Water transport mechanisms in coal stockpiles

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DECLARATION

I, Chané Bernadette Espag, hereby declare that the dissertation entitled: “Water transport mechanisms in coal stockpiles”, submitted in fulfilment of the requirements for a Master’s degree in Chemical Engineering (MEng), is my own work, unless otherwise specified in text, and that this dissertation has not been submitted to any other tertiary institution either in part or as a whole.

Signed at Potchefstroom, on the 13th day of November 2015.

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Chané Espag

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ABSTACT

One of the key indicators of coal product quality is the moisture content. Excess moisture can have a negative effect as it results in handling problems and a reduction in coal value by decreasing the heating value. The moisture content of the coal can be regulated by way of the natural drainage and evaporation which occurs within stockpiles. Various factors influence the redistribution of moisture within a stockpile and it was the objective of this study to understand and quantify the influence which each of these factors has on the movement of water. For this investigation, the mechanisms (runoff, infiltration, evaporation and drainage) by which water moves within a stockpile was simulated separately and then compared to the results obtained from an experimental 9 tonne coal stockpile.

Results showed that there exists a strong linear correlation between the rainfall intensity and the amount of surface runoff water. Once the surface of the stockpile became saturated, the infiltration rate was constant; thus meaning that any increase in rainfall intensity will result in an increased amount of surface runoff. Small interparticulate void spaces (either as a result of compaction or high fines content) inhibited infiltration, leading to an increased runoff proportion. An increased stockpile slope decreased the coal-water contact time, which increased the amount of runoff. Erosion occurred more readily at high slopes and high fines content.

The natural drainage of a stockpile was simulated through the use of drainage columns. It was found that the fines content (especially the -0.5 mm fraction) had a large influence on the dewatering efficiency of drainage. Two coals were used during this investigation. The high-ash coal showed greater retention of moisture, even though the low-ash coal had a larger fines proportion. This was attributed to the large content of the clay mineral kaolinite in the high-ash coal. Moisture profiles were determined for each coal sample and it was found that moisture gradually migrated towards the bottom of the sample.

Evaporation proved to be significantly more effective than drainage at drying coal stockpiles, but the effect was only seen up to a certain depth. While the fine coal bed had a large surface area, the small interparticulate voids had a negative influence on the rate of evaporation. It was found that the surface of a fine coal stockpile will evaporate faster than that of a coarse stockpile, but that a coarse stockpile will experience evaporation more effectively as a result of its porous structure. Results showed that a fine coal bed will only experience evaporation on its surface, while coarse coal beds showed evidence of evaporation up to 0.4 m below the surface. Weather conditions such as temperature, relative humidity, and wind speed influenced the rate of evaporation. The coal beds showed cyclic behaviour through adsorbing moisture during the night, and desorbing moisture during the day as part of the evaporation process. This is a result of the coal particles attempting to remain in equilibrium with the atmosphere.

Results from the 9 tonne experimental stockpile supported the finding that the rate of infiltration (or by definition the final moisture content) was independent of the rainfall intensity. The final moisture samples confirmed that the redistribution of moisture took place by means of drainage and evaporation. Similar to the coal beds used in the small-scale evaporation experiment, the stockpile showed signs of cyclic behaviour – although to a lesser extent. All small-scale experiments – with the exception of the experiment which investigated the depth of evaporation – were representative of the way by which moisture migrated or were retained in a coal stockpile.

The inherent moisture content of the coal particles remained constant for all experiments, which proved that the moisture of the greatest importance in the dewatering of coal is the surface moisture content.

Keywords: Coal stockpile, gravity drainage, runoff, infiltration, evaporation

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

Symbol	Description	Unit
a	Constant	
b	Constant	
K	Runoff coefficient	-
RI	Rainfall intensity	mm/h
R_m	Retained water	%
t	time	minutes
ρ_B	Bulk density	kg/m^3

LIST OF ABBREVIATIONS

Abbreviation	Definition
Bt	Billion tonnes
BTU	British Thermal Units
CV	Calorific value
C	Carbon
H	Hydrogen
Mt	Million tonnes
O	Oxygen
S	Sulphur
PSD	Particle size distribution
PSR	Particle size range
XRD	X-ray diffraction

CHAPTER 1: INTRODUCTION

This chapter gives a short introduction to the background and motivation behind the project in section 1.1. The problem statement is given in section 1.2 and the objectives and scope of the study are discussed in sections 1.3 and 1.4 respectively.

