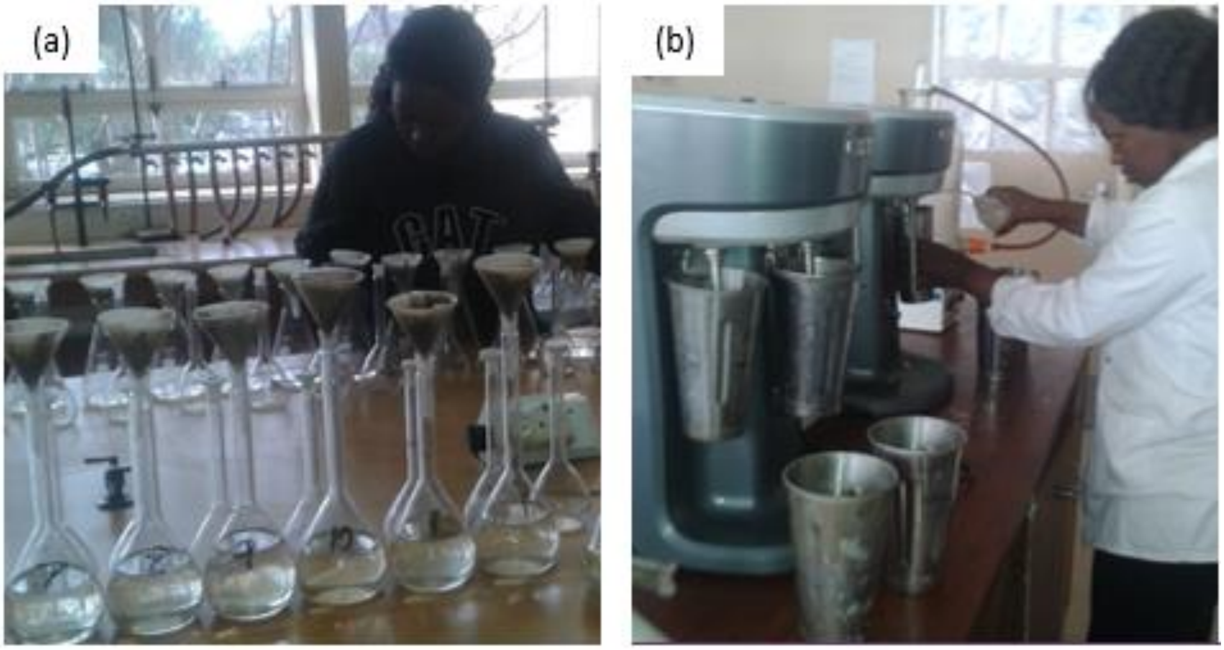


**Figure 3.2** Laboratory procedures during soil analyses: (a) leaching soil specimens with unbuffered ammonium acetate for CEC measurement, and (b) mechanical stirrer with 30 g of soil in Calgon and water for soil texture analyses.

***Saturated hydraulic conductivity (Ksat) and drained upper limit (DUL)***

For the determination of $K_{sat}$, the constant head permeameter method by Klute & Dirksen (1986) was used, the method was developed based on Darcy's Law. The specimen were sampled from the aforementioned profile pits from each master horizon using a core sampler with dimensions of 75 mm height and 105 mm in diameter (Blake & Hartge, 1986). The specimens were sampled horizontally from each of the four walls of each profile pit to represent replicates, carefully wrapped with plastic to avoid evaporation and transported to the laboratory. On arrival in the laboratory samples were weighed to obtain the initial weight and then dried at 65$^{o}$C for 7 days. Subsequently, samples were saturated for one week by putting them in a half full container with water to ensure saturation. After saturation, the samples were covered below by cheesecloth to retain the soil (conductance of the cloth is high so the head loss is ignored) and mounted as shown in Figure 3.3 for $K_{sat}$ determination. Continuous water supply is let to flow from a reservoir to the sample to maintain a constant head. The water that flows through the sample is collected in a collection jar. $K_{sat}$ value was determine once the steady flow rate was achieved. The $K_{sat}$ value was determine once the steady flow rate was achieved flow rate, hydraulic head difference, length and cross section of the core are noted and substituted into Equation 3.1 to compute for $K_{sat}$.

$$K = q * \left(\frac{\Delta Z}{\Delta H}\right) \tag{3.2}$$

The initial equation by Darcy is:

$$q = -\,k\,\frac{\Delta H}{\Delta Z} \tag{3.3}$$

Where, $q = \frac{Q}{A}$

Q = Volume of water passing through the soil ($mm^3$)

A = Cross sectional area of core ($mm^2$)

K = Hydraulic conductivity (mm/h)

Z = Length of the core sample (mm)

H = Pressure head

The same samples used to determine $K_{sat}$, was then used to determine DUL. For this the standard *in situ* internal drainage procedure of Hillel *et al*. (2004), modified to be applied in the laboratory, was employed (Figure 3.4).

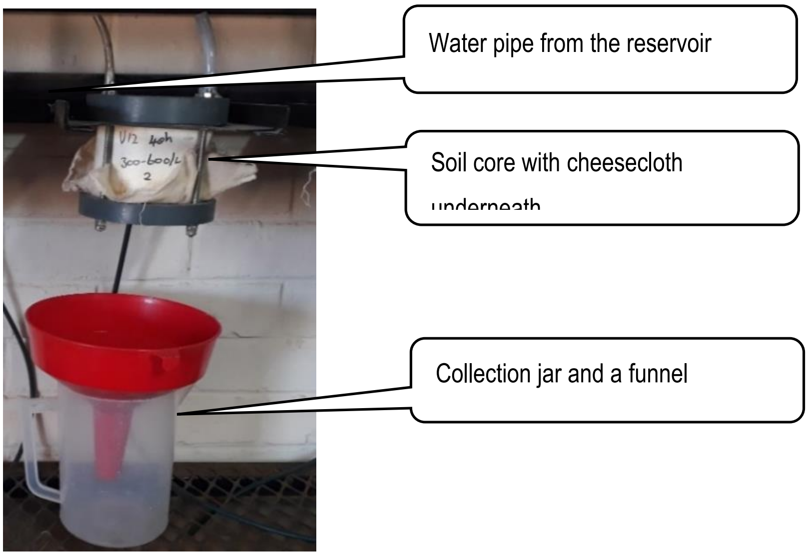


**Figure 3.3** Setup of the constant head permeameter.

**Figure 3.4** A modified drained upper limit procedure.

***Organic carbon***

Organic carbon (OC) was determined by the Walkey-Black procedure involving oxidation of organic carbon by the dichromate oxidation technique (1939).

***Cation exchange capacity and exchangeable cations***

Cation exchange capacity (CEC) and exchangeable cations (Na, K, Mg and Ca) were determined by leaching soil samples with an unbuffered ammonium acetate solution (Figure 3.2a). The displaced cations were measured by flame photometry and atomic adsorption spectrophotometry.

***Electrical conductivity, electrical resistivity and pH***

Electrical conductivity of the samples was determined using the saturated paste extract method, commonly used and accepted as the most accurate method to measure salinity (McNeill, 1992). A slightly flowing paste was prepared by saturating a soil sample of 250 g with de-ionized water in a 1:2 ratio. The soil paste was then covered with plastic over night for salts to dissolve. A set of Buchner funnels with highly retentive filter paper were mounted airtight onto Buchner flasks and connected to a suction pressure pipe. The pastes were transferred to the funnels and extracts collected to determine EC using the Metrohm Module-856 conductivity meter.

Electrical resistance of the soils was determined following the standard procedure according to the US Salinity Laboratory Staff (1954). A soil paste was prepared and transferred to an electronic cup and placed on a bridge resistance board. The resistivity of the saturated paste was measured with a Metrohm AG Model-E382 conductivity meter. The $pH_{(water)}$ was measured in a 1:2.5 soil-water suspension using a pH meter fitted with a glass electrode. Sodium Adsorptiion ratio was calculated as:

$$\mathrm{SEP} = \left(\frac{\mathrm{N}a^{+}}{(\mathrm{C}a^{2+} + Mg^{2+} + K^{+} + Mg^{+})}\right) * 100 \qquad (3.3)$$

## 3.3 Results and discussion

### 3.3.1 Sepane soil form

The Sepane soil form in Botshabelo is of the Katdoorn family (1210) (Figure 3.5). The morphological, physical and chemical characteristics are presented in Tables 3.1 and 3.2. It was found to have an orthic A, pedocutanic B and C horizon with unconsolidated material containing lime concretions. The horizons were found to be well structured with clay percentage from 33 to 35% and corresponding bulk density ranging from 1.46 to 1.53 g $cm^{-3}$, both parameters increasing with depth. The plasticity index increased slightly from 25.5% in A horizon to 26.9% in B horizon. The OC was higher than expected, 2.18 to 5.85%. This could be due to the fact that the site is being used as a vegetable garden surrounded by fruit trees. The exchangeable cations (with the exception of magnesium), CEC, ESP and EC were found to increase with sampling depth. The DUL increased with depth with total of 469 mm, while $K_{sat}$ of horizon B was lower than in A.

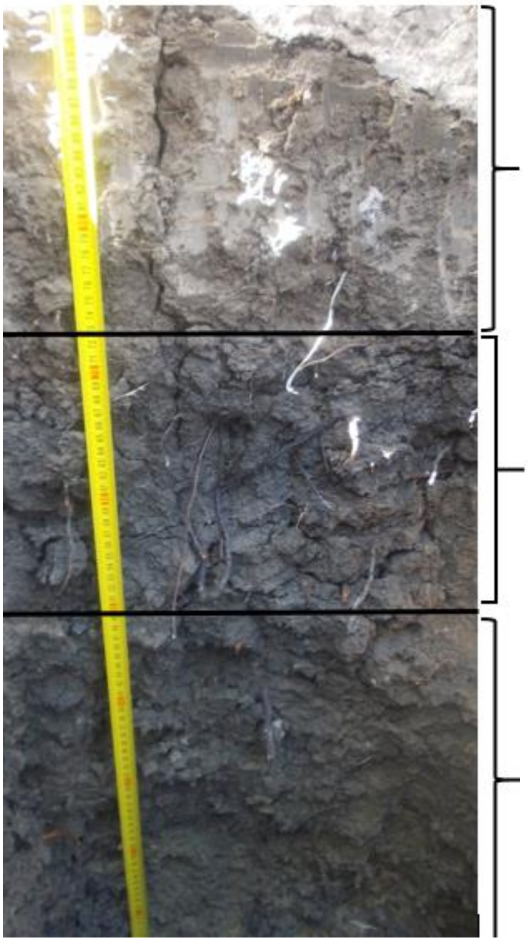


**Figure 3.5** Profile of the Sepane (1210) soil form in Botshabelo residential area.

**Table 3.1** Profile description of Sepane (1210) soil form

| Horizon | Depth (mm) | Description | Diagnostic horizons |
|---|---|---|---|
| **A** | 0-230 | Colour: Moist 10YR3/2 and dry 10YR4/3; Undisturbed clay; Strong sub-angular blocky; Few roots; Clear transition; No clay cutans; No mottles. | Orthic |
| **B** | 230-500 | Colour: Moist 2.5Y3/3 and dry 2.5Y4/2; Undisturbed clay; Strong angular blocky; Many roots; Clear transition; Many clay cutans; No mottles. | Pedocutanic |
| **C** | 500-1000 | Colour: Moist 5Y4/4 and dry 2.5Y5/3; Undisturbed clay; Strong platy; Few roots; No clay cutans; Transition not observed. | Unconsolidated material with signs of wetness |

**Table 3.2** Summary of physical and chemical properties of the Sepane (1210) soil form

| Soil property | | Horizon | | |
|---|---|---|---|---|
| | | A | B | C |
| Physical properties | Sand: Coarse (2-0.5 mm) % | 4.6 | 2.3 | 1.7 |
| | Medium (0.5-0.25 mm) % | 3.7 | 3.4 | 3.2 |
| | Fine (0.25-0.106 mm) % | 17.6 | 11.2 | 8.3 |
| | Very fine (0.106-0.53 mm) % | 31.3 | 20.1 | 19.8 |
| | Silt: Coarse % | 5.3 | 10.3 | 12.1 |
| | Fine % | 5.1 | 18.3 | 18.1 |
| | Clay % | 33 | 35 | 35 |
| | Texture class | Sandy Clay Loam | Clay Loam | Clay Loam |
| | Bulk density (g $cm^{-3}$) | 1.46 | 1.51 | 1.55 |
| | Liquid limit (%) | 47.4 | 51.1 | 52.3 |
| | Plastic limit (%) | 21.9 | 25.7 | 25.7 |
| | Plasticity index (%) | 25.5 | 25.9 | 26.6 |
| | $K_{sat}$ (mm $hr^{-1}$) | 2.271 | 0.000 | 0.003 |
| | DUL (mm) | 106 | 127 | 236 |
| Chemical properties | OC % | 5.85 | 2.37 | 2.18 |
| | pH (water) | 8.08 | 8.1 | 8.21 |
| | Ca (cmolc $kg^{-1}$) | 15.88 | 23.25 | 25.88 |
| | Mg (cmolc $kg^{-1}$) | 3.75 | 3.29 | 2.50 |
| | K (cmolc $kg^{-1}$) | 0.54 | 0.62 | 0.68 |
| | Na (cmolc $kg^{-1}$) | 0.26 | 0.39 | 0.76 |
| | CEC (cmolc $kg^{-1}$) | 23.7 | 32.1 | 32.9 |
| | Resistivity (ohms) | 410 | 240 | 160 |
| | EC (mS $m^{-1}$) | 183 | 293 | 411 |
| | ESP % | 1.28 | 1.43 | 2.56 |

### 3.3.2 Swartland soil form

The Swartland soil form in Thaba Nchu is of the Gemvale (1121) family (Figure 3.6). The soil comprises of an orthic A, pedocutanic B and a saprolite C horizon. According to Table 3.4, the textural classes of horizons A to C were sandy clay sandy, clay loam and clay loam with 38%, 43% and 41% clay contents, respectively. The bulk density ranged from 1.44 to 1.69 g $cm^{-3}$, increasing with depth. The plasticity index ranged from 10.7 to 15.1%. The OC in A horizon was 0.69% and decreased with sampling depth to 0.57%. The exchangeable cations, ESP and CEC increased with sampling depth, whilst EC and $K_{sat}$ decreased from A to B horizons. The DUL of this soil was found to be the total of 417 mm.

**Table 3.3** Profile description of Swartland (1121) soil from

| Horizon | Depth (mm) | Description | Diagnostic horizon |
|---|---|---|---|
| **A** | 0-220 | Colour: Moist 2.5Y4/3 and dry 10YR5/4; Undisturbed clay; Strong sub-angular blocky; Many roots; Diffuse transition; No clay cutans; No mottles; No concretions. | Orthic |
| **B** | 220-460 | Colour: Moist 2.5Y3/2 and dry 2.5Y 5/3; Undisturbed clay; Strong angular blocky; Few roots; Abrupt transition; Clay cutans; No mottles; No concretions. | Pedocutanic |
| **C** | 460-1000 | Colour: Moist 2.5Y3/1 and dry 2.5Y4/2; Undisturbed clay; Strong angular blocky; Few roots; No clay cutans; Few clay cutans; Grey and red faint mottles; No concretions; Transition not observed. | Saprolite |

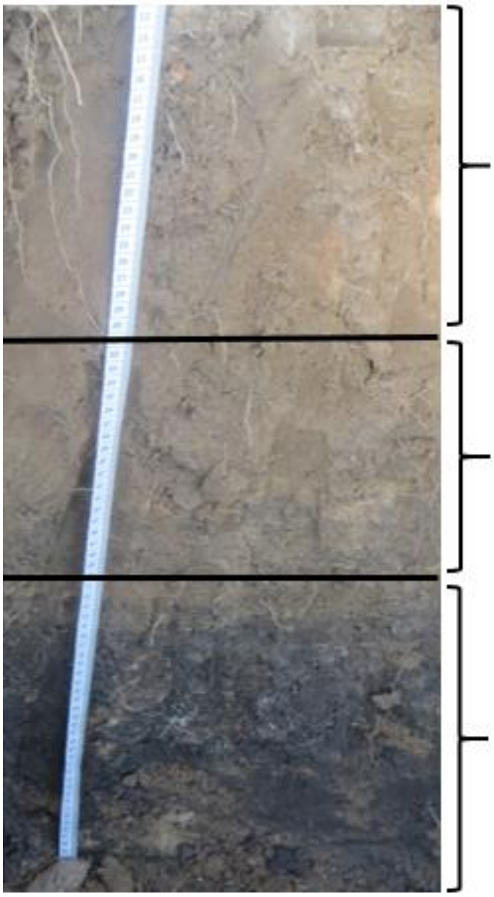


**Figure 3.6** Swartland (1121) soil form in Thaba Nchu town.

**Table 3.4** Summary of physical and chemical properties of the Swartland (1121) soil form

| | Soil property | Horizon | | |
|---|---|---|---|---|
| | | A | B | C |
| Physical properties | Sand: Coarse (2-0.5 mm) % | 0.8 | 0.4 | 0.9 |
| | Medium (0.5-0.25 mm) % | 2.4 | 3.4 | 1.9 |
| | Fine (0.25-0.106 mm) % | 17.1 | 8 | 11 |
| | Very fine (0.106-0.53 mm) % | 27.5 | 20.3 | 22.7 |
| | Silt: Coarse % | 4.9 | 15.8 | 14.6 |
| | Fine % | 9.9 | 12.3 | 5.5 |
| | Clay % | 38 | 43 | 41 |
| | Texture Class | Sandy Clay | Sandy Clay Loam | Clay Loam |
| | Bulk density g $cm^{-3}$ | 1.44 | 1.55 | 1.59 |
| | Liquid limit (%) | 26.2 | 33.4 | 38.3 |
| | Plastic limit (%) | 15.5 | 18.3 | 27.2 |
| | Plasticity index (%) | 10.7 | 15.1 | 11.1 |
| | $K_{sat}$ (mm $hr^{-1}$) | 0.892 | 0.414 | 0.040 |
| | DUL (mm) | 36 | 73 | 308 |
| Chemical properties | OC % | 0.69 | 0.57 | 0.61 |
| | pH (water) | 8.79 | 8.52 | 8.77 |
| | Ca (cmolc $kg^{-1}$) | 17.06 | 17.23 | 20.09 |
| | Mg (cmolc $kg^{-1}$) | 4.17 | 4.79 | 6.46 |
| | K (cmolc $kg^{-1}$) | 0.29 | 0.29 | 0.43 |
| | Na (cmolc $kg^{-1}$) | 0.27 | 0.34 | 0.72 |
| | CEC (cmolc $kg^{-1}$) | 19.22 | 25.21 | 29.04 |
| | Resistivity (ohms) | 1020 | 790 | 720 |
| | EC (mS $m^{-1}$) | 41 | 50 | 49 |
| | ESP % | 1.25 | 1.49 | 2.60 |

### 3.3.3 Valsrivier soil form

The Valsrivier soil form in Thaba Nchu belongs to Goedemoed (1120) family (Figure 3.7). The morphological, physical and chemical parameters are presented in Tables 3.5 and 3.6. The soil profile has an orthic A, pedocutanic B and unconsolidated materials with signs of wetness in the C horizon. The orthic A horizon covers a depth of 160 mm with a weak sub-angular blocky structure, the B and C horizons both have strong angular blocky structures. There was an abrupt transition between A and B and a clear transition to the C horizon. The clay percentages increased from 28 to 39% from the A to the C horizon, with their corresponding textural classes as sandy clay loam, clay and clay loam (Table 3.6).

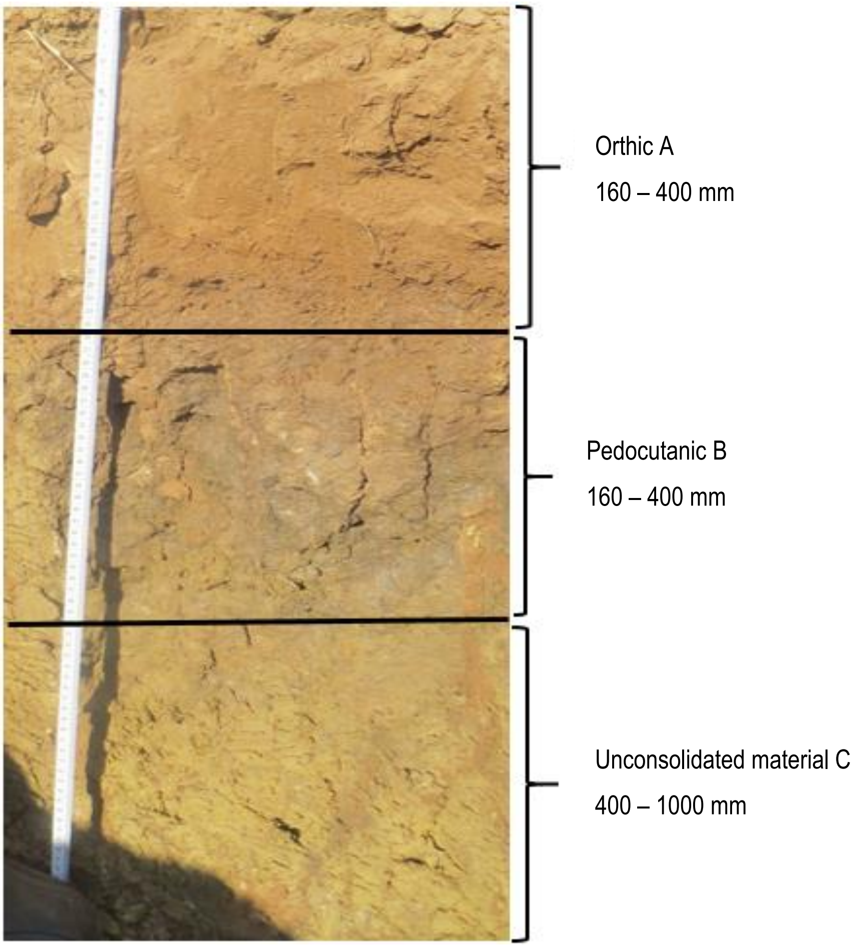


**Figure 3.7** Valsrivier (1120) soil form in Thaba Nchu rural

**Table 3.5** Profile description of Valsrivier (1120) soil from

| Horizon | Depth (mm) | Description | Diagnostic horizons |
|---|---|---|---|
| **A** | 0-160 | Colour: Moist 10YR3/6 and dry 7.5YR4/4; Undisturbed clay; Weak sub-angular blocky; Abrupt transition; Concretions; Deposition of sand. | Orthic |
| **B** | 160-400 | Colour: Moist 2.5Y4/4 and dry 2.5Y5/4; Undisturbed clay; Strong angular blocky; Few roots; Clear transition; Clay cutans; Mottles. | Pedocutanic |
| **C** | 400-1000 | Colour: moist 5Y4/4 and dry 2.5Y6/4; Undisturbed clay; Strong angular blocky; Few roots; Clay cutans; Many mottles; Manganese concretions; Infillings between the pads. | Unconsolidated material without signs of wetness |

The bulk density, plasticity index and liquid limits were found to increase with depth. It was observed that as the clay content increased, the plasticity index and liquid limit were increasing as well. The total DUL for the soil profile was 364 mm, while $K_{sat}$ decreased to 0.016 mm $hr^{-1}$ with depth. The ESP of the soil form was found to be decreasing with sampling depth.

**Table 3.6** Summary of physical and chemical properties of the Valsrivier (1120) soil form.

| Soil property | | Horizon | | |
|---|---|---|---|---|
| | | A | B | C |
| Physical properties | Sand: Coarse (2-0.5 mm) % | 0.8 | 1.1 | 2.6 |
| | Medium (0.5-0.25 mm) % | 3.1 | 1.9 | 1.9 |
| | Fine (0.25-0.106 mm) % | 22.6 | 19.6 | 16.2 |
| | Very fine (0.106-0.53 mm) % | 19.9 | 14.3 | 19.2 |
| | Silt: Coarse % | 10.2 | 10.1 | 2.5 |
| | Fine % | 15.2 | 15.4 | 18.3 |
| | Clay % | 28 | 39 | 37 |
| | Texture class | Sandy Clay Loam | Clay | Clay Loam |
| | Bulk density g $cm^{-3}$ | 1.46 | 1.57 | 1.6 |
| | Liquid limit (%) | 35.7 | 46.6 | 50.6 |
| | Plastic limit (%) | 20.8 | 29.3 | 25.1 |
| | Plasticity index (%) | 14.7 | 17.3 | 25.5 |
| | $K_{sat}$ (mm $hr^{-1}$) | 5.00 | 4.713 | 0.016 |
| | DUL (mm) | 52 | 83 | 229 |
| Chemical properties | OC % | 1.32 | 1.1 | 0.95 |
| | pH (water) | 6.79 | 7.71 | 8.27 |
| | Ca (cmolc $kg^{-1}$) | 7.48 | 11.58 | 10.85 |
| | Mg (cmolc $kg^{-1}$) | 3.54 | 8.33 | 8.75 |
| | K (cmolc $kg^{-1}$) | 0.69 | 1.13 | 1.10 |
| | Na (cmolc $kg^{-1}$) | 0.32 | 0.79 | 1.15 |
| | CEC (cmolc $kg^{-1}$) | 16.87 | 24.34 | 23.21 |
| | Resistivity (ohms) | 930 | 610 | 485 |
| | EC (mS $m^{-1}$) | 42 | 40 | 74 |
| | ESP % | 2.63 | 3.60 | 5.25 |

### 3.3.4 Arcadia soil form

The Arcadia soil form in this study belongs to the Lonehill (1100) family. The morphological characteristics are presented in Table 3.7, and physical and chemical properties are given in Table 3.8. The soil form comprises of vertic A horizon, $B_1$ and $B_2$ horizons (Figure 3.8). The profile has a vertic A and unspecified material in the $B_1$ horizon. Both these horizons have a strong blocky structure with a clay texture. The $B_2$ horizon is unspecified material of coarse blocky structure with a clay content of 44%. The average pH of the profile was 8.1, with EC that decreases with depth. As expected, the bulk density of the soil slightly increased from 1.47 to 1.55 g $cm^{-3}$ with depth. The exchangeable cations (except for Ca) and ESP increased with depth. The DUL was found to increase with depth, with total of 643 mm over the profile, while $K_{sat}$ was 0.06 and 2 mm $hr^{-1}$ for the A and $B_1$ horizons, respectively.

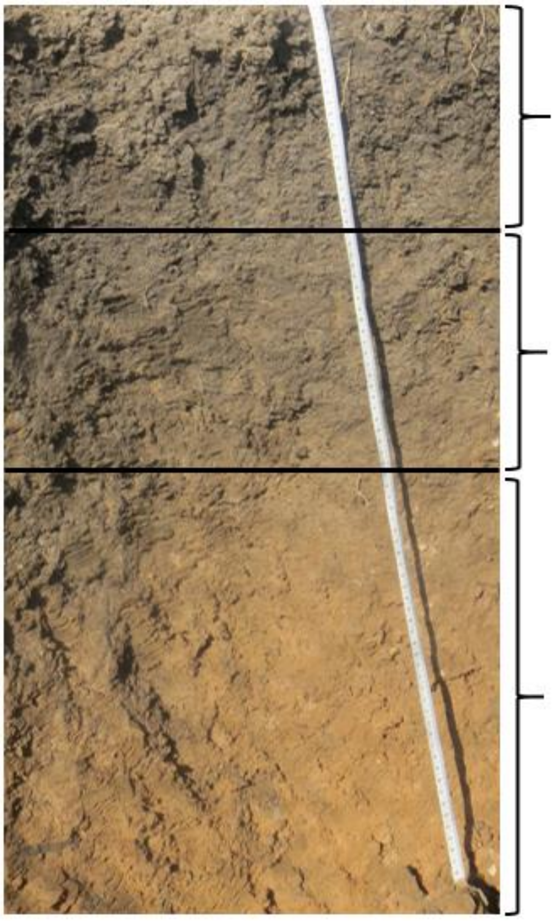


**Figure 3.8** Arcadia (1100) soil form in Yoxford.

**Table 3.7** Profile description of Arcadia (1100) soil from.

| Horizon | Depth (mm) | Description | Diagnostic horizon |
|---|---|---|---|
| **A** | 0-350 | Colour: Moist 10YR2/1 and dry 2.5Y4/2; Undisturbed clay; Strong blocky; Few roots; Diffuse transition; Many clay cutans; No mottles; Infillings of root channels. | Vertic |
| **$B_1$** | 350-500 | Colour: Moist 10YR3/2 and dry 10YR5/3; Undisturbed clay; Strong blocky; Roots channels; Clear transition; Many clay cutans; Many mottles; Many lime concretions. | Unspecified material |
| **$B_2$** | 500-1000 | Colour: Moist 10YR4/3 and dry 10YR5/2; Undisturbed clay; Coarse blocky; Few roots; Many lime concretions; Transition not observed. | Unspecified material |

**Table 3.8** Summary of physical and chemical properties of the Arcadia (1100) soil form

| Soil property | | Horizon | | |
|---|---|---|---|---|
| | | A | $B_1$ | $B_2$ |
| Physical properties | Sand: Coarse (2-0.5 mm) % | 4.4 | 0.9 | 1.4 |
| | Medium (0.5-0.25 mm) % | 2.4 | 1.7 | 1.7 |
| | Fine (0.25-0.106 mm) % | 19.6 | 8.4 | 7.6 |
| | Very fine (0.106-0.53 mm) % | 14.1 | 21.2 | 19.5 |
| | Silt: Coarse % | 14.7 | 5.1 | 10.2 |
| | Fine % | 1.5 | 10.3 | 15.3 |
| | Clay % | 43 | 52 | 44 |
| | Texture Class | Clay | Clay | Clay Loam |
| | Bulk density g $cm^{-3}$ | 1.47 | 1.59 | 1.55 |
| | Liquid limit (%) | 57.7 | 59.6 | 57.6 |
| | Plastic limit (%) | 31.1 | 32.13 | 26.9 |
| | Plasticity index (%) | 26.6 | 27.5 | 30.9 |
| | $K_{sat}$ (mm $hr^{-1}$) | 0.058 | 1.985 | 0.000 |
| | DUL (mm) | 95 | 162 | 386 |
| Chemical properties | OC % | 1.41 | 0.7 | 0.21 |
| | pH (water) | 7.47 | 8.35 | 8.5 |
| | Ca (cmolc $kg^{-1}$) | 16.88 | 19.51 | 9.00 |
| | Mg (cmolc $kg^{-1}$) | 8.96 | 8.06 | 12.29 |
| | K (cmolc $kg^{-1}$) | 0.96 | 0.87 | 0.96 |
| | Na (cmolc $kg^{-1}$) | 0.87 | 1.20 | 1.31 |
| | CEC (cmolc $kg^{-1}$) | 31.65 | 34.78 | 29.30 |
| | Resistivity (ohms) | 630 | 495 | 355 |
| | EC (mS $m^{-1}$) | 60 | 20 | 30 |
| | ESP % | 3.16 | 3.93 | 5.56 |

### 3.3.5 Bonheim soil form

The Bonheim soil form in Dewetsdorp belongs to the Windermere (1210) family (Figure 3.9). Table 3.9 provides the morphological characteristics and Table 3.10 presents physical and chemical properties of this soil form. The melanic A horizon of this soil form covers a depth of 200 mm with a weak sub-angular blocky structure. The underlying B horizon is pedocutanic with angular blocky structure covering a depth of 420 mm.

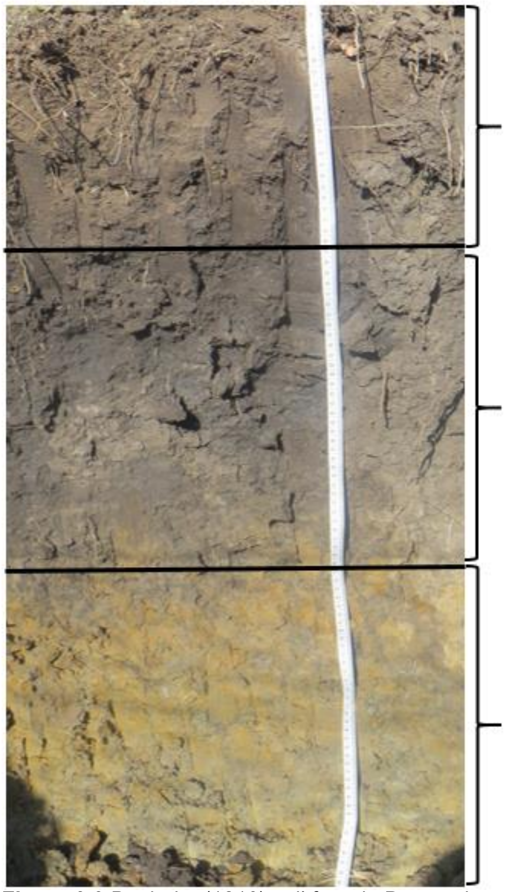


**Figure 3.9** Bonheim (1210) soil form in Dewetsdorp.

**Table 3.9** Profile description of Bonheim (1210) soil from

| Horizon | Depth (mm) | Description | Diagnostic horizons |
|---|---|---|---|
| **A** | 0-200 | Colour: Moist 2.5Y2.5/1 and dry 10YR4/2; Undisturbed clay; Weak sub-angular blocky; Many Roots; Diffuse transition. | Melanic |
| **B** | 200-620 | Colour: Moist 7.5YR3/2 and dry 2.5Y4/2; Undisturbed clay; Strong angular blocky; Few roots; Clear transition; Few clay cutans; | Pedocutanic |
| **C** | 620-1000 | Colour: Moist 2.5Y4/4 and dry 2.5Y5/3; Undisturbed clay; Prismatic structure; Many clay cutans; Prominent red and grey mottles | Unspecified material with signs of wetness |

The C horizon comprises of unspecified material with signs of wetness over a depth of 380 mm. The structure of this horizon is prismatic with clay content of 52%. From Table 3.10, the exchangeable cations of Bonheim (except for K) and CEC increased with depth. The average pH of the soil was 7.84, with resistivity decreasing from 1200 to 292 ohms at the C horizon. The measured EC and calculated ESP increased with sampling depth. The DUL was found to total 489 mm, while $K_{sat}$ was highest in the A horizon, 16.7 mm $hr^{-1}$.

**Table 3.10** Summary of physical and chemical properties of the Bonheim (1210) soil form

| | Soil property | Horizon | | |
|---|---|---|---|---|
| | | A | B | C |
| Physical properties | Sand: Coarse (2-0.5 mm) % | 0.8 | 0.9 | 1.4 |
| | Medium (0.5-0.25 mm) % | 2.9 | 3.2 | 2.4 |
| | Fine (0.25-0.106 mm) % | 17.8 | 21.8 | 15.9 |
| | Very fine (0.106-0.53 mm) % | 15.3 | 16.2 | 16.5 |
| | Silt: Coarse % | 5.1 | 5.1 | 15.2 |
| | Fine % | 5.1 | 5.6 | 9.4 |
| | Clay % | 39 | 47 | 52 |
| | Texture Class | Clay | Clay | Clay |
| | Bulk density (g $cm^{-3}$) | 1.52 | 1.81 | 1.74 |
| | Liquid limit (%) | 36.6 | 39 | 38 |
| | Plastic limit (%) | 19.3 | 19.9 | 20.2 |
| | Plasticity index (%) | 17.3 | 19.1 | 17.8 |
| | $K_{sat}$ (mm $hr^{-1}$) | 16.701 | 0.000 | 0.014 |
| | DUL (mm) | 96 | 137 | 256 |
| Chemical properties | OC % | 1.4 | 1.2 | 0.7 |
| | pH (water) | 7.1 | 8.17 | 8.25 |
| | Ca (cmolc $kg^{-1}$) | 11.49 | 12.45 | 15.38 |
| | Mg (cmolc $kg^{-1}$) | 5.21 | 7.29 | 7.71 |
| | K (cmolc $kg^{-1}$) | 0.53 | 0.31 | 0.27 |
| | Na (cmolc $kg^{-1}$) | 0.33 | 0.62 | 1.08 |
| | CEC (cmolc $kg^{-1}$) | 21.47 | 22.43 | 26.09 |
| | Resistivity (ohms) | 1200 | 620 | 292 |
| | EC (mS $m^{-1}$) | 32 | 100 | 270 |
| | ESP % | 1.87 | 3.01 | 4.42 |

The field observations in collaboration with laboratory analyses contributed in characterization of five soil forms from Land Type Dc17.The mentioned characteristics qualifies the soils to be in Land Type Dc17 since it was mentioned earlier that duplex and margalitic soils dominate the land type (Land Type Survey Staff, 2002; Botha *et al*., 2007).