1.1 Background and motivation

The global energy demand has almost doubled over the past three decades (Beretta, 2007:2) and it is predicted by the World Coal Association (2012:3) that it will double again over the course of the next 30 years. With the bulk of the world's current energy requirements provided for by the consumption of fossil fuels, it is a priority to efficiently manage the usage of these finite natural resources. According to the World Coal Association (2012:2), coal can be viewed as the current most important global provider of energy – generating approximately 41% of the world's electricity requirements. Taking the current rate of consumption into account, global coal reserves are estimated to only last another 110 years (BP, 2015:31).

South Africa – the seventh largest coal producing country (BP, 2015:32) – has substantial coal reserves estimated at 30156 Mt (BP, 2015:30). Around 73% of the mined coal is used to provide energy to the country – primarily in the form of electricity and synthetic fuels (Department of Minerals Resources, 2012:54; Eberhard, 2011:1; Jeffrey, 2005:95). The remaining coal – around 63.4 Mt annually (SANEDI, 2011:III) – is exported to international markets (Department of Minerals Resources, 2012:52). The export of coal provided R35.4 billion in export revenues in 2011 (SANEDI, 2011:III). According to the WCI (2009), more than 92% of the electricity generated in South Africa is provided for by the combustion of coal. These figures showcase South Africa's dependency on coal – not only as a source of energy, but also as a revenue stream. With increasing strain placed on a dwindling resource, it is becoming crucial to optimise the management of South Africa's coal.

To ensure the smooth operation of coal consuming processes such as electricity generation, a buffer or surge capacity in the form of coal stockpiles is required. With the increased demand for coal products, surge times are becoming shorter and good stockpile management is even more essential (Keleher *et al*., 1998:422). Stockpiles are also used for blending and moisture control (Mahr, 2010). Moisture is a key indicator of coal quality and can change depending on time and weather conditions (Leeder *et al*., 2011:1; Mahr, 2010). Excess moisture in coal results in increased transportation costs per MJ (Rong, 1997:1; Hand, 2000:10; Williams, 2006:223) as a result of the decreased heating value of the coal (Hand, 2000:10) as well as handling problems (Leeder *et al*., 2011:1; Williams, 2006:223).

1.2 Problem statement

In order to improve the management of coal stockpiles with specific focus on moisture control, the mechanisms by which water moves within a stockpile must be properly understood. There are four mechanisms of water movement in coal stockpiles. When water falls onto a coal stockpile, it either runs off the surface or infiltrates the stockpile. The infiltrated water will evaporate from the surface, drain out from the bottom, or remain within the stockpile and add to the total moisture of the coal. Each of these mechanisms is influenced by different factors including weather conditions, particle size distribution (PSD) and clay mineral content.

The amount of information in the public domain regarding coal moisture control by means of stockpiling is remarkably limited. While there are some international industrial reports regarding the subject, little to none information is available for South African coals. This study will focus on understanding the drying of a South African coal stockpile by investigating each of the mechanisms mentioned above.

1.3 Aim and objectives

The aim of this investigation is to understand and investigate the mechanisms by which water is transported within a typical South African coal stockpile. To achieve this goal, the following objectives were defined:

- Determine the influence which the compaction of the coal, PSD, stockpile slope angle and the intensity of rainfall have on the amount of water which runs off the coal stockpile surface.
- Establish the influence which the PSD and stockpile height have on the gravity drainage of a coal stockpile.
- Determine the extent to which the rate of evaporation of water from the coal is influenced by the PSD and weather conditions.
- Determine the depth to which moisture evaporation occurs within a coal stockpile as a function of time, PSD and weather conditions.
- Compare the results from the small scale experiments to an experimental coal stockpile and establish whether these experiments are a good representation of what happened in an actual stockpile.

1.4 Scope of the investigation

To ensure that the objectives of the study are met, a scope was created to direct the research process. This scope is graphically represented by Figure 1.4.1. Experimental setups for the runoff versus infiltration and the evaporation work will need to be designed and existing setups such as the drainage column and the experimental stockpile platform will need to be modified.