The soils have three prominent characteristics. Firstly, all the soils are formed from sandstone, shale and mudstone of the Beaufort group with intrusion of dolerite. The dolerite has plagioclase that was altered to smectite, responsible for shrinking and swelling of the mentioned soils (Tekle, 2004). Secondly, all the soils have pedocutanic B horizons with a strong structure. The cutans are commonly found in luvic soils due to eluviation of clay and the horizons are considered as root limiting due to high clay content resulting in strong soil structures that inhibit root growth (Botha *et al*., 2003). The root growth limiting nature of these soils restricts crop production in this particular land type. The roots in ped faces and root channels found in the profiles are indications that roots grow in between cracks during dry conditions and become compressed in the process of swelling in rainy seasons. Lastly, the Sepane and Bonheim soil forms have occurrence of wetness down the profiles indicating that during rainy seasons, when rainfall exceeds evapotranspiration, the soils retain water for some time (Botha *et al*., 2003).

It was observed that clay contents of all the soil forms increased from the A horizon to the underlying B horizon. The increase of clay content with depth could be explained by the illuviation process which is the movement of clay particles down the soil profile. The same results were reported by Botha *et al.* (2003), Botha *et al*. (2014) and Mavimbela & Van Rensburg (2015), they found a similar trend of clay content increasing with soil depth on the same soil forms. Besides Valsrivier's A horizon, the soils were all found to have a clay content of more than 30% – an important characteristic of expansive soils (M'Ndegwa, 2012). The low clay content in the A horizon of the Valsrivier profile could have been caused by sand deposition from the surrounding area.

In general, bulk density increased with sampling depth. This can probably be explained by compaction, as well as the higher OC in most of the surface horizons that decreased with depth. The results found were in agreement with those of Chaudhari *et al.* (2013), they attributed the increase of bulk density with depth to natural compaction and decreasing amount of OC for soils in general. Ratoa (2009) for same soil forms in Free State and Lebenya (2012) for the wide range of soils in the Eastern Cape, reported the same pattern of decreasing OC with profile depth.

Furthermore, observations indicated that LL and PI seemed to be increasing with CEC and clay content from the A to the underlying B horizons in all soil forms. This trend is in agreement with Yilmaz (2004; 2006) and Moradi (2013) who found a correlation between consistency indices and CEC in clay soils. Yilmaz (2004) elaborated that CEC of soils differ according to the type of clay mineral present in the soil. With an increase in expansive clay minerals the CEC increases and the LL and PI increases correspondingly. Ahmadi *et al*. (2012) also confirmed that there is a low correlation of PL with clay content, suggesting that clay mineralogy is of more significance in determining consistency limits. Using PI as criterion for swelling potential, as indicated by Chen (1988), for the soils in this study Arcadia has high swelling potential, while Sepane, Bonheim, Valsrivier and Swartland fall under medium swelling potential.

The hydraulic properties of a soil give insight into the rate and extent of water flow in soils with contrasting layers. These properties are frequently used in agronomic, engineering and environmental applications. The results indicate that the DUL was increasing with sampling depth in all the soil forms. This is similar to results of Botha *et al.* (2003), Chimungu (2009), Botha *et al*. (2014) for the same soil forms. The increase of DUL with depth is associated with the corresponding increase of clay content with depth. In clay soils, there is a large proportion of micro-pores and the soils are negatively charged, these pores together with negative charges retain more water resulting in more imbibed water than in coarse textured horizons (Hillel, 2004; Chimungu, 2009). The higher DUL with depth show the more strongly developed structure caused by the swelling clay and the slightly higher bulk density with depth. The $K_{sat}$ exhibited a decrease with depth and this was associated with an increase in micro-pores and slight increase in bulk density from the A to the B horizons. It was further observed that as $K_{sat}$ decreased LL and PI increased in all soils except in Arcadia soil. It is suspected that there must be a connection between these three soil properties since Benson *et al.* (1994) detailed that the higher the amount of clay, the more plastic the soil is and the lower the hydraulic conductivity. The observations in the current study were in line with findings of Benson *et al.* (1994) where a decrease in $K_{sat}$ with an increase in both LL and PI was observed. A greater quantity and quality of clay mineral is associated with high LL and PI, consequently, a connection between hydraulic conductivity and consistency indices is expected.

The cations varied with depth with exchangeable $Ca^{2+}$ and $Mg^{2+}$ present in the highest quantities, while $Na^{+}$ and $K^{+}$ contents were lowest at 0 to 1 cmolc $kg^{-1}$. In most cases, soil structural deterioration and low hydraulic conductivity is associated with adsorbed $Na^{+}$, but in these soils it is not the case. Karen (1991) found that the adsorbed $Mg^{2+}$ by montmorillonitic soil enhances erosion and lowers infiltration rate. The evidence from the literature then points out that the low $K_{sat}$ and the swelling of these soil forms cannot be ascribed to high clay contents alone, but also to the amount of $Mg^{2+}$ adsorbed. Lastly, according to the US Salinity Staff (1969), soils with EC lower than 400 mS $m^{-1}$ are non-saline, meaning the soil forms in this study are found to be non-saline.

## 3.4 Conclusions

The study was conducted in the first instance to classify selected expansive soils in Land Type Dc17. The soils were classified as Sepane, Swartland, Valsrivier, Arcadia and Bonheim. Soil physical and chemical properties were determined in the laboratory and further contributed to the soil classification. The soil forms are classified as non-saline soils, with low $K_{sat}$ and shallow depth which regard them as not suitable for crop production. According to the criteria followed, the Arcadia soil form was found to have highest swelling potential, while the remaining soil forms had a medium swelling potential.

# CHAPTER 4. EFFECT OF WATER CONTENT ON THERMAL PROPERTIES OF EXPANSIVE SOILS

## 4.1 Introduction

Soil thermal properties are the soil physical parameters responsible for heat flow and temperature changes in soils (Hillel, 2004; Lajos, 2008; Usowicz *et al.*, 2009). Normally, when solar energy reaches the soil surface, it is either reflected back to the atmosphere, stored or propagated down the soil profile. The amount of energy absorbed or transmitted mainly depends on the thermal properties of the soil (Abu-Hamdeh, 2003; Mengistu *et al.*, 2017), which includes thermal conductivity, heat capacity and thermal diffusivity. Thermal conductivity quantifies the heat flow rate through the soil, heat capacity measures the ease at which the soil is heated and diffusivity quantifies effectiveness at which the soil gains heat energy (Hanson *et al.,* 2000). The understanding of thermal properties is essential for safe and proper execution of engineering projects, agriculture and meteorology. These fundamental thermal properties are affected by soil physical properties such as bulk density, water content, particle size distribution, mineralogical composition, structural arrangement and temperature of the soil (Abu-Hamdeh, 2003; Pramanik & Aggarwal, 2013; Rubio, 2013; Mengistu *et al.*, 2017).

Studies have shown that thermal properties depend largely on soil water content (Willis & Raney, 1971; Misra *et al.,* 1995; Smits *et al.,* 2009; Oladunjoye & Sanuade, 2012; Oladunjoye *et al.,* 2013; Rubio, 2013; Busby, 2015; Mengistu *et al.*, 2017). The water content affects thermal properties by enhancing contact between dry soil particles and maximizing heat conduction (Misra *et al.,* 1995). At a given bulk density, heat capacity of soils tend to increase with an increase in soil water content regardless of the soil texture (Abu-Hamdeh & Reeder, 2000; Abu-Hamdeh, 2003). However, the effect of water is more evident in sandy soils than in clay soils (Misra *et al.*, 1995; Abu-Hamdeh, 2003; Rubio, 2013).

Numerous studies and reviews on expansive soils have been published (for example Chen, 1975; Nelson & Miller, 1992; Fredlund & Rahardjo, 1993; Terzaghi *et al.*, 1996; Pedarla *et al.*, 2011; Das & Roy, 2012; Mokhtar & Deghani, 2012; Azam *et al*., 2013; Puppala *et al.*, 2013; Shi *et al*., 2014; King, 2015; Soltani & Estabragh, 2015), but still little is known on their thermal properties. Thermal properties of expansive soils are more complex in response to changing water content, since changes in water content is also accompanied by changes in bulk density. Therefore, this study was conducted to contribute to the limited current knowledge on thermal properties of expansive soils in South Africa. The objective of the study was to determine the effect of changing water content on fundamental thermal properties, including heat capacity, thermal conductivity and thermal diffusivity, on selected expansive soils in Land Type Dc17 (Sepane, Swartland, Valsrivier, Arcadia and Bonheim soil forms).

## 4.2 Materials and methods

### 4.2.1 Field description

The soil samples were collected at five locations in Land Type Dc17, situated east of Bloemfontein in the Free State Province of South Africa. Detailed descriptions of the locations and the five soil forms are given in Chapter 3.

### 4.2.2 Sample preparation

The profile pits described in Chapter 3 were used in this study. Prior to sampling, the profile pits were filled with water until the soil was assumed to be near saturation, where after the water was drained. Sampling commenced immediately and five samples were taken with intervals of one week in between to represent five natural soil water contents. The five water contents were categorized as: field dry (0.09 – 0.14 $mm^3$ $mm^{-3}$), moderate (0.15 – 0.20 $mm^3$ $mm^{-3}$), moist (0.21 – 0.25 $mm^3$ $mm^{-3}$), wet (0.26 – 0.30 $mm^3$ $mm^{-3}$) and assumed saturation (0.31 $mm^3$ $mm^{-3}$ upwards). Specimens were collected from each master horizon. After sampling, specimens were wrapped with plastic cling film to prevent evaporation, then transported to the laboratory and kept at 25°C controlled temperature to mimic field temperature. Specimens were stored for two nights prior to measurements for thermal properties commenced. During storage the samples were turned twice a day to allow even distribution of water.

It is worth noting that although five water treatments were employed, problems were encountered during measurement of the thermal properties of the dry samples. Hence the “dry” water range was not included in the analysis and only results from moderate to near saturation water levels will be reported for thermal conductivity, volumetric heat capacity and thermal diffusivity.

### 4.2.3 Instrument calibration and measurement of thermal properties

Thermal conductivity, volumetric heat capacity and thermal diffusivity were determined using the KD2 Pro thermal analyzer, developed by Decagon devices (Figure 4.2). Prior to measurements, a simple calibration was performed on the device. The device sensors were inserted into the Derlin block (Figure 4.1) for 15 minutes to equilibrate the temperature and verify thermal property values to the ranges given by the quality assurance certificate. The procedure followed was based on the instruction manual provided with the kit (Decagon Devices Inc., 2011).

The KD2 Pro analyzer uses the transient line heat source method to measure the mentioned thermal properties (Decagon Devices Inc., 2011). In the analyzer kit there are a number of sensors, in this study the SH-1 thermal dual sensor was employed. The sensor uses a heat pulse mechanism where one needle is a heater, a current passes through the heater to a sample and is detected by a temperature sensor in the other needle. The needles of the SH-1 dual sensor is 30 mm long with diameter of 1.3 mm and a spacing of 6 mm between the needles.

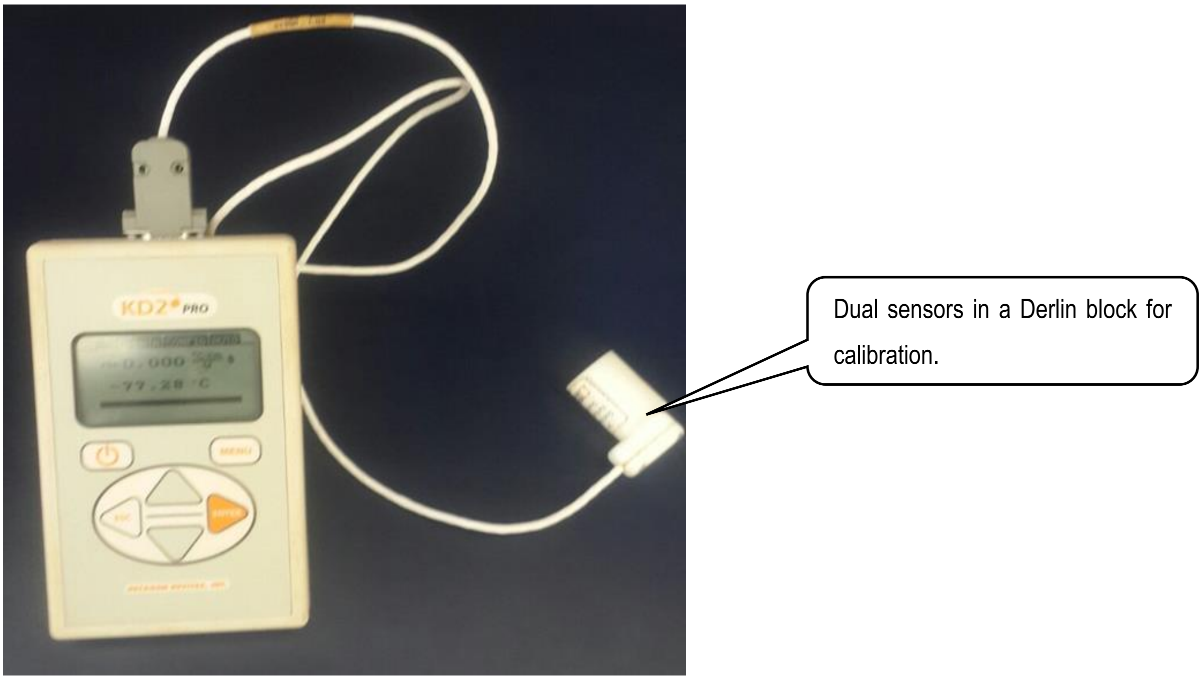


**Figure 4.1** KD2 Pro analyzer sensors in a calibration block as recommended by the instruction manual.

**Figure 4.2** KD2 Pro analyzer measuring soil thermal properties in a room with controlled temperature (25˚C).

For the moderate to near saturation, the needles were pushed and inserted with care (Figure 4.2). Some of the dry samples were too hard to insert the needles, therefore, holes were drilled with a drill bit provided with kit. A 10 mm steel guide was used to channel drill bits into the samples to ensure the shafts were parallel.

### 4.2.4 Statistical analyses

The collected data of the five soil forms were subjected to analysis of variance (ANOVA) using SAS software version 9.4 (SAS Institute, 2013). The fundamental thermal properties means were separated by the LSD procedure (Fischer) at alpha level 5%.

## 4.3 Results and discussion

### 4.3.1 Thermal conductivity ($K_t$)

In all three horizons, soil water content significantly affected $K_t$ on five soil forms (Table 4.1). The ANOVA revealed that there was a significant interaction between soil form and water contents (Table A1), implying that the effect of water on $K_t$ depended on the soil type.

**Table 4.1** Thermal conductivity (W $m^{-1}$ $K^{-1}$) of five soil forms at increasing water contents (ANOVA in Table A1)

| Horizon | Soil type | Soil water content | | | |
|---|---|---|---|---|---|
| | | Moderate* | Moist* | Wet* | Near saturation* |
| A | **Sw** | 0.639 h | 0.885 gh | 1.531 ab | 1.413 abcde |
| | **Va** | 0.915 gh | 1.166 defg | 1.637 a | 1.423 abcd |
| | **Se** | 1.339 bcde | 1.497 abc | 1.695 a | 1.569 ab |
| | **Ar** | 1.00 fg | 1.159 defg | 1.159 defg | 1.148 defg |
| | **Bo** | 1.416 abcd | 1.233 cdef | 1.172 defg | 1.119 efg |
| | | LSD 0.295 | | | |
| B | **Sw** | 1.119 ef | 1.574 abc | 1.661 ab | 1.275 de |
| | **Va** | 1.155 def | 1.166 def | 1.427bcd | 1.423 bcd |
| | **Se** | 1.339 cde | 1.746 a | 1.758 a | 1.184 def |
| | **Ar** | 1.148 def | 1.151 def | 1.266 de | 1.056 ef |
| | **Bo** | 1.572 abc | *** | 1.620 abc | 1.336 cde |
| | | LSD 0.284 | | | |
| C | **Sw** | 1.395 cde | 1.409 cde | 1.462 bcd | 1.347 cdefg |
| | **Va** | 1.273 defg | 1.330 cdefg | 1.336 cdefg | 1.245 efg |
| | **Se** | 1.476 bcd | 1.661 ab | 1.697 a | 1.491 abc |
| | **Ar** | 1.211 efg | 1.261defg | 1.303 cdefg | 1.155 g |
| | **Bo** | 1.177 gf | *** | 1.373 cdef | 1.231 efg |
| | | LSD 0.216 | | | |

For each horizon, means followed by different letters are significantly different according to LSD at ($P<0.05$)

*Moderate = 0.15 – 0.20 $mm^3$ $mm^{-3}$; moist = 0.21 – 0.25 $mm^3$ $mm^{-3}$; wet = 0.26 – 0.30 $mm^3$ $mm^{-3}$; near saturation ≥ 0.31 $mm^3$ $mm^{-3}$

*** missing value

In horizon A, there was general trend of $K_t$ increasing with increasing water content from moderate to wet for all the soil forms. For Swartland, Valsrivier and Sepane soil forms, the increase was statistically significant, while for Bonheim and Arcadia the increase was not significant. With further increase of water content, the $K_t$ decreased but the decreasing pattern was not significant for any of the soils. For horizon B, there was a significant increase in $K_t$ from moderate to wet for Swartland and Sepane, while Valsrivier, Arcadia and Bonheim exhited a non-significant increase in $K_t$. From wet to near saturation, $K_t$ in all soil forms, except Arcadia and Bonheim, showed significant decline. Horizon C followed the same pattern as the above horizons, but the increase in $K_t$ was not significant in all the soil forms except in Sepane. This was followed by slight and non-significant decline of $K_t$ in all the soil forms wet to near saturation.

Farouki (1981) and Abu-Hamdeh & Reeder (2000) reported an increase of $K_t$ with increasing water content in clay soils, and Usowicz *et al.* (2009) for undisturbed silt loam soils in Italy using an empirical formula to determine $K_t$. The same pattern of increasing $K_t$ with water content was also reported by Mengistu *et al.* (2016) for South African sandy soils using the transient-line heat source mechanism. In the studies of Ross & Bridge (1987) using the same sampling method as in the current study (hydraulic sampler) and Ardianshyah *et al.* (2008) for sieved and repacked soils that are comparable to the current, found similar results for swelling clays. It is of importance to highlight that in all the mentioned studies, desorption was obtained under controlled laboratory conditions using pressure plates, as opposed to the current study where the water content ranges were obtained under field conditions. This was done in order to allow the soils to swell to their natural capacity. The main reason for an increase of $K_t$ is that addition of water to the soils establishes contact bridges by an increase of the water film around the negatively charged clay particles, increasing the quality of contact between the particles (Farouki, 1981; Abu-Hamdeh, 2003). Besides the formation of bridges that enhanced contact, the other contributing factor is the different $K_t$ values of soil constituents. De Vries (1963) stated that soil constituents have different $K_t$ values (water 0.56, air 0.024 and soil minerals 2.5 W $m^{-1}K^{-1}$). Hence, with an increase of soil water the air in the soil pores is replaced by water, therefore $K_t$ of the soil should increase.

When increasing soil water contents to near saturation conditions, the results found in the current study share similarities with those of Ross & Bridge (1987) and Ardiansyah *et al.* (2008). Although the water content in the cited studies were controlled, the effect on $K_t$ was found to be comparable to the study. The evidence pointed that expansive soils at saturation or near saturation experience a change in void ratio. Unlike in rigid soils, an excessive amount of water in expansive soils increases void ratio. The solid volume decreases resulting in decrease of $K_t$, since water possesses lower $K_t$ values than solids (Ardiansyah *et al.,* 2008).

### 4.3.2 Volumetric heat capacity (Cv)

The results of $C_v$ for five soil forms (with three horizons) subjected to different water contents are summarized in Table 4.2. The ANOVA showed that there was a significant interaction between soil form and soil water (Table A2), so all the soil forms was not affected in the same way by $K_t$ increasing water content.

**Table 4.2** Volumetric heat capacity (MJ $m^{-3}$ $K^{-1}$) of five soil forms at increasing water contents (ANOVA in Table A2)

| Horizon | Soil type | Moderate* | Moist* | Wet* | Near Saturation* |
|---|---|---|---|---|---|
| A | **Sw** | 1.825 f | 2.088 def | 2.359 bcde | 2.401 abcde |
| | **Va** | 2.003 ef | 2.095 cdef | 2.795 ab | 2.882 a |
| | **Se** | 2.094 cdef | 2.117 cdef | 2.504 abcde | 2.649 ab |
| | **Ar** | 2.362 bcde | 2.562 abcd | 2.611 abc | 2.755 ab |
| | **Bo** | 2.223 cdefgh | 2.305 bcdef | 2.329 bcdef | 2.418 abcde |
| | | | LSD 0.521 | | |
| B | **Sw** | 2.089 fg | 2.143 efg | 2.320 defg | 2.550 cdefg |
| | **Va** | 2.570 bcdefg | 2.638 abcdef | 2.747 abcde | 3.212 a |
| | **Se** | 2.094 gh | 2.470 cdefg | 2.543 cdefg | 3.026 abc |
| | **Ar** | 1.972 g | 2.543 cdefg | 2.481 cdefg | 2.611 abcdef |
| | **Bo** | 2.584 abcdefg | 2.920 abcd | 2.834 abcd | 3.190 ab |
| | | | LSD 0.631 | | |
| C | **Sw** | 2.457 d | 2.516 bcd | 2.507 bcd | 2.527 bcd |
| | **Va** | 2.369 d | 2.488 cd | 2.495 abcde | 2.915 abc |
| | **Se** | 2.487 dc | 2.543 bcd | 2.582 bcd | 2.805 abcd |
| | **Ar** | 2.495 bcd | 2.510 bcd | 2.646 abcd | 2.960 ab |
| | **Bo** | 3.073 a | 3.070 a | 2.801 bcd | 2.701 abcd |
| | | | LSD 0.458 | | |

For each horizon, means followed by different letters are significantly different according to LSD at ($P<0.05$)

*Moderate = 0.15 – 0.20 $mm^3$ $mm^{-3}$; moist = 0.21 – 0.25 $mm^3$ $mm^{-3}$; wet = 0.26 – 0.30 $mm^3$ $mm^{-3}$; near saturation ≥ 0.31 $mm^3$ $mm^{-3}$

As water content was increased, there was a pattern of increase in $C_v$ in A and B horizons for all the soil forms. In the A horizon, the increase was not significant for Arcadia and Bonheim, while for Swartland, Valsrivier and Sepane, $C_v$ increased significantly. For the B horizon, the increase was not significant for Swartland and Bonheim soil forms. For horizon C, only Sepane showed a significant increase in $C_v$ as water content increased, as for the other soil forms, the effect was non-significant.

The results observed are similar to the expectations that with increasing soil water content, the $C_v$ of soils increases monotonously. Similar results to the current study were reported for a wide range of soils including clays (Farouki, 1981), for Jordanian clay soils (Abu-Hamdeh & Reeder, 2000; Abu-

Hamdeh, 2003), for sandy soils (Mengistu *et al*., 2017) and for expansive soils by Ross & Bridge (1987) and Ardiansyah *et al.* (2008). The increase of $C_v$ with water content, as is the case with $K_t$, is explained by the replacement of air in the micro pores by water, creating hulls around the soil particles, assisting in bridge formation between soil particles. With regard to expansive soils, other studies have reported linear increase in $C_v$ with increasing water content, and the rate drops once swelling starts (Ross & Bridge, 1987). In the current study, it was difficult to say exactly where the increase rate dropped since each soil form behaved differently and the water contents were not exact amounts, but ranges. The different behaviour of the soil forms could be brought about by differences in mineralogy and particle composition, since heat capacity is affected by mineralogical composition of the soil (Abu-Hamdeh, 2003). Despite the fact that there was inconsistency, the results still showed a general increase of $C_v$ with water content.

### 4.3.3 Thermal diffusivity (D)

In all three horizons, water content significantly affected D on five soil forms (Table 4.3). The ANOVA revealed that there was a significant interaction between soil form and water content (Table A3), indicating the effect of soil water content on D depend on the soil type.

In horizon A, only Valsrivier showed a significant increase in D from moderate to wet conditions. However, the other soils exhibit a general trend of increase in D. From wet to near saturation, there was a slight, but not significant decrease of D for all soil forms. For horizon B, there were no significant effect in all the soil forms with addition of water from moderate to near saturation, although D showed the pattern of increase followed by a slight decrease. For horizon C, there was a significant increase of D in all the soil forms, followed by a decline in D with further addition of water to saturation that was significant only for Sepane and Arcadia. In all three horizons, Sepane had the highest D values in general, irrespective of water content.

The pattern found in the current study were found by Ardiansyah *et al.* (2008) and Ross & Bridge (1987) in investigating the effect of changing water content on diffusivity in expansive soils. It appears that increase in soil water content replaces air in the soil pores and increases particle to particle contact. Furthermore, at near saturation, a decrease of D was observed. The thermal diffusivity could have been affected by the changes in both $K_t$ and $C_v$, since by definition, thermal diffusivity is a ratio of thermal conductivity and volumetric heat capacity. When a soil is at near saturation, $K_t$ decreases while $C_v$ still increases but more gradually, therefore, D will decrease with further addition of water following the trend reported by Ardiansyah *et al.* (2008).

**Table 4.3** Thermal diffusivity (mm$^2$ s$^{-1}$) of five soil forms at increasing water contents (ANOVA in Table A3)

| Horizon | Soil type | Moderate | Moist | Wet | Near Saturation |
|---|---|---|---|---|---|
| A | **Sw** | 0.443 bcde | 0.541 abcd | 0.575 abc | 0.511 abcde |
| | **Va** | 0.393 de | 0.532 abcde | 0.615 a | 0.602 ab |
| | **Se** | 0.615 a | 0.630 a | 0.664 a | 0.550 abcd |
| | **Ar** | 0.415 cde | 0.426 cde | 0.522 abcde | 0.403 de |
| | **Bo** | 0.432 cde | 0.518 abcde | 0.504 abcde | 0.370 e |
| | | | LSD 0.169 | | |
| B | **Sw** | 0.500 bcde | 0.542 abcd | 0.551 abcd | 0.507 bcde |
| | **Va** | 0.460 de | 0.475 de | 0.514 abcd | 0.477 cde |
| | **Se** | 0.634 abc | 0.648 ab | 0.666 a | 0.567 abcd |
| | **Ar** | 0.435 de | 0.474 de | 0.474 de | 0.430 de |
| | **Bo** | 0.551 abcd | 0.429 de | 0.422 de | 0.354 e |
| | | | LSD 0.158 | | |
| C | **Sw** | 0.516 defg | 0.638 abc | 0.672 ab | 0.591 bcd |
| | **Va** | 0.379 i | 0.410 hi | 0.588 cde | 0.532 def |
| | **Se** | 0.554 cde | 0.644 abc | 0.692 a | 0.506 defg |
| | **Ar** | 0.426 ghi | 0.485 efgh | 0.585 bcd | 0.483 efgh |
| | **Bo** | 0.176 j | 0.260 j | 0.510 defg | 0.442 fghi |
| | | | LSD 0.092 | | |

For each horizon, means followed by different letters are significantly different according to LSD at ($P<0.05$)

*Moderate = 0.15 – 0.20 mm$^3$ mm$^{-3}$; moist = 0.21 – 0.25 mm$^3$ mm$^{-3}$; wet = 0.26 – 0.30 mm$^3$ mm$^{-3}$; near saturation ≥ 0.31 mm$^3$ mm$^{-3}$

## 4.4 Conclusion

In this study, the main objective was to investigate the effect of changing water contents, at room temperature, on thermal properties including thermal conductivity, volumetric heat capacity and thermal diffusivity of selected expansive soils in Land Type Dc17, South Africa.

It was observed from the results that thermal conductivity and diffusivity increased with water contents until wet conditions, where after further water increase lead to a decline in both properties, although the effect was not significant for all soil forms. In contrast, volumetric heat capacity was observed to constantly increase with water increasing from moderate to near saturation.

In conclusion, thermal properties of the selected expansive soils showed water content dependence. The behaviour of the soil forms differed although they are all classed as expansive soils. It cannot be said with certainty whether, at each specific water level, the differences were caused by mineralogical composition or a difference in water content, since the study did not employ exact water content, but ranges (so at a certain range soils did not have exactly the same water content). If one wants to determine the effect of soil water content on thermal properties more precisely, it is advisable to thoroughly control water content, since even the slightest change in water can cause a volume change in expansive soils as mentioned in the literature review. This can help improve results in the future.

# CHAPTER 5. EFFECT OF TEMPERATURE ON THERMAL PROPERTIES OF EXPANSIVE SOILS

## 5.1 Introduction

The capability of soil to transfer heat is greatly influenced by its thermal properties. These properties affect the temperature of the soil, the heat under and around engineering structures and thermal radiation from the soil (Ross & Bridge, 1987). Research has shown that thermal properties of soils are not only affected by soil type, mineralogy, bulk density, porosity and water content, but also by temperature (Kersten, 1949; Willis & Raney, 1971; Sawada, 1977; Farouki, 1981; Sakaguchi *et al*, 2007; Mengistu *et al.* 2017). Willis & Raney (1971), Sawada (1977), Farouki (1981) and Sakaguchi *et al*. (2007) found an increase in thermal conductivity and/or diffusivity with every unit of temperature increase in a wide range of soils. This can be explained by the fact that water migration and particle contact is improved by increasing temperatures. Furthermore, the effect of temperature on thermal properties of a soil may also be affected by the amount of water in the soil (Kersten, 1949; Mengistu *et al.*, 2017).

Although there is ample literature available on different aspects of expansive soils, little has been published on thermo-physical properties of these soils. Studies that are available, however, concentrate on effects of bulk density, porosity and water content on thermal properties, while the possible effect of temperature has been largely neglected.

As a result, this study intended to contribute to the current limited knowledge on thermal properties of expansive soils. The objective was to determine the effect of a range of temperatures on thermal conductivity, volumetric heat capacity and thermal diffusivity of selected expansive soils in Land Type Dc17, under moist soil water conditions.

## 5.2 Materials and methods

### 5.2.1 Field description

The soil samples were collected on Land Type Dc17, located east of Bloemfontein in the Free State Province of South Africa. The location and soil descriptions of the five soil forms are given in Chapter 3 of this thesis.

### 5.2.2 Sample preparations and thermal properties determination

Only the moist soil samples (21 – 25 $mm^3 mm^{-3}$) from Chapter 5 were used in this study. These samples were specifically chosen to provide the best chance of observing a temperature effect on thermal properties, since this effect may be negligible at very dry or saturated conditions. After sampling, the specimens were transported to the laboratory wrapped with plastic cling film to avoid evaporation. The samples were then subjected to five different temperature treatments: 0°C and 10°C in a cold room, 25°C, 40°C and 60°C in a temperature regulated oven, starting at the lowest temperature to the highest. At every temperature, the specimens were stored for two nights prior to measuring the thermal properties. During storage the samples were turned twice a day to allow even distribution of water.

The thermal properties (thermal conductivity, specific heat capacity and thermal diffusivity) were determined using the KD2 Pro thermal properties analyzer, developed by Decagon devices as described in Chapter 5.

### 5.2.3 Statistical analyses

The collected data of the five soil forms were subjected to analysis of variance (ANOVA) using SAS software version 9.4 (SAS Institute, 2013). The fundamental thermal properties means were separated by the LSD procedure (Fischer) at alpha level 5%.

## 5.3 Results and discussion

### 5.3.1 Thermal conductivity ($K_t$)

In all three horizons, temperature significantly affected $K_t$ on five soil forms (Table 5.1). The ANOVA revealed that there was a significant interaction between soil form and temperature, implying that the effect of temperature on $K_t$ depended on the individual soil type.

In horizon A, there was general trend of $K_t$ increasing with increasing temperature from 0 to 60˚C. For Swartland, Valsrivier and Bonheim soil forms, the increase was statistically significant, while for Sepane and Arcadia the increase was not significant. For horizon B, there was drop in $K_t$ from 0 to 10˚C for all the soil forms although this drop was not significant. This was followed by a gradual increase in $K_t$ from 10 to 60˚C that was significant for all the soil forms except Acardia. Horizon C followed the same pattern as horizon B, however, the decrease in $K_t$ from 0 to 10˚C was significant for Sepane, Arcadia and Bonheim. The increase in $K_t$ from 10 to 60˚C was significant for all the soil forms.

**Table 5.1** Thermal conductivity (W $m^{-1}$ $K^{-1}$) of five soil forms at increasing temperature (ANOVA in Table A4)

| Horizon | Soil type | Temperature (°C) | | | | |
|---|---|---|---|---|---|---|
| | | 0 | 10 | 25 | 40 | 60 |
| A | Sw | 0.885 g | 1.082 efg | 1.243 bcdef | 1.303 abcde | 1.378 ab |
| | Va | 1.194 cbdef | 1.270 abcdef | 1.266 abcdef | 1.377 abc | 1.382 a |
| | Se | 1.187 bcdef | 1.297 abcde | 1.320 abcd | 1.342 abcd | 1.314 abcd |
| | Ar | 0.916 fg | 1.052 fg | 1.159 cdef | 1.129 cdef | 1.142 cdef |
| | Bo | 1.000 fg | 1.093 defg | 1.111 defg | 1.170 bcdef | 1.240 bcde |
| | | | | LSD 0.139 | | |
| B | Sw | 1.309 cdef | 1.275 defg | 1.275 defgh | 1.391 abc | 1.405 abc |
| | Va | 1.194 efghi | 1.113 ij | 1.166 ghi | 1.391 abc | 1.415 ab |
| | Se | 1.173 ghi | 1.114 hij | 1.246 efgh | 1.471 a | 1.447 a |
| | Ar | 1.174 ghi | 1.122 hij | 1.151 ghij | 1.214 efghi | 1.212 efghi |
| | Bo | 1.194 fghi | 1.081 ij | 1.163 ghi | 1.260 efgh | 1.324 bcde |
| | | | | LSD 0.101 | | |
| C | Sw | 1.391 c | 1.390 c | 1.409 bc | 1.531 ab | 1.563 a |
| | Va | 1.210 ef | 1.199 f | 1.330 cde | 1.350 cde | 1.314 de |
| | Se | 1.385 cd | 1.250 ef | 1.461 bc | 1.508 ab | 1.395 c |
| | Ar | 1.222 ef | 1.061 hi | 1.261 ef | 1.358 cde | 1.370 cde |
| | Bo | 1.098 fghi | 0.873 j | 1.019 i | 1.095 ghi | 1.124 fgh |
| | | | | LSD 0.117 | | |

For each horizon, means followed by different letters are significantly different according to LSD ($P<0.05$)

Kersten (1949) and Farouki (1981) reported a decline in $K_t$ from freezing to thawing temperatures for a wide range of soils. In the current study such a decrease from 0 to 10 ˚C was only evident in horizon B and C (although not always significant), but not in horizon A. This is possibly because the temperatures in this study was not low enough to have caused an effect in all samples, since other studies monitoring the freezing and thawing effect on $K_t$ had temperatures lower than -5˚C. Higher $K_t$ values at freezing point can mainly be attributed to phase change, since $K_t$ of ice is four times higher than that of water (Farouki, 1981). In addition, the water that is strongly held in fine grained soils remain unfrozen even at temperatures as low as -40°C, this water is believed to have an important effect in improving the thermal contact between soil skeleton and the frozen free water (Pavlova, 1970).

The increase of $K_t$ of expansive soils with increasing temperature in this study is in line with what was reported by Farouki (1981) and Hiraiwa & Kasubuchi (2000) for clay soils and Mengistu *et al.* (2017) for sandy soils. The range of $K_t$ values observed in the current study is comparable to what has been found with other clay soils (Hiraiwa & Kasubuchi, 2000), while it is considerably lower than $K_t$ measured for sandy soils (Mengistu, 2017). This is in accordance with what has been reported by Hillel (2004), that sandy soils have higher $K_t$ than clay soils under moist conditions. The temperature dependence of $K_t$ is accredited to transfer of latent heat. It has been found that $K_t$ of the mineral fraction is independent of temperature, only the conductivity of water increases with temperature (Campbell *et al*., 1988). With an increase in temperature, water molecules experience molecule-soil particle collision. The frequency at which the water molecules and soil particles collide increases and liberates more latent heat through condensation at the water film surrounding the soil particles and results in an increase of $K_t$ (Cass *et al*., 1984).