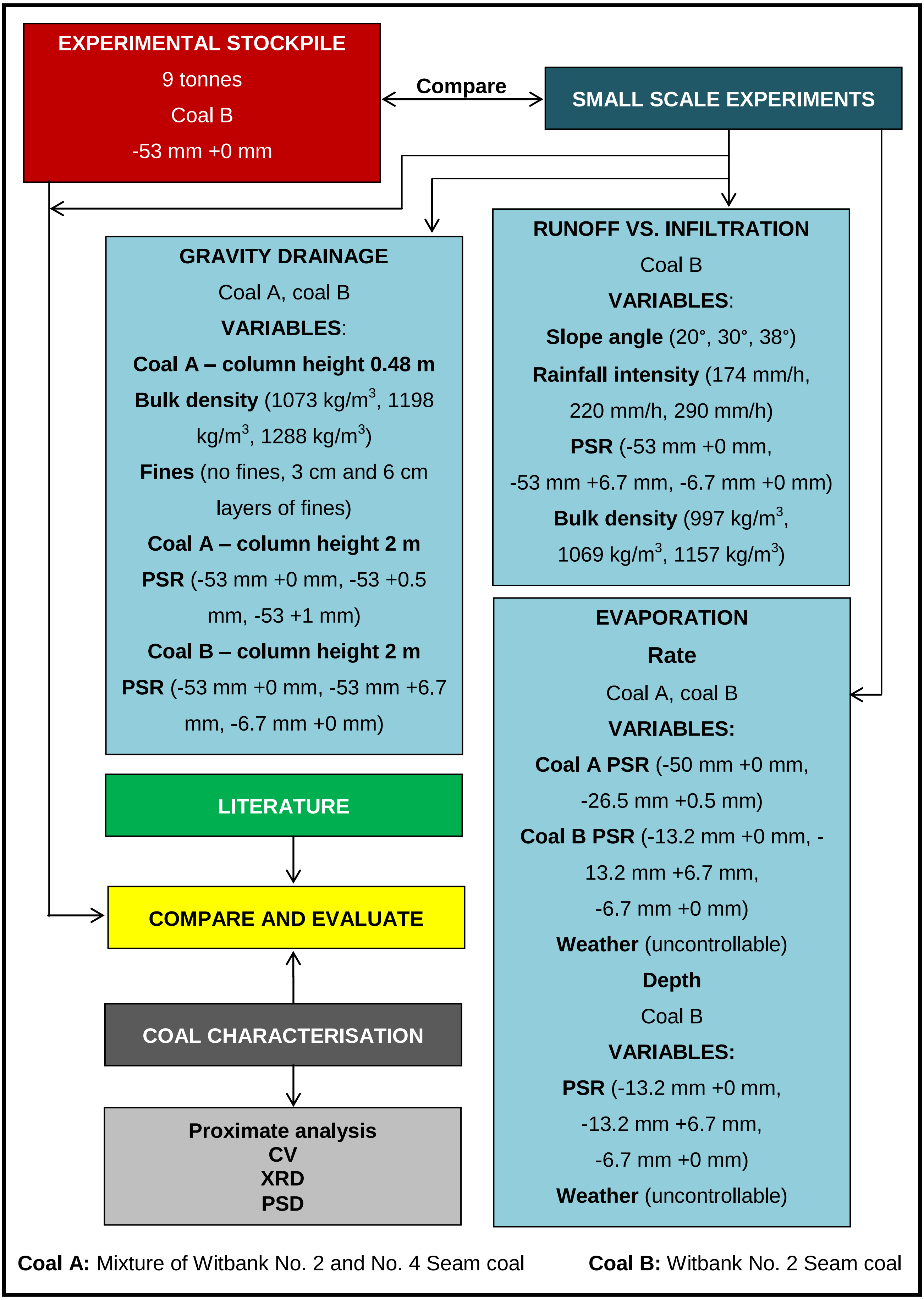

Figure 1.4.1: Scope of the investigation

CHAPTER 2: LITERATURE REVIEW

An extensive review of the available literature concerning the retention and migration of moisture in coal stockpiles is given in this chapter. Section 2.1 gives an introduction to South African coal fields and general coal properties, with specific emphasis on the Witbank coalfield. Section 2.2 is focussed on moisture in coal and the properties which determine the extent to which coal retains moisture. Section 2.3 discusses stockpiles in general, and section 2.4 investigates the mechanisms by which moisture migrates and is retained within a coal stockpile by identifying the factors which influence each mechanism.

2.1 Coal

Coal is characterised as a sedimentary rock, either black or brown in colour, comprised primarily of organic composites such as carbon, hydrogen and oxygen and, to a lesser extent, some mineral components (Osborne, 1988: 1175). The properties associated with a certain type of coal are determined by its degree of coalification – the more mature the coal, the higher the rank. Lignite and sub-bituminous coals are categorised as low rank coals with high moisture content and notably lower calorific values compared to high rank coals such as anthracite and bituminous coal (WCI, 2009:2-3).

2.1.1 South African coalfields

South Africa currently has an approximated 32 Bt of economically viable coal reserves (SANEDI, 2011:IV). Around 70% of these reserves are located in the Waterberg, Witbank and Highveld coalfields (Jeffery, 2005:95; SANEDI, 2011:IV) as shown in Figure 2.1.1. The majority of South African coal is ranked as either bituminous or sub-bituminous (Jeffery, 2005).