### 5.3.2 Volumetric heat capacity ($C_v$)

The results of $C_v$ for five soil forms (with 3 horizons) subjected to different temperatures are summarized in Table 5.2. The ANOVA showed that there was a significant interaction between soil form and temperature, so all the soil forms was not affected in the same way by increasing temperature.

**Table 5.2** Volumetric heat capacity (MJ $m^{-3}$ $K^{-1}$) of five soil forms at increasing temperature (ANOVA in Table A5)

| Horizon | Soil type | Temperature (°C) | | | | |
|---|---|---|---|---|---|---|
| | | **0** | **10** | **25** | **40** | **60** |
| A | **Sw** | 2.288 abcd | 2.029 bcd | 2.088 bcd | 2.241 abcd | 2.159 abcd |
| | **Va** | 2.722 a | 2.282 abcd | 2.095 bcd | 2.193 abcd | 2.318 abcd |
| | **Se** | 2.155 abcd | 1.799 d | 2.117 abcd | 1.896 cd | 1.861 cd |
| | **Ar** | 2.640 ab | 2.295 abcd | 2.562 ab | 2.590 ab | 2.619 ab |
| | **Bo** | 2.464 abc | 2.305 abcd | 2.305 abcd | 2.434 abc | 2.323 abcd |
| | | | | LSD 0.622 | | |
| B | **Sw** | 2.597 abc | 2.247 bc | 2.248 abc | 2.362 abc | 2.458 abc |
| | **Va** | 2.715 a | 2.562 abc | 2.638 abc | 2.660 abc | 2.728 a |
| | **Se** | 2.706 ab | 2.234 abc | 2.470 abc | 2.670 ab | 2.577 abc |
| | **Ar** | 2.493 abc | 2.205 abc | 2.543 abc | 2.273 abc | 2.180 abc |
| | **Bo** | 2.454 abc | 2.080 c | 2.688 abc | 2.323 abc | 2.229 abc |
| | | | | LSD 0.570 | | |
| C | **Sw** | 3.024 abc | 2.516 defg | 2.516 defg | 3.143 ab | 2.697 bcdef |
| | **Va** | 2.581 cdefg | 2.369 efg | 2.369 efg | 3.443 a | 2.653 cdefg |
| | **Se** | 2.836 bcd | 2.587 cdefg | 2.583 cdefg | 2.725 bcde | 2.696 bcdef |
| | **Ar** | 2.696 bcdef | 2.249 fg | 2.510 defg | 2.725 bcde | 2.575 cdefg |
| | **Bo** | 2.761 bcde | 2.216 g | 2.541 defg | 2.986 bc | 2.420 defg |
| | | | | LSD 0.452 | | |

For each horizon, means followed by different letters are significantly different according to LSD ($P<0.05$)

As temperature was increased from 0 to 10, there seemed to be a decline in $C_v$ in all the horizons for all the soil forms. The decrease was not significant the A and B horizons for any of the soils, but the decrease was significant in C horizon for Swartland and Bonheim. With a further increase in temperature there was a trend of $C_v$ increasing slightly, followed by a decrease at 60. However this trend was not significant in any of the soils.

From literature, it was expected to observe a decline in $C_v$ from freezing to thawing temperatures and then an increase as temperatures rise further. This pattern has been reported for clay soils (Anderson & Morgenstern, 1973; Farouki, 1981) and for sandy soils, without the decrease at high temperatures (Mengistu *et al*., 2017). At freezing phase, moist soil is believed to consist of three phases: frozen soil particles and smaller ice crystals (solid), an unfrozen water film (liquid) and water vapour (gas). In this case the $C_v$ will be the sum of the three components and the latent heat of ice (Anderson & Morgenstern, 1973; Farouki, 1981). During thawing, $C_v$ of the soil will only be that of the gas and liquid components since there is no ice. Furthermore, the increase of $C_v$ with temperature above freezing is explained by the increase of the vibrational energy of the soil particle atoms brought about by increasing temperatures (Mengistu *et al*., 2017). It was further pointed out by Callister (2001) that with every increase of atom vibration, there is an increase in particles ability to store and transmit energy.

### 5.3.3 Thermal diffusivity (D)

In all three horizons, temperature significantly affected D on five soil forms (Table 5.3). The ANOVA revealed that there was a significant interaction between soil form and temperature, indicating the effect of temperature on D depend on the individual soil type.

In horizon A, there was no significant effect of temperature on D from 0 to 10˚C. From 10 to 60 there was a slight, but not significant increase of D. The Valsrivier and Sepane soil forms had the highest D values followed by Swartland, while Arcadia and Bonheim had the lowest. For horizon B, Swartland, Valsrivier and Arcadia soils, the increase in temperature from 0 to 10˚C had no effect. However, Bonheim had a significant increase and Sepane had a significant decrease in D. Further temperature increase generally resulted in slight increase in D. Irrespective of the temperature, Sepane had the highest D. For horizon C, there a slight decrease of D for most of the soils from 0 to 10˚C. Further temperature increase resulted in increase in D which was significant for all the soil forms except Valsrivier. In general, Sepane had the highest D and Bonheim the lowest.

Similar patterns were reported by Farouki (1981) where there is an increase in D for temperatures above freezing point. Farouki (1981) also reported a distinct in D from freezing to thawing temperatures. As mentioned earlier, the temperatures evaluated in the current study were not as low as ones reported by Farouki (1981), hence the freezing thawing effect was not clearly visible. The behaviour of D is attributed to the trends of both $K_t$ and $C_v$, since D is the ratio of thermal conductivity and volumetric heat capacity, therefore, any change in both properties has a direct impact on thermal diffusivity.

**Table 5.3** Thermal diffusivity (mm$^{-2}$ s$^{-1}$) of five expansive soils subjected to increasing temperature (ANOVA in Table A6)

| Horizon | Soil type | Temperature (°C) 0 | 10 | 25 | 40 | 60 |
|---|---|---|---|---|---|---|
| A | Sw | 0.490 abcde | 0.485 abcde | 0.505 abcde | 0.559 abcd | 0.541 abcde |
| | Va | 0.535 abcde | 0.522 abcde | 0.532 abcde | 0.550 abcd | 0.562 abc |
| | Se | 0.515 abcde | 0.538 abcde | 0.569 abc | 0.593 ab | 0.630 a |
| | Ar | 0.402 de | 0.385 e | 0.426 cde | 0.475 abcde | 0.497 abcde |
| | Bo | 0.414 cde | 0.419 cde | 0.421 cde | 0.467 abcde | 0.490 abcde |
| | | | | LSD 0.159 | | |
| B | Sw | 0.420 ghi | 0.495 fgh | 0.638 bcde | 0.643 bcde | 0.578 cdef |
| | Va | 0.376 hi | 0.380 hi | 0.410 ghi | 0.537 defg | 0.526 defgh |
| | Se | 0.866 a | 0.678 bcd | 0.745 ab | 0.680 bcd | 0.722 abc |
| | Ar | 0.512 bcdef | 0.474 fghi | 0.327 l | 0.448 hijkl | 0.586 defg |
| | Bo | 0.376 hi | 0.662 bcd | 0.399 ghi | 0.417 ghi | 0.460 fghi |
| | | | | LSD 0.156 | | |
| C | Sw | 0.500 cdefgh | 0.458 efghij | 0.465 efghij | 0.542 bcdef | 0.583 abcd |
| | Va | 0.454 fghij | 0.422 ghijk | 0.552 cdefgh | 0.475 efghi | 0.484 defghi |
| | Se | 0.585 abc | 0.496 cdefgh | 0.518 cdefg | 0.648 a | 0.630 ab |
| | Ar | 0.353 ghi | 0.390 ijk | 0.417 hijk | 0.474 efghi | 0.554 abcde |
| | Bo | 0.323 kl | 0.281 l | 0.324 kl | 0.369 jkl | 0.425 ghij |
| | | | | LSD 0.099 | | |

For each horizon, means followed by different letters are significantly different according to LSD at ($P<0.05$)

## 5.4 Conclusion

The study was conducted to observe the effect of temperature, under a constant range of soil water on thermal properties, including thermal conductivity, volumetric heat capacity and thermal diffusivity of selected expansive soils in Land Type Dc17, South Africa.

In general, the study managed to explain the impact of temperature by grouping two temperature categories: freezing to thawing (0 to 10˚C) and increasing temperature (10 to 60˚C). In horizon A there was a non-significant increase of $K_t$ from 0 to 60. In horizon B and C, $K_t$ decreased insignificantly while in horizon C the decrease was significant. In general, $K_t$ in expansive soils was in the same range as other clay soils. For $C_v$, horizon A, B and C tend to decrease from 0 to 10 although most of the soils the decrease was not significant. Further increase of temperature show a slight drop at 60 although it was not significant. Regarding D, for horizon A, there was a slight increase with temperature in all soil forms while for horizon C, there was a slight drop of from 0 to 10 followed by an increase with increasing temperatures. As for horizon B, there were some discrepancies with the results.

In conclusion, thermal properties of the selected expansive soils showed temperature dependence and the pattern followed was similar to what has been found with other soil types. It is clear that studying similar soil types does not imply exactly similar behaviour. Therefore, it is advisable to thoroughly study the mineral composition concurrently in order to improve the results.

# CHAPTER 6. CHARACTERIZING SOIL TEMPERATURE REGIMES UNDER A LOW-COST HOUSE AND BARE SOIL

## 6.1 Introduction

Soil temperature depends on the ratio of energy absorbed and lost from the soil, which fluctuates annually, daily and hourly due to air temperature as well as radiant energy (Onwuka, 2016). This parameter is affected by the soil covering since surface cover may obstruct radiation and have an isolation effect – influencing the soil temperature underneath. A number of studies have reported on the response of soil temperature under different surface covers. For example, Oliver *et al.* (1987), Rodskjer *et al*. (1989) compared vegetation covered areas with bare soil, while Decker e*t al.* (2003), Zhang *et al.* (2003) and Alves & Soares (2016) focused on snow covered soils. Halverson & Heisler (1981), Eusuf & Asaeda (1998), Adjali *et al.* (1998; 2000), Zheng & Braun (2007), Lapisa (2013) and Wu *et al.* (2014) monitored and modelled soil temperature in areas covered by pavements and concrete slabs exposed to sunlight. Most of the studies on soil temperature under buildings have been done in colder climates, for example Dawson & Fisher (1963) in Wairakei, New Zealand, and Adjali *et al.* (2000) in Wales. Few recent studies have reported on this aspect in warmer climates, only a study by Parker *et al.* (2016) in Florida, US, was available. Less is known on this important parameter under built structures in Southern Africa, specifically for expansive soils in the central parts of South Africa, with its semi-arid temperate climate.

Most studies on expansive soils have focused on the effect of changing water content and how this affects constructed buildings in South Africa (Pidgeon, 1987; Pidgeon & Pellissier, 1987; Bester *et al*., 2016). The possible role of soil temperature, as a driving force of water migration in these soils, have apparently been neglected. This study was conducted in an attempt to quantify soil temperature under a basic house with a concrete floor, compared to uncovered soil in an expansive soil profile. This was accomplished by using air temperature as a reference to firstly evaluate soil temperature for a typical day in each season and secondly, to monitor the seasonal evolution of temperature in the soil profile and its variation with depth.

## 6.2 Materials and methods

### 6.2.1 Site description

***Location*:** The study was conducted at Botshabelo (29° 41'44 E, 29° 12'35 S), Figure 3.1, approximately 60 km east of Bloemfontein in the Mangaung Metropolitan Municipality, South Africa, for a period of two years (1st September 2014 to 31st August 2016).

The altitude of the study area is 1 425 m above sea level in a mid-slope terrain unit. The slope percentage is 0.1 with a south-east aspect.

***Climate***: The area is classified as a semi-arid region with cold, dry winters and rainy summers. The mean annual rainfall is 573 mm with the highest monthly average (71 mm) during February and the lowest (2 mm) in July. The average maximum temperatures of the area range from 17.7°C in July to 30.9°C in January. The lowest average minimum temperatures are recorded during July, at 1.9 °C (SAWS, 2017).

***Soil***: The soil form at the experimental site was classified as Sepane of the Katdoorn family (1210), a moderately expansive soil. A detailed description of this soil is presented in Chapter 3 Section 3.3.1.

***House structure and control site:*** The house used in this study forms part of the government-funded social housing project, with dimensions of 8 m x 7 m. The house is built with concrete bricks and roofed with corrugated iron roofing sheets without a ceiling, making it cold in winter and hot during summer. The foundation is a typical raft foundation and the floor a concrete slab, approximately 7.5 mm thick (standard thickness from the Department of Human Settlement). Adjacent to the house, an open plot was marked out as a control site. The control site was exposed to direct sunlight for most of the day and was kept clear of weeds with herbicide for the study period.

**Figure 6.1** Selected low-cost governmental subsidy house in Botshabelo.

### 6.2.2 Description of measuring instrument

Soil temperatures were measured with DFM capacitance probes (DFM Software Solutions, South Africa). These probes collect both soil water and temperature data simultaneously. Soil temperature is measured indirectly by relating the resistance of the conductor to temperature. The accuracy of the sensors to measure temperature is ±0.06°C (Mjanyelwa *et al*., 2016). Temperature data is collected at selected time intervals that can range from a minute to a day, and can be stored for more than 60 days. The device can withstand harsh climatic conditions due to a PVC cap protecting the electronics (DFM Software Solutions, 2016). Prior to commencement of this study, capacitance probes were calibrated in the laboratory for measuring temperature in order to improve the accuracy of data collected by the probes. Two sets of DFM probes were used, one set for testing the performance of the temperature sensors and another set to evaluate the derived calibration curve. The probes were generally accurate and constant in their performance. The detailed methodology and results of the calibration are reported in a recently published article (Mjanyelwa *et al.,* 2016) provided in Appendix B.

### 6.2.3 Description and layout of experiment

To measure soil temperature underneath the house, seven capacitance probes were installed in north-south and east-west transects (Figure 6.3). The probes were installed by drilling through the concrete floor, creating a shaft down the soil profile. To prevent the probe heads from being damaged, an 11 cm (length) x 7.7 cm (diameter) piece of PVC pipe was inserted into each hole in the concrete floor. After insertion of the probes an expanding foam filler was sprayed into the gap between the PVC pipe and the probe head (Figure 6.2). The probes were installed to a meter depth with temperature sensors positioned at 0.10, 0.20, 0.40, 0.60, 0.80 and 1 m depth in the soil underneath. Soil temperature was recorded on an hourly basis over the two year period and was downloaded once a month by a data logger (DFM logger model 5.01) for further analysis.

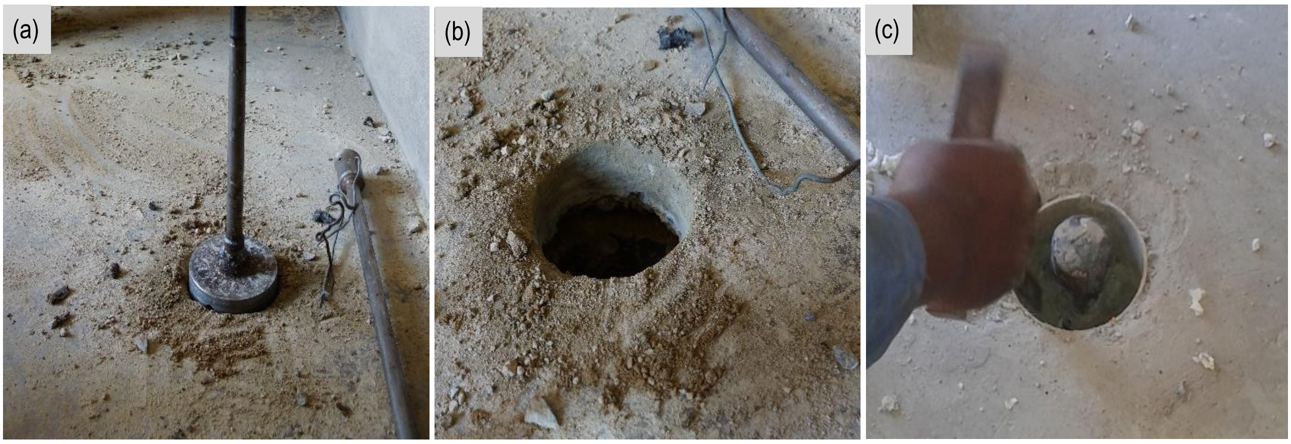


**Figure 6.2** (a) Drilling into the concrete floor slab, (b) shaft for capacitance probe, (c) the installation of a capacitance probe.

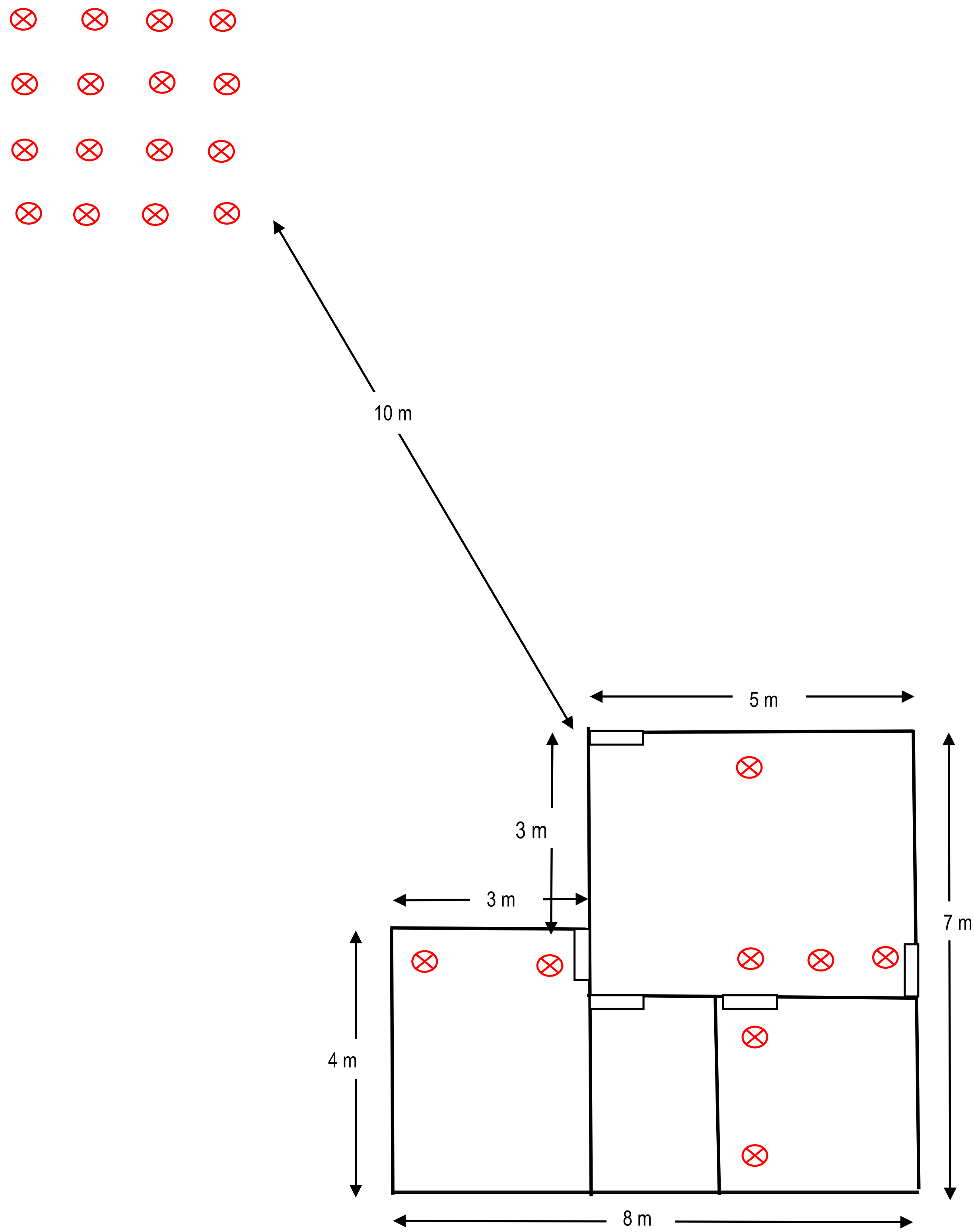


**Figure 6.3** Schematic representation of the probes installed under the house concrete floor slab and the control site.