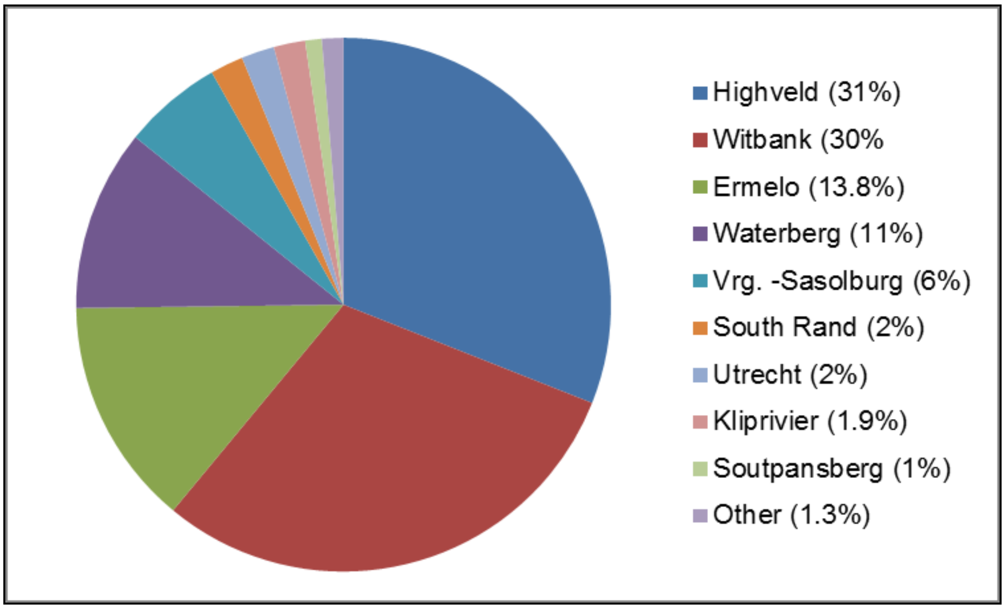

Figure 2.1.1: South African coalfields reserves (Keaton Energy, s.a.)

2.1.1.1 The Witbank coalfield

The Witbank coalfield produces metallurgical and steam coal (Goldschmidt *et al*., 2010) and consists of five seams – each seam or parts thereof associated with individual properties and characteristics. According to Goldschmidt *et al*. (2010), the No. 2 Seam, No. 4 Seam, and parts of the No.5 Seam are the principal economic seams.

Coals from the No. 2 and No. 4 Seams are used in this investigation. Some of the highest quality coal is found in the No. 2 Seam, which is distinctly divided in up to seven different coal zones – each zone containing coal of a different quality. Low-ash metallurgical and export steam coal is mined from the three basal seam zones, while the top part of the seam is mostly shaly and unmineable (Smith and Whittaker, 1986). Poor quality coal is found in the No. 4 Seam, with only the lower 3.5 m of the seam mined for power station feedstock and domestic steam coal (Smith and Whittaker, 1986).

2.1.2 Coal composition

Coal, as a sedimentary rock, is heterogeneously composed of a variety of elements (Mukhopadhyay & Hatcher, 1993:79). According to Schweinfurth (2009), coal can comprise of as many as 76 of the 90 naturally occurring elements – the majority classified as trace elements. Coal primarily consists of organic matter (Mukhopadhyay & Hatcher, 1993:79) consisting of carbon, nitrogen, sulphur, and hydrogen with trace amounts of other elements (Schweinfurth, 2009).

On a macroscopic level, the different components which form coal are characterised as lithotypes (Snyman, 1996; Stach *et al*., 1982). These lithotypes consists of macerals (Mukhopadhyay & Hatcher, 1993:80; Snyman, 1996) and other small amounts of minerals on a microscopic level (Snyman, 1996). Based on its lithotypes, coal can be classified according to two categories – humic and sapropelic coals (Falcon & Snyman, 1986; Mukhopadhyay & Hatcher, 1993:80). Macerals are categorised in three groups, termed vitrinite, liptinite and inertinite (Falcon & Snyman, 1986). While the physical and chemical properties of these macerals are coal rank dependent, the proportions and shape remain rather unaffected (Falcon & Snyman, 1986; Snyman 1996). Each maceral gives a unique characteristic to the coal (Snyman, 1996).