As mentioned, a bare, uncovered area adjacent to the house was selected as a control site for measuring soil temperatures (Figure 6.3). Here, 16 probes were installed in a fenced off 4 x 4 m area with spaces of 1 m between probes. To protect the probes from harsh environmental conditions, steel caps were engineered to cover the heads. Out of the 16 probes, data from only seven probes were used in order to ensure an equal number of replications between the house and the control site. Depth of installation and sensor positions, as well as data recording on an hourly basis, were identical to the probes installed in the house.

### 6.2.4 Temperature data processing and statistical analyses

Average air temperature for the study period was used as a reference point. Air temperature data were obtained from the nearest automatic weather station in Bloemfontein about 50 km from the study site, managed by the South African Weather Service (SAWS). The data were processed to present the air temperature trend for the period of two years. In order to select typical days in terms of temperature for each season, the average air temperature for each season was first calculated: September to November for spring, December to February for summer, March to May for autumn, and June to August for winter. In each season, days were screened and the day closest to the average temperature of the particular season was chosen as a typical day to represent that season. The typical day representing a season (air temperature) was used to select the corresponding day for soil temperature data. Days with average soil temperature 1°C above or below the soil temperature of the typical day were extracted in each season. The created group of days was further screened to include days with soil temperature similar or 0.5°C above/below the chosen typical day. From this group, eight days (4 each year) were randomly chosen to represent each season. These eight replications improved the accuracy of the analyses.

To study the diurnal temperature cycle for each season, hourly averages were calculated from the replications to create graphs of the daily temperature cycles. The following statistics were then calculated from the hourly soil temperature data under the house and the control site as an average over the entire profile: daily average temperature, daily maximum and minimum temperatures for each season. Furthermore, the day warming (from 06:00 to maximum temperature), day cooling (maximum to 18:00), as well as night cooling (18:00 to minimum) rates were determined. Peak-trough fluctuation analysis was used to compare the daily temperature variation of the two surface treatments. Daily average temperatures of the selected days were subjected to analysis of variance (ANOVA) using SAS software version 9.4 (SAS Institute, 2013), and the means were separated using the LSD procedure (Fischer) at alpha level 5%.

To study seasonal temperatures, the raw data was used to calculate average seasonal soil temperature distribution in a profile of 0.8 m and at individual depths of 0.1, 0.2, 0.4, 0.6 and 0.8 m. A t-test was employed to compare the difference between the seasonal averages of the two surface treatments.

## 6.3 Results and discussion

### 6.3.1 Diurnal temperature cycle

The results for air and soil temperature in a typical day in spring, summer, winter and autumn are presented in Table 6.1 as well as in Figure 6.4. Air temperature exhibited three distinct phases for all seasons. Phase 1 represents the radiant warming period, commencing at about 6:00 (taken as arbitrary sunrise for all seasons) and continues towards its maximum at 14:00, 12:00, 15:00 and 16:00 hours for spring, summer, autumn and winter, respectively (Table 6.1). The calculated warming rates were found to differ between seasons with summer having the highest warming rate, followed by spring, autumn and winter as expected. Phase 2 was identified by a rapid drop in temperature, beginning from the maximum temperatures until approximately 18:00 (taken as arbitrary sunset for all seasons). Here, winter days cooled down more rapidly, followed by autumn, spring and lastly summer. The third phase was the night cooling phase where air temperature gradually decreased from approximately 18:00 and reached its minimum towards 06:00 the following morning. Despite having the same general temperature response pattern, the seasons had different time durations from arbitrary sunrise to maximum and minimum temperatures. As mentioned earlier, air temperature was used as reference point to compare soil temperature response under two surface treatments (bare soil and a house) over a period of 24 hours for the mentioned seasons.

Regarding daily evolution of soil temperature in correspondence with air temperature, the results indicated that temperature in bare soil followed the same pattern of the three phases as air temperature, but with a decreased amplitude and phase shift (Figure 6.4). Similar to air temperature, phase 1 began at about 6:00 but maximum temperatures were reached 2 hours later for spring, summer, autumn and 1 hour later in winter. Summer had the highest warming rate followed by spring and winter, while autumn had much lower rates (Table 6.1).

Phase 2 commenced later than for air temperature, it started after midday for summer and towards sunset for spring, autumn and winter with summer having the highest cooling rate and winter the lowest. Phase 2 in bare soil continued until past midnight (clearly visible in Figure 6.4 a and b) as opposed to air temperature where it continued from midday to 20:00. Although it was difficult to visually notice from the graphs, especially for winter and autumn, phase 3 commenced just after midnight until sunrise with winter and autumn having the lowest night cooling rate.

**Table 6.1** Daily average, minimum, maximum, sunrise and sunset temperatures and the corresponding warming and cooling rates of a soil profile average under two surface treatments

| | | Soil temperature (°C) | | | | | | | Warming/cooling rates (°C hr $^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Maximum | | Minimum | | | | Day | Day | Night |
| **Season** | **Treatment** | **Average** | **Temperature** | **Time** | **Temperature** | **Time** | **06:00** | **18:00** | **warming** | **cooling** | **cooling** |
| | *Air* | *19* | *28* | *2pm* | *12* | *6am* | *12* | *24* | *2.04* | *-0.7* | *-1.1* |
| Spring | Bare soil | 19.25 b | 20.45 c | 4pm | 17.88 c | 7am | 18 | 20 | 0.23 | -0.13 | -0.18 |
| | House | 20.22 b | 20.28 c | 7pm | 20.16 b | 11am | 20 | 20 | 0.005 | -0.006 | -0.007 |
| | *Air* | *24* | *33* | *12pm* | *15* | *5am* | *16* | *31* | *2.8* | *-0.2* | *-1.5* |
| Summer | Bare soil | 25.48 a | 26.50 a | 2pm | 23.78 a | 6am | 24 | 26 | 0.34 | -0.14 | -0.18 |
| | House | 24.09 a | 24.14 b | 5pm | 24.07 a | 9am | 24 | 24 | 0.003 | -0.030 | -0.001 |
| | *Air* | *17* | *26* | *3pm* | *9* | *6am* | *9* | *21* | *1.90* | *-1.4* | *-1.1* |
| Autumn | Bare soil | 16.19 c | 16.53 d | 5pm | 15.74 d | 7am | 16 | 16 | 0.07 | -0.09 | -0.05 |
| | House | 20.72 b | 20.78 e | 7pm | 20.68 b | 9am | 21 | 21 | 0.004 | -0.088 | -0.001 |
| | *Air* | *10* | *20* | *4pm* | *1* | *6am* | *1* | *15* | *1.84* | *-1.8* | *-1.2* |
| Winter | Bare soil | 8.21 d | 8.72 e | 5pm | 7.60 e | 7am | 7 | 8 | 0.09 | -0.11 | -0.08 |
| | House | 15.80 c | 15.81 d | 9pm | 15.79 d | 12pm | 14 | 14 | 0.002 | -0.007 | -0.001 |
| LSD | | 1.83 | 1.88 | | 1.79 | | | | | | |

Means in each column followed by different letters are significantly different according to LSD $_{(0.05)}$,

Air temperature was not part of the analyses as it was used as a reference point.

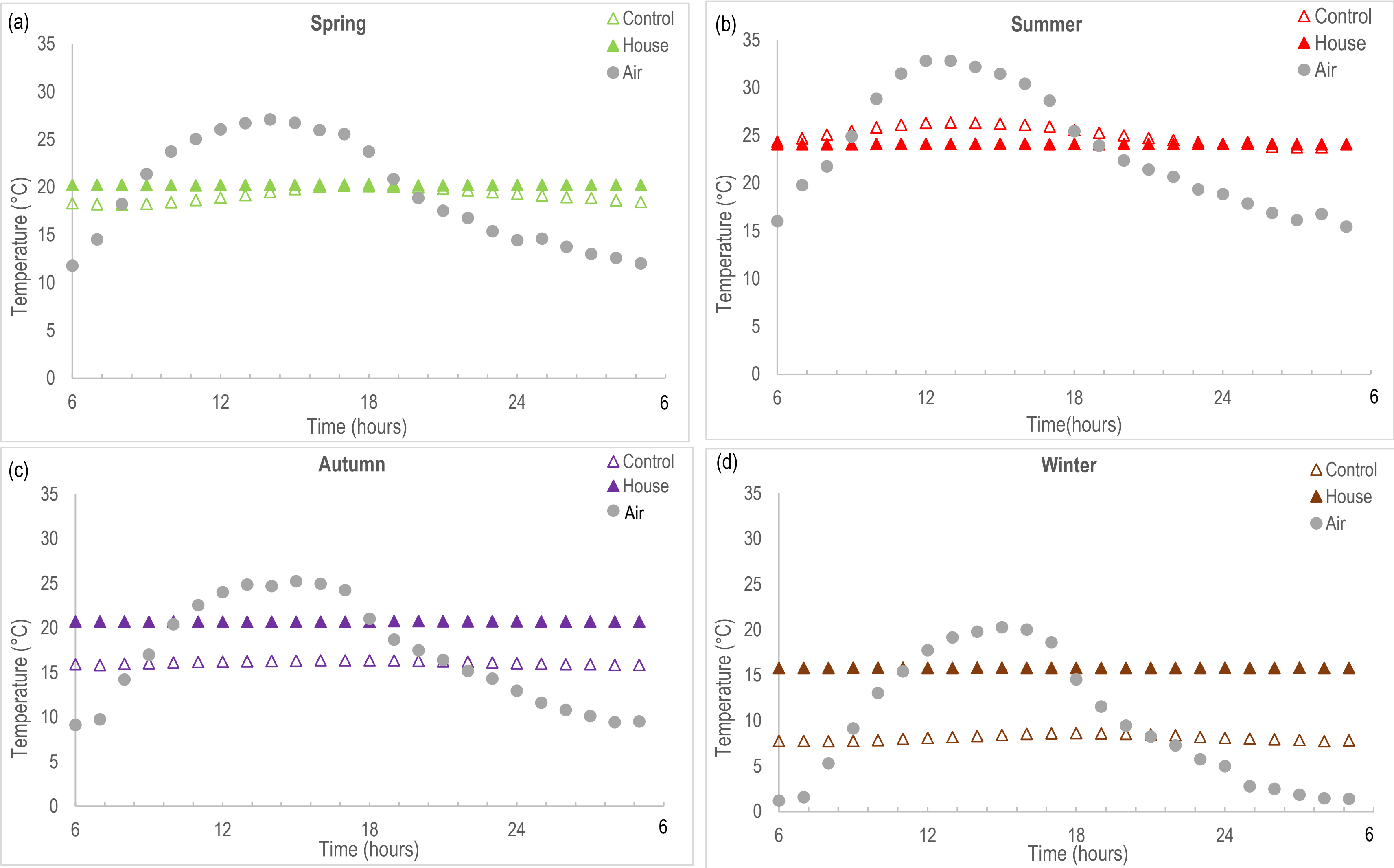


**Figure 6.4** Average hourly air and soil profile temperatures over a typical (a) spring, (b) summer, (c) autumn and (d) winter day.

Analysis of peak-trough fluctuations revealed a significant difference in temperature variation between the bare soil and the house for the period of 24 hours (Table A8, Appendix A). Soil temperature under the house had only slight fluctuations, visually displaying a constant pattern over a 24 hour period in all the seasons (Figure 6.4). The daily temperature variation for the soil profile under the house was only between 0.1 and 0.2°C (Table A8, Appendix A), hence the pattern that was observed for the bare soil was not visible here. Furthermore, the temperature lag was greater under the house than for bare soil in all seasons (Table 6.1). The soil took longer to heat up and cool down underneath the house as compared to bare soil, winter had the longest lag time followed by autumn, spring and lastly summer.

The results further showed that in spring and summer, the average daily soil temperatures were not significantly different, while in winter and autumn the temperature under the two surface treatments were significantly different (Table 6.1). The daily average soil temperatures under the house were found to be significantly higher than in bare soil for both winter and autumn. With regards to maximum temperatures, there was no significant difference between the surface treatments in spring. On the contrary, soil temperatures for summer was significantly lower for under the house, while in autumn and winter the temperature under the house was significantly warmer than for bare soil. With regards to minimum temperatures, for summer the treatments were not different, but in all other seasons soil under the house had significantly higher minimums.

The comparison of the soil temperature response under two surface treatments in the four seasons, highlights the effect of surface cover on soil temperature dynamics. The rate at which soil temperature respond to radiant energy is slow since soil has higher thermal inertia and specific heat capacity as compared to that of air (Florides & Kalogirou, 2005). Because of high thermal inertia and volumetric heat capacity, diurnal soil temperatures lagged behind that of corresponding air temperature in all seasons, except at night. Generally at night, the soil acts as a heat source, having higher temperatures than air (Alves & Soares, 2016).

The diurnal cycle of soil temperature under build structures are seldom reported. Dawson & Fisher (1963) evaluated the temperature fluctuations only for two summer months, the diurnal pattern was similar to that of the current study with lower temperatures measured under the building in summer. For the other seasons, results may be compared to the study of Alves & Soares (2016) investigating diurnal soil temperature variation under snow cover. The mentioned study indicated that soil temperature under covered soils are more stable with smaller amplitudes while higher amplitudes were associated with bare soils.

### 6.3.2 Seasonal soil temperature variation

There was a significant difference between the two surface treatments within seasons over the period of 2 years (Appendix A, Table A9). The average seasonal variation of temperatures in bare soil, under the house and air temperature (as a reference) are graphically shown in Figure 6.5.

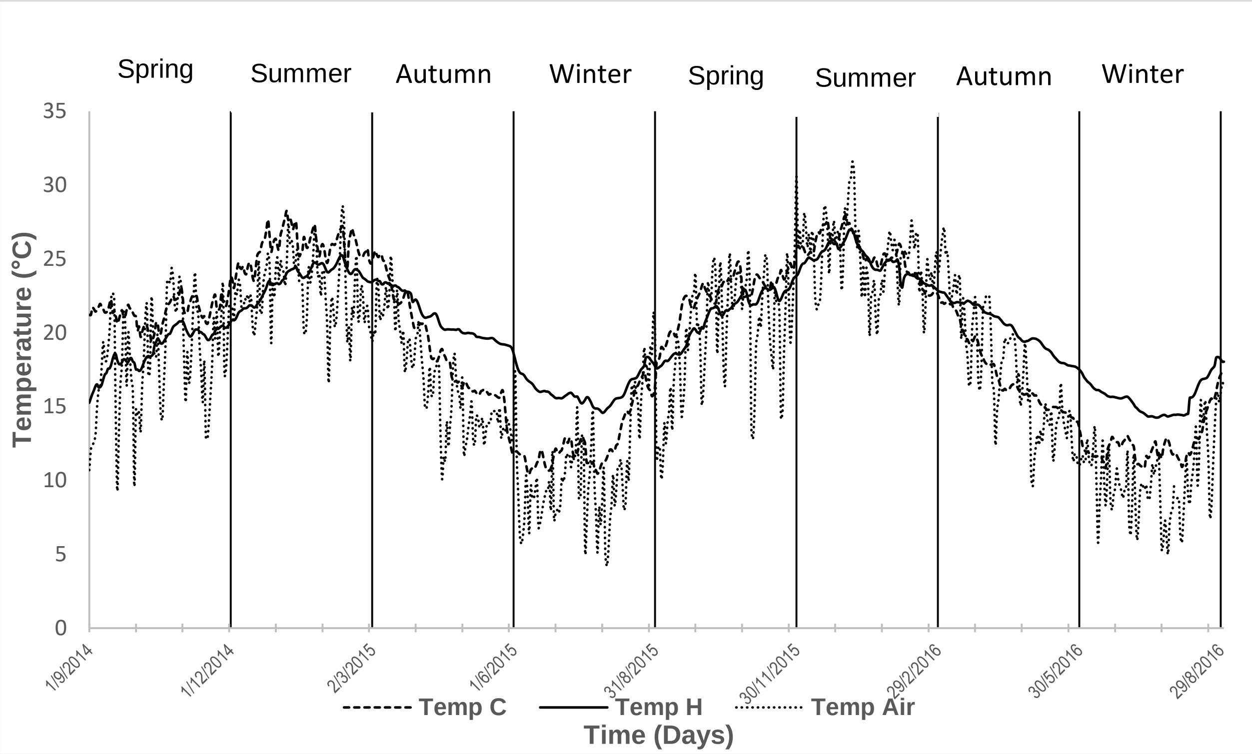


**Figure 6.5** Air and average soil profile temperature in bare soil and under the house for a period of 2 years.

Differences between the two surface treatments are shown in Figure 6.6.

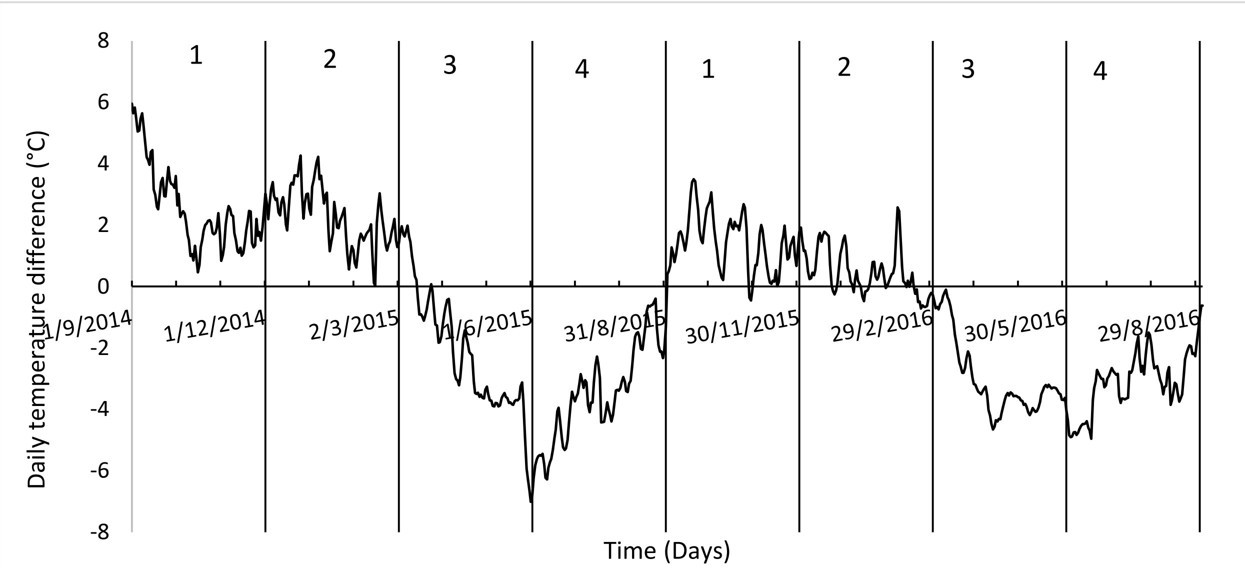


**Figure 6.6** Soil temperature difference between the two surface treatments for a period of two years (1 = Summer; 2 = Autumn; 3 = Winter; 4 = Spring).

The temperature curves of both surface treatments show a similar pattern of a sine wave following the pattern of air temperature. The curves had peaks in summer and in winter, increasing in spring and decreasing in autumn. For both years, temperature under bare soil was slightly higher than that underneath the house in spring and summer. However, in autumn and winter, the surface treatments alternated and temperatures in bare soil were markedly lower than that underneath the house. The two curves intersected in autumn for year 1 (18th March) while in year 2 it intersected earlier, in late summer (19th February). Comparing the two surface treatments, the graphs exhibit that in spring and summer the curves were further apart in year 1 than in year 2. This is also showed by lower temperature differences between the two surface treatments in year 2 (1.4 °C spring and 0.4 °C summer) than in year 1 (2.5 for spring and 2.3 for summer) (Figure 6.6). Bare soil temperatures were more variable (11 to 28°C) and under the house the temperatures were more stable (14 to 25°C). The annual average temperature in bare soil for both years was 19°C, while under the house annual average was slightly higher at 20°C for year 1 and 21°C for year 2 (results not shown).

The differences in soil temperature can be attributed to different surface covers and meteorological elements. The seasonal soil temperature patterns were similar to those of Adjali *et al*. (2000) in Wales and Parker *et al.* (2016) in Florida, US. In both studies, the measuring devices were cemented under the foundation as in the current study. These studies indicated that soil temperature beneath a building declined in winter and increased in summer exhibiting a sinusoidal wave as in the current study. In comparing soil temperature underneath a house to bare soil, Parker *et al.* (2016) found similar patterns to the current study with seasonal temperatures under the house lagging behind the temperature in bare soil. The main contributing factors to difference between two surface treatments are exposure direct sunlight and thermal properties of the surface treatments.

It is generally known that different surface covers have different thermo-physical properties that affect the subsurface soil temperature (Ministry of Construction, 1993; Guan, 2011). Although it is not within the scope of this study, it is of importance to mention the effects of thermo-physical properties of building materials. Building material have higher thermal conductivity and lower heat capacity than soils. This means it absorbs more heat from the environment or solar radiation which is converted to heat, but it does not store heat energy to be transmitted to the soil beneath. Studies where temperature distribution over the area of the building is reported, show that soil temperatures close to the outside walls fluctuate more than in the center of the building, indicating lower energy losses or gains in the center of the building (Parker *et al.*, 2016). Therefore, soil temperature under buildings is primarily determined by heat conducted by foundation walls from the bare soil.

The bare soil in the current study was completely exposed to sunlight conducted radiant energy and propagated the heat down the soil profile, while the concrete slab of the house was not exposed to direct sunlight, the soil underneath was shielded by the construction materials. The soil under the house had a low energy input and the concrete floor acted as an isolating barrier. Hence firstly, the seasonal amplitude in bare soils is larger than temperature beneath the house (Dawson & Fisher, 1963). And secondly, the soil beneath the house is slower to respond to environmental temperature changes, creating a larger phase lag behind air temperature than is observed in bare soil.

### 6.3.3 Soil temperature distribution over depth

At all soil depths, the temperature patterns under both surface treatments show similar sinusoidal waves as the seasonal profile average (Figure 6.7 and 6.8). As expected, temperature curves at 0.10 m had the highest amplitude and at 0.80 m there was a decrease in amplitude, associated with a phase shift. In other words, temperatures near the surface were more variable and responded more to atmospheric changes than temperature at deeper layers.

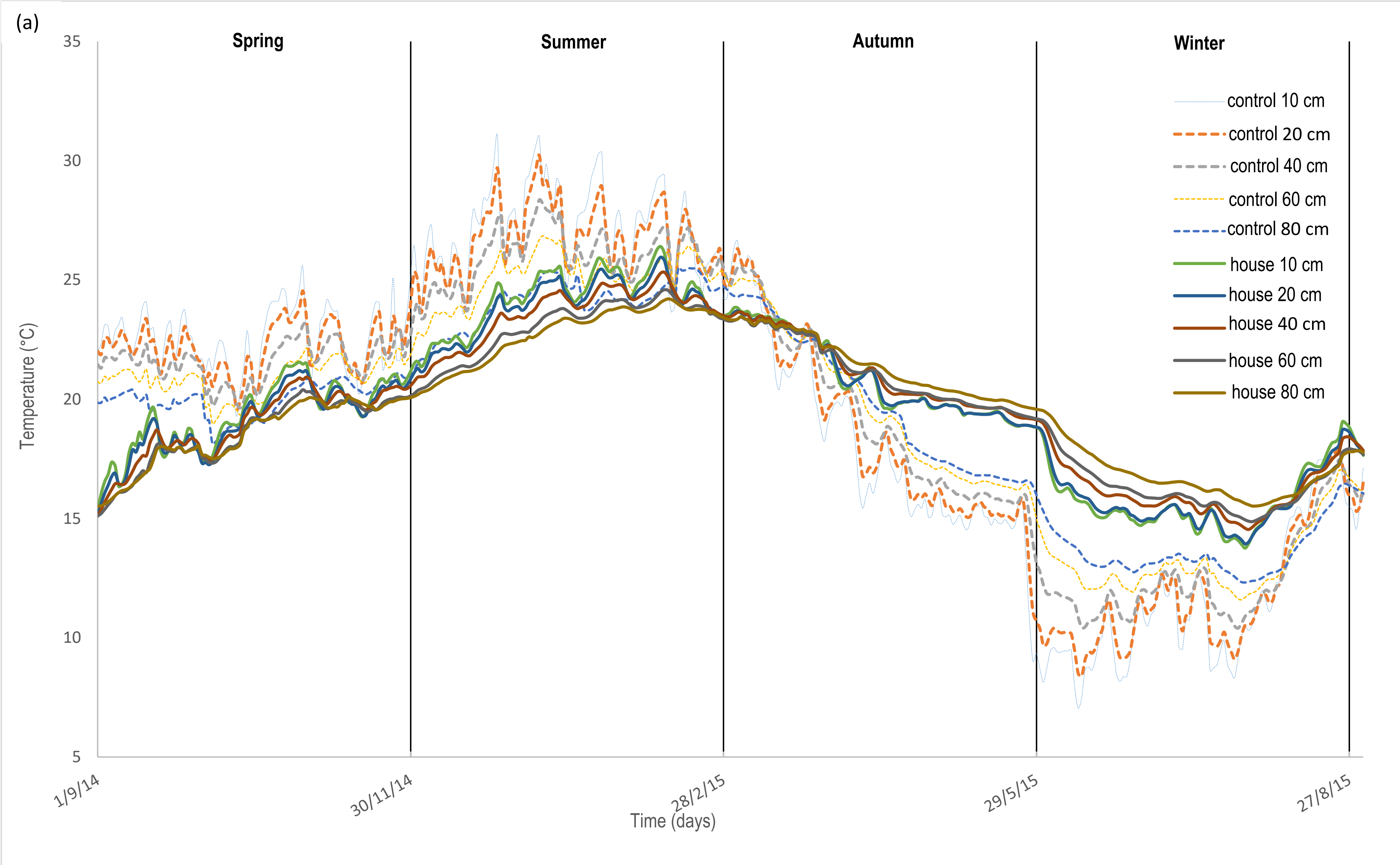


**Figure 6.7** Seasonal soil temperature variation with depth under two surface treatments for year 1 (solid lines are under the house and broken lines in bare soil).

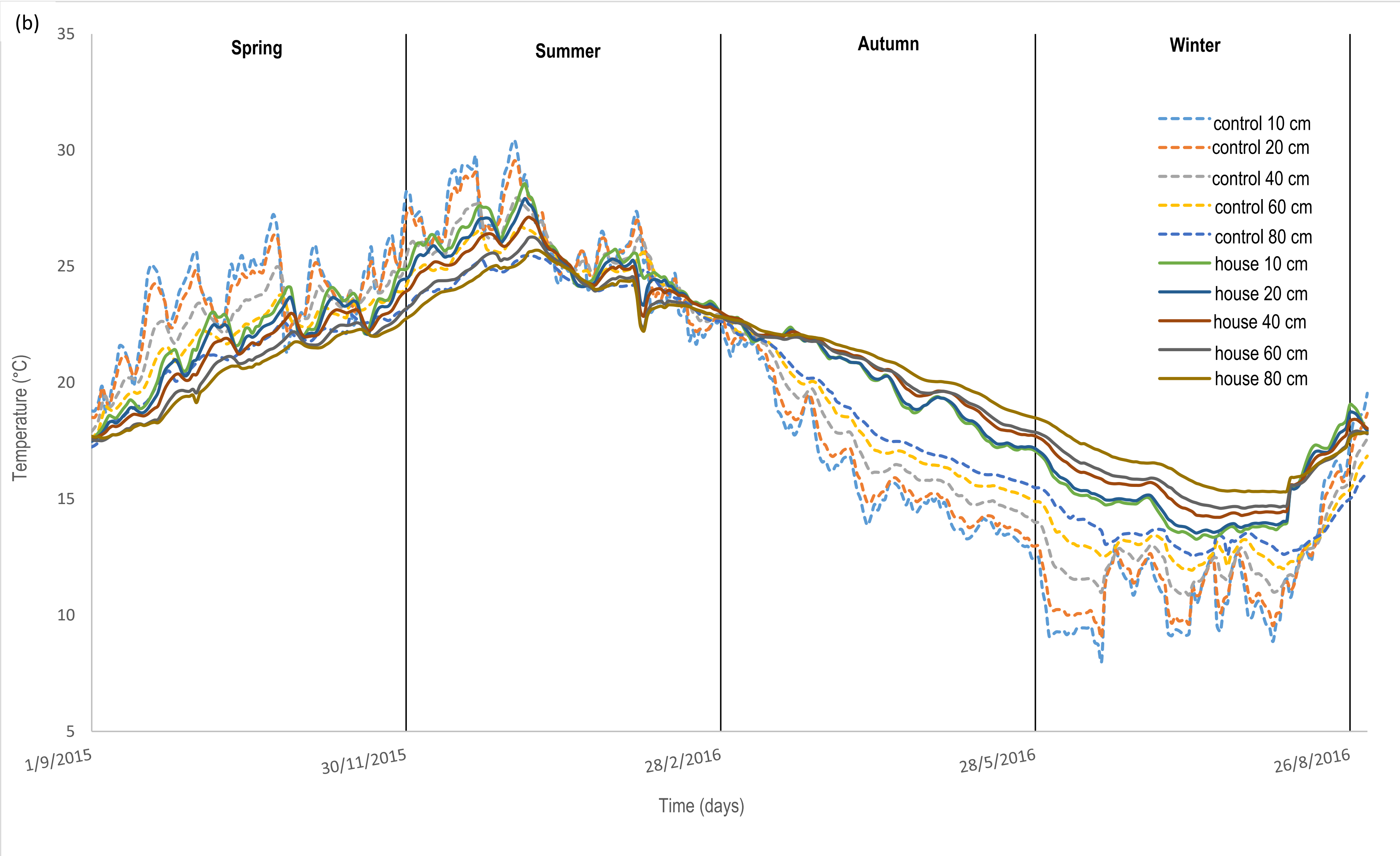


**Figure 6.8** Seasonal soil temperature variation with depth under two surface treatments for year 2 (solid lines are under the house and broken lines in bare.

At all depths, variation was more pronounced in the bare soil than beneath the house. In spring and summer, the temperatures decreased with depth, while in winter and autumn the temperatures increased down the soil profile regardless of the surface cover. At all depths, temperatures in bare soil were higher than underneath the house in spring and summer, but lower in autumn and winter as was the case for the average profile temperatures.

The soil temperature variation with time at different depths offers understanding of heat energy exchange between the soil surface and the atmosphere. In studying temperature variation over depth for bare soils, Holmes *et al.* (2008), Jin & Mullens (2014) and Wu *et al.* (2014) had similar results as the current study. It was reported that incoming radiation mostly exceeded the soil's capacity to transport heat energy from the surface area of the soil, therefore the surface layers will consequently undergo a large, but temporary, increase or decrease in temperature with fluctuating climatic conditions.

The higher temperature under the house for winter and autumn, and lower temperatures in summer and spring, is consistent with findings of William & Gold, (1976), Dawson & Fisher (1963), Adjali *et al. (*2000) and Parker *et al.* (2016) under buildings and Wu *et al.* (2014) under concrete pavement**.**

## 6.4 Conclusion

The study was conducted to characterize the diurnal and seasonal evolution of soil temperature underneath a basic house in comparison to bare soil, for the profile average and at different depths. On a daily basis, irrespective of the season, soil temperature in bare soil followed the air temperature trend, but with decreased amplitude accompanied by a phase shift. Temperature under the house was less variable. In comparison of the two surface treatments, hourly soil temperature under the house was higher than in bare soil for autumn and winter throughout the day, but lower at night in summer and spring. Seasonally, soil temperatures in spring and summer were higher and more variable in bare soil than under the house, but winter and autumn soil temperatures in bare soil were lower and still showed more variation. Considering the soil temperature with depth, there was a decrease in amplitude with depth for both surface treatments. At any depth, temperature variation was greater in bare soil. Soil temperature decreased with depth in summer and spring, but increased with depth in winter and autumn in both surface treatments throughout the study period.

In conclusion, it was observed that soil temperature response depends on environmental factors, surface cover and thermal properties of both the soil and the surface cover. Further analyses of the data could provide a perspective on spatial distribution of soil temperature under the house to visibly see how the temperature at the edges is affected by the mentioned factors.

# CHAPTER 7. GENERAL CONCLUSION AND RECOMMENDATIONS

## 7.1 Conclusions

Expansive soils are rich in smectite clay minerals regardless of their origin, and they shrink and swell in response to changes in soil water content. These soils are found worldwide, particularly in arid and semi-arid regions, identified by deep cracks in drier seasons and are sticky in wet seasons. Due to the shrink and swell character, expansive soils are regarded as a global problem that causes extreme damage to engineering structures, as is the case for low-cost houses in Land Type Dc17 in the Free State Province of South Africa. Damage caused by these problematic soils amounts up to billions annually in various countries and exceeds that of natural disasters. Although changes in soil water content is responsible for volume changes in these soils, temperature is the main driving force for soil water migration. Little is known on soil temperatures underneath structures built on expansive soils and how this may contribute to the problem. Thus, the main aim of this study was to characterize soil temperature underneath a basic house constructed on expansive soil. However, it is of importance to first understand the character of the soil, including chemical, physical and thermo-physical characteristics.

The first objective was to classify and categorize the swelling potential of selected expansive soils in Land Type Dc17. Therefore, laboratory analyses of different soil properties for expansive soils was performed. The soils were classified as Sepane of the Katdoorn family (1210), Bonheim of the Windermere (1210) family, Swartland of the Gemvale (1121) family, Valsrivier of the Goedemoed (1120) family and Arcadia of the Lonehill (1100) family. Furthermore, the Arcadia soil form had high swelling potential, with Sepane, Bonheim, Swartland and Valsrivier having a medium swelling potential.

As mentioned earlier, soil temperature is a major driving force of soil water migration. This soil parameter is governed by the soil thermal properties. Typically, three parameters are measured to characterize thermal properties: i.e. thermal conductivity, volumetric heat capacity and thermal diffusivity. Together these parameters are responsible for heat propagation in a soil profile. Thermal properties are influenced by mineralogy of the soil, bulk density, structural arrangement, water content and temperature amongst other factors. Thermal properties are rarely reported in the available literature for expansive soils, especially the effect of changing temperatures. Consequently, the third and the forth objectives of this study were to monitor the effect of increasing soil water content and temperature on the mentioned thermo-physical properties. This was achieved by saturating profile pits and sampling during the desorption period, creating different water content ranges, from moderate to near saturation. The samples the “moist” water range were then subjected to increasing temperatures, from 0 to 60°C. The thermal properties of the selected expansive soils were found to be affected by changes in both the soil water content and temperature. The degree of the significance was however depended upon individual soil form. Generally, with increasing water content, thermal properties increased, with thermal conductivity and thermal diffusivity decreasing slightly at near saturation. With increasing temperature, thermal properties showed a trend of decrease from 0 to 10°C and increase from 10 to 60°C.

The last objective was directed at characterizing the temperature variation underneath the house in comparison to bare soil. On a daily basis, bare soil temperature was found to follow the air temperature pattern but under the house the variation was too minor to distinguish such a pattern. The amplitude of soil temperature was lower as compared to air temperature and this was accompanied by a phase shift. Temperature responded differently under the two surface treatments (bare soil and house). The diurnal soil temperature under the house for winter and autumn was higher than bare soil at night while in spring the temperatures were cooler. Seasonally, soil temperature under the house showed variability and cooler than in bare soil in summer and spring, while in winter and autumn, soil temperatures under the house were warmer than in bare soil. In depth analyses, the soil temperature decreased with depth in summer and spring and regardless of any depth, soil temperatures under the house were cooler than in bare soil. In winter and autumn, the soil temperatures for both surface treatments increased with depth, with warmer temperatures under the house at any depths. The soil temperature variation was found to depend on the surface cover and environmental factors.

## 7.2 Recommendations

The study was part of a pilot project that was investigating the problem of early degradation of low-cost governmental houses in Botshabelo. Together with the water part of the project (Bester *et al.*, 2016), the data collected throughout the two year study period managed to give insight and understanding of how water and temperature are intergraded in house deterioration. Collectively this information could be used to make recommendations to the affected parties to better understand and mitigate this problem.

***House owners***

Although water was not the focus in this current study, it was found from the literature that even the slightest soil water change causes volume changes in expansive soils. It is therefore of importance to create awareness to house owners about the importance of creating buffer zones to prevent water accumulation at the house peripherals. This could be achieved by creating water ways that divert water away from the house or building pavements around the houses and avoiding vegetable gardens directly next to the houses.

***Structural engineers***

The present study has classified expansive soils in different parts of Land Type Dc17 and their swelling potentials. This information could help structural engineers to better design foundations on these soil types, since the raft foundation design currently used in building the low-cost government houses are not providing sufficient support against indifferent settlement caused by the swelling and shrinking of the soil. The house used in this study was less than three years old and already showed significant structural damage caused by volume changes of the soil. The available water and temperature data can also be used to model both water distribution and heat flow to further improve the foundation designs.

***Policy makers***

Information from this project as a whole could help policy makers to improve construction guidelines for building low-cost government houses. Guidelines need to state clearly the expectations related to the construction of these houses on expansive soils, preferably taking into consideration different swelling potentials of various expansive soils. It would also be ideal if appropriate soil surveys could be undertaken in the areas allocated for low-cost housing before construction commences, mapping areas and including information on soil form and swelling potential. This could help in saving the government billions in repairs to houses damaged by expansive soils.

***Further research***

The data available from the project as a whole can be further analysed to investigate combined temperature and water distribution under the low-cost house concrete floor. This will allow the development of models for heat flow and water distribution under the house. There is sufficient data to calibrate and validate models, one set of data from year 1 to develop the model and the year 2 data to test the model. Since temperature is governed by thermal properties, it is recommended that the thermal properties of the expansive soils already measured in this study be used in developing such models. Hence, the data available can develop individual models for water and temperature and a model that integrate both parameters for future use.

Although the current study compared the response of soil temperature under the house to a control area, the temperature effect on soil water migration from the peripherals to the centre of the house foundation, could be better understood if a second house is incorporated into a new study. The second house is advised to be in a sloped area where water runs away freely and does not form puddles adjacent to the house as was the case in the current study. Comparison of the two houses should give a better idea on how temperature affects water migration under a built structure.

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# APPENDIX A

**Table A1** Summary of the ANOVA of effect of water content on thermal conductivity of five soil forms for the three diagnostic horizons (Table 4.1)

| Horizon | Source | DF | Anova SS | Mean square | F-value | Pr > F |
|---|---|---|---|---|---|---|
| A | **ST** | 4 | 3.38 | 0.85 | 18.28 | <.0001 |
| | **Water** | 4 | 0.94 | 0.24 | 5.09 | 0.0011 |
| | **ST*Water** | 16 | 5.64 | 0.35 | 7.63 | <.0001 |
| | **Rep** | 3 | 0.65 | 0.22 | 4.72 | 0.7546 |
| B | **ST** | 4 | 2.41 | 0.60 | 18 | <.0001 |
| | **Water** | 4 | 2.69 | 0.67 | 20.13 | <.0001 |
| | **ST*Water** | 16 | 7.20 | 0.45 | 13.45 | <.0001 |
| | **Rep** | 3 | 0.22 | 0.07 | 2.19 | 0.0968 |
| C | **ST** | 4 | 3.35 | 0.84 | 26.73 | <.0001 |
| | **Water** | 4 | 0.20 | 0.05 | 1.56 | 0.1939 |
| | **ST*Water** | 16 | 2.80 | 0.18 | 5.58 | <.0001 |
| | **Rep** | 3 | 0.02 | 0.01 | 0.26 | 0.8561 |

**Table A2** Summary of the ANOVA of effect of water content on volumetric heat capacity of five soil forms for the three diagnostic horizons (Table 4.2)

| Horizon | Source | DF | Anova SS | Mean square | F-value | Pr > F |
|---|---|---|---|---|---|---|
| A | **ST** | 4 | 2.50287974 | 0.62571993 | 4.83 | 0.0017 |
| | **Water** | 4 | 3.29170354 | 0.82292588 | 6.35 | 0.0002 |
| | **ST*Water** | 16 | 9.86722526 | 0.61670158 | 4.76 | <.0001 |
| | **Rep** | 3 | 1.23733400 | 0.41244467 | 3.18 | 0.1289 |
| B | **ST** | 4 | 3.64270896 | 0.91067724 | 4.49 | 0.0027 |
| | **Water** | 4 | 5.38923276 | 1.34730819 | 6.64 | 0.0001 |
| | **ST*Water** | 16 | 18.81953454 | 1.17622091 | 5.80 | <.0001 |
| | **Rep** | 3 | 0.55701176 | 0.18567059 | 0.92 | 0.4378 |
| C | **ST** | 4 | 0.92855336 | 0.23213834 | 2.18 | 0.0799 |
| | **Water** | 4 | 0.87058886 | 0.21764722 | 2.04 | 0.0974 |
| | **ST*Water** | 16 | 4.46730644 | 0.27920665 | 2.62 | 0.0028 |
| | **Rep** | 3 | 0.06686099 | 0.02228700 | 0.21 | 0.8897 |

**Table A3** Summary of the ANOVA of effect of water content on thermal diffusivity of five soil forms for the three diagnostic horizons (Table 4.3)

| Horizon | Source | DF | Anova SS | Mean square | F-value | Pr > F |
|---|---|---|---|---|---|---|
| A | ST | 4 | 0.43231796 | 0.10807949 | 9.31 | <.0001 |
| | Water | 4 | 0.27421065 | 0.06855266 | 5.90 | 0.0004 |
| | ST*Water | 16 | 0.69427804 | 0.04339238 | 3.74 | <.0001 |
| | Rep | 3 | 0.01380789 | 0.00460263 | 0.40 | 0.7560 |
| B | ST | 4 | 1.18924255 | 0.29731064 | 20.57 | <.0001 |
| | Water | 4 | 0.47256955 | 0.11814239 | 8.17 | <.0001 |
| | ST*Water | 16 | 4.17151360 | 0.26071960 | 18.04 | <.0001 |
| | Rep | 3 | 0.01535551 | 0.00511850 | 0.35 | 0.7863 |
| C | ST | 4 | 0.55161760 | 0.13790440 | 22.39 | <.0001 |
| | Water | 4 | 0.20017322 | 0.05004331 | 8.13 | <.0001 |
| | ST*Water | 16 | 0.27864261 | 0.01741516 | 2.83 | 0.0014 |
| | Rep | 3 | 0.00240408 | 0.00080136 | 0.13 | 0.9419 |

**Table A4** Summary of the ANOVA of effect of water content on thermal conductivity of five soil forms for the three diagnostic horizons (Table 5.1)

| Horizon | Source | DF | Anova SS | Mean square | F-value | Pr > F |
|---|---|---|---|---|---|---|
| A | ST | 4 | 0.63113930 | 0.15778482 | 1.63 | 0.0175 |
| | Temp | 4 | 0.17111450 | 0.04277862 | 0.44 | 0.0777 |
| | ST*Temp | 16 | 4.76738920 | 0.29796182 | 3.09 | 0.0006 |
| | Rep | 3 | 0.24770027 | 0.08256676 | 0.85 | 0.4686 |
| B | ST | 4 | 2.73915044 | 0.68478761 | 22.51 | <.0001 |
| | Temp | 4 | 0.27133224 | 0.06783306 | 2.23 | 0.0741 |
| | ST*Temp | 16 | 1.96322426 | 0.12270152 | 4.03 | <.0001 |
| | Rep | 3 | 0.17028576 | 0.05676192 | 1.87 | 0.1430 |
| C | ST | 4 | 1.85707466 | 0.46426867 | 12.90 | <.0001 |
| | Temp | 4 | 1.06777286 | 0.26694322 | 7.41 | <.0001 |
| | ST*Temp | 16 | 1.93719544 | 0.12107472 | 3.36 | 0.0002 |
| | Rep | 3 | 0.19292976 | 0.06430992 | 1.79 | 0.1575 |

**Table A5** Summary of the ANOVA of effect of water content on volumetric heat capacity of five soil forms for the three diagnostic horizons (Table 5.2)

| Horizon | Source | DF | Anova SS | Mean square | F-value | Pr > F |
|---|---|---|---|---|---|---|
| A | ST | 4 | 14.05880466 | 3.51470117 | 18.07 | <.0001 |
| | Temp | 4 | 0.92249886 | 0.23062471 | 1.19 | 0.3243 |
| | ST*Temp | 16 | 12.51672524 | 0.78229533 | 4.02 | <.0001 |
| | Rep | 3 | 0.28549787 | 0.09516596 | 0.49 | 0.6908 |
| B | ST | 4 | 7.94826296 | 1.98706574 | 12.13 | <.0001 |
| | Temp | 4 | 0.71838286 | 0.17959571 | 1.10 | 0.3649 |
| | ST*Temp | 16 | 12.36868974 | 0.77304311 | 4.72 | <.0001 |
| | Rep | 3 | 0.22520851 | 0.07506950 | 0.46 | 0.7122 |
| C | ST | 4 | 0.37185476 | 0.09296369 | 0.91 | 0.4656 |
| | Temp | 4 | 1.98462096 | 0.49615524 | 4.83 | 0.0017 |
| | ST*Temp | 16 | 4.50353584 | 0.28147099 | 2.74 | 0.0019 |
| | Rep | 3 | 0.31017539 | 0.10339180 | 1.01 | 0.3949 |

**Table A6** Summary of the ANOVA of effect of water content on thermal diffusivity of five soil forms for the three diagnostic horizons (Table 5.3).

| Horizon | Source | DF | Anova SS | Mean square | F-value | Pr > F |
|---|---|---|---|---|---|---|
| A | ST | 4 | 0.06227449 | 0.01556862 | 1.22 | 0.3097 |
| | Temp | 4 | 0.22818469 | 0.05704617 | 4.47 | 0.0028 |
| | ST*Temp | 16 | 0.35331253 | 0.02208203 | 1.73 | 0.0418 |
| | Rep | 3 | 0.01711667 | 0.00570556 | 0.45 | 0.7200 |
| B | ST | 4 | 2.67616082 | 0.66904020 | 75.22 | <.0001 |
| | Temp | 4 | 0.20637076 | 0.05159269 | 5.80 | 0.0004 |
| | ST*Temp | 16 | 2.33765175 | 0.14610323 | 16.43 | <.0001 |
| | Rep | 3 | 0.03436295 | 0.01145432 | 1.29 | 0.2851 |
| C | ST | 4 | 0.39767318 | 0.09941830 | 20.04 | <.0001 |
| | Temp | 4 | 0.25919104 | 0.06479776 | 13.06 | <.0001 |
| | ST*Temp | 16 | 0.17958698 | 0.01122419 | 2.26 | 0.0099 |
| | Rep | 3 | 0.11127285 | 0.03709095 | 7.48 | 0.4002 |

**Table A7** ANOVA representing the interaction between the 2 surface treatments in a diurnal temperature cycle (Table 6.2)

| | Average | Maximum | Minimum |
|---|---|---|---|
| **DF** | 3 | 3 | 3 |
| **MS** | 58.9 | 76.2 | 46.54 |
| **F** | 17.71 | 21.89 | 14.51 |
| **P-value** | <.0001 | <.0001 | <.0001 |

**Table A8** Peak-trough fluctuation of temperature in bare soil and under a house for spring, summer autumn and winter in a diurnal temperature cycle.

| | Variation | | Difference | |
|---|---|---|---|---|
| **Season** | **Bare soil (°C)** | **House(°C)** | **Bare-House (°C)** | **P-value** |
| **Spring** | 2.82 | 0.2 | 2.62 | <.0001 |
| **Summer** | 3.21 | 0.1 | 3.1 | <.0001 |
| **Autumn** | 1.12 | 0.16 | 0.96 | 0.001 |
| **Winter** | 1.31 | 0.13 | 1.18 | <.0001 |

**Table A9**Comparison of seasonal soil temperature under two surface treatments for a period of two years.

| | Spring | | Summer | | Autumn | | Winter | |
|---|---|---|---|---|---|---|---|---|
| | **DF** | **p-values** | **DF** | **p-values** | **DF** | **p-values** | **DF** | **p-values** |
| **Y1BH** | 12 | 0.003 | 12 | 0.024 | 12 | 0.03 | 12 | 0.03 |
| **Y2BH** | 12 | 0.04 | 12 | 0.018 | 12 | 0.02 | 12 | 0.051 |

**Table A10** Annual seasonal soil temperature changes throughout soil profile depth for a period of two years.

| | | | Average | | Max | | Min | | SE | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | **Seasons** | **Depth(cm)** | **B** | **H** | **B** | **H** | **B** | **H** | **B** | **H** |
| Year 1 | **Spring** | **10** | 23 | 19 | 26 | 22 | 19 | 15 | 0.480 | 0.840 |
| | | **20** | 22 | 19 | 25 | 21 | 20 | 15 | 0.510 | 0.870 |
| | | **40** | 22 | 19 | 23 | 21 | 20 | 15 | 0.510 | 0.790 |
| | | **60** | 21 | 19 | 22 | 20 | 19 | 15 | 0.530 | 0.780 |
| | | **80** | 20 | 19 | 21 | 20 | 18 | 16 | 0.550 | 0.760 |
| | **Summer** | **10** | 27 | 24 | 31 | 26 | 24 | 21 | 0.820 | 2.070 |
| | | **20** | 27 | 24 | 30 | 26 | 24 | 21 | 0.880 | 1.940 |
| | | **40** | 26 | 24 | 28 | 25 | 23 | 21 | 0.890 | 1.700 |
| | | **60** | 25 | 23 | 27 | 25 | 22 | 20 | 0.880 | 1.430 |
| | | **80** | 24 | 23 | 26 | 24 | 24 | 20 | 0.830 | 1.210 |
| | **Autumn** | **10** | 18 | 21 | 27 | 24 | 8 | 18 | 0.710 | 0.860 |
| | | **20** | 18 | 21 | 26 | 24 | 10 | 19 | 0.710 | 0.820 |
| | | **40** | 19 | 21 | 26 | 24 | 12 | 19 | 0.680 | 0.490 |
| | | **60** | 20 | 21 | 25 | 23 | 14 | 19 | 0.450 | 0.580 |
| | | **80** | 20 | 21 | 25 | 23 | 20 | 20 | 0.700 | 0.590 |
| | **Winter** | **10** | 12 | 16 | 18 | 19 | 7 | 14 | 0.500 | 0.740 |
| | | **20** | 12 | 16 | 18 | 19 | 8 | 14 | 1.410 | 0.710 |
| | | **40** | 13 | 16 | 17 | 19 | 10 | 15 | 0.430 | 0.470 |
| | | **60** | 13 | 16 | 17 | 19 | 12 | 15 | 0.290 | 1.530 |
| | | **80** | 14 | 17 | 16 | 19 | 14 | 16 | 0.250 | 0.300 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Spring** | **10** | 24 | 22 | 28 | 25 | 19 | 17 | 0.680 | 0.270 |
| | **20** | 23 | 22 | 27 | 24 | 19 | 17 | 0.680 | 0.250 |
| | **40** | 23 | 21 | 25 | 24 | 18 | 18 | 0.700 | 0.290 |
| | **60** | 22 | 21 | 24 | 23 | 18 | 18 | 0.680 | 0.280 |
| | **80** | 21 | 20 | 23 | 23 | 17 | 18 | 0.660 | 0.280 |
| **Summer** | **10** | 26 | 25 | 30 | 29 | 22 | 23 | 0.300 | 0.240 |
| | **20** | 26 | 25 | 30 | 28 | 22 | 23 | 0.280 | 0.240 |
| | **40** | 25 | 25 | 28 | 27 | 23 | 23 | 0.280 | 0.230 |
| | **60** | 25 | 24 | 27 | 26 | 23 | 22 | 0.290 | 0.220 |
| | **80** | 24 | 24 | 25 | 26 | 23 | 22 | 0.280 | 0.210 |
| **Autumn** | **10** | 16 | 20 | 22 | 23 | 10 | 17 | 0.630 | 0.660 |
| | **20** | 16 | 20 | 22 | 23 | 11 | 17 | 0.600 | 0.660 |
| | **40** | 17 | 20 | 22 | 23 | 13 | 17 | 0.570 | 0.640 |
| | **60** | 18 | 20 | 22 | 23 | 15 | 18 | 0.520 | 0.560 |
| | **80** | 18 | 21 | 22 | 23 | 15 | 18 | 0.490 | 0.540 |
| **Winter** | **10** | 12 | 15 | 20 | 19 | 8 | 13 | 0.570 | 0.730 |
| | **20** | 12 | 15 | 19 | 19 | 9 | 14 | 0.570 | 0.760 |
| | **40** | 13 | 16 | 18 | 18 | 11 | 14 | 0.560 | 0.740 |
| | **60** | 13 | 16 | 17 | 18 | 12 | 15 | 0.530 | 0.690 |
| | **80** | 14 | 16 | 16 | 18 | 13 | 15 | 0.520 | 0.650 |

# APPENDIX B. ACCURACY AND PRECISION OF DFM CAPACITANCE PROBES FOR MEASURING SOIL TEMPERATURE