2.2 Moisture in coal

Moisture is a key indicator of coal quality and has an influence on both the physical and chemical characteristics of coal (Buckley & Nicol, 1995:2; Karthikeyan *et al*., 2007:101; Leeder *et a*l., 2011:1; Mahr, 2010; Nkolele, 2004:171). Moisture content has a direct effect on the transportation economics, ignition point and combustibility limit of coals (Karthikeyan *et al*., 2007:1602). Excess moisture in coal results in handling problems and a decreased calorific value (Buckley & Nicol, 1995:2; Hand, 2000:10; Karthikeyan *et al*., 2007:1601; Leeder *et al*., 2011:1; Osman *et al*., 2011:1763; Rong, 1997:1; Williams, 2006:223). Excessive coal moisture levels are also known to have a significant unfavourable effect on power station performance. These unwarranted moisture levels characteristically result from excessive rain, uncontrollable high surface water contained in the raw coal, inadequate clay removal methods or poor plant dewatering practices for washed coals.

As a result of these factors, coal moisture contract specifications are becoming more stringent and are associated with economic penalties (Buckley & Nicol, 1995:2). Thermal coal contract specifications commonly include limitations on the maximum moisture and ash levels, as well as a minimum calorific value on a net as received basis. This demands advancement in overall stockpile management (Eckersley, 1999:1; Keleher *et al*., 1998:422).

In order to understand the effects that water has on the various applications of coal, it is necessary to have sufficient knowledge of the types of moisture and the factors which influence the coal moisture retaining characteristics.

2.2.1 Types of moisture

The range of terminology which describes the types of moisture associated with coal is vast (Buckley & Nicol, 1995:3-12; Karthikeyan *et al*., 2009:404; le Roux & Campbell, 2003:999; Williams, 2006:224). Superficially, coal moisture can be described on a purely physical basis as being either interacting or non-interacting. Water that interacts with the surface of the coal is defined as interacting moisture. This classification is dependent on whether the water considered demonstrates the thermodynamic properties of bulk water (Buckley & Nicol, 1995:3).

Another type of moisture contained in coal is chemically bound moisture – which is the moisture of least interest when regarded from a coal dewatering standpoint. This type of moisture is located in the chemical structure of the ash fraction of the coal (le Roux & Campbell, 2003:999; Karthikeyan *et al*., 2007:1602; Rozgonyi & Szigeti, 1985). A practical definition for this type of moisture is the amount of water which is retained by the coal after oven drying at 110 °C under flowing nitrogen (Buckley & Nicol, 1995:4). According to Buckley and Nicol (1995:4), chemically bound moisture may be released during pyrolysis. The assumption can be made that the bulk of this type of moisture is related to the inherent and adventitious mineral matter contained within the coal. Interacting water includes some chemically bound moisture (Buckley & Nicol, 1995:4-5).

The total moisture content of the coal consists of free moisture and residual moisture (Buckley & Nicol, 1995:5; le Roux & Campbell, 2003:999; Williams, 2006:224). Chemically bound moisture does not form part of this definition. Free moisture is defined as the amount of moisture which is removed by air drying under ambient temperature and humidity for three days, or by oven drying at 40 °C for three hours. Residual or inherent moisture is the moisture which remains after the free moisture is lost and is determined by oven drying at 105 – 110 °C. In real-world coal dewatering, free moisture the most significant type of coal moisture (Buckley & Nicol, 1995:5).

Wet coal contains physically combined water by way of interparticulate and intraparticulate moisture. Interparticulate moisture is the water content found between coal particles, and intraparticulate moisture is the water contained within a coal particle (Buckley & Nicol, 1995:5; le Roux & Campbell, 2003:999; Karthiyekan *et al*., 2009:404). Interparticulate moisture is the water type with the most manageable influence on the final coal moisture (Buckley & Nicol, 1995:5). This type of moisture forms menisci at the particle-particle interface, which – because of surface tension – results in the interparticulate water being at a lower pressure than the atmospheric pressure. Consequentially, the negative pressure works against the forces of gravity – resulting in the water being held in the coal even when several meters above a water table. These suction forces can act both horizontally or vertically in any direction (Eckersley, 1999:12). Intraparticle moisture can be described as either surface moisture – held on the surface of the coal particle – or hydroscopic moisture which is held by capillary action within the microfractures of coal (de Korte & Mangena, 2004:5; le Roux & Campbell, 2003:999; Karr, 1978; Karthiyekan *et al*., 2009:404).

Surface moisture is relatively easily removed by the use of pressure, gravity drainage, compaction and/or vibration, or by wind and solar action (Williams, 2006:224). Adhesion water is the water that forms a thin film around the surface of individual or agglomerated particles (Karthiyekan *et al*., 2009:404; Nkolele, 2004:173). The different types of water are illustrated in Figure 2.2.1. In this study, the two types of moisture of importance is surface and inherent moisture.

A summary of the different coal moisture types is given in Table 2.2.1.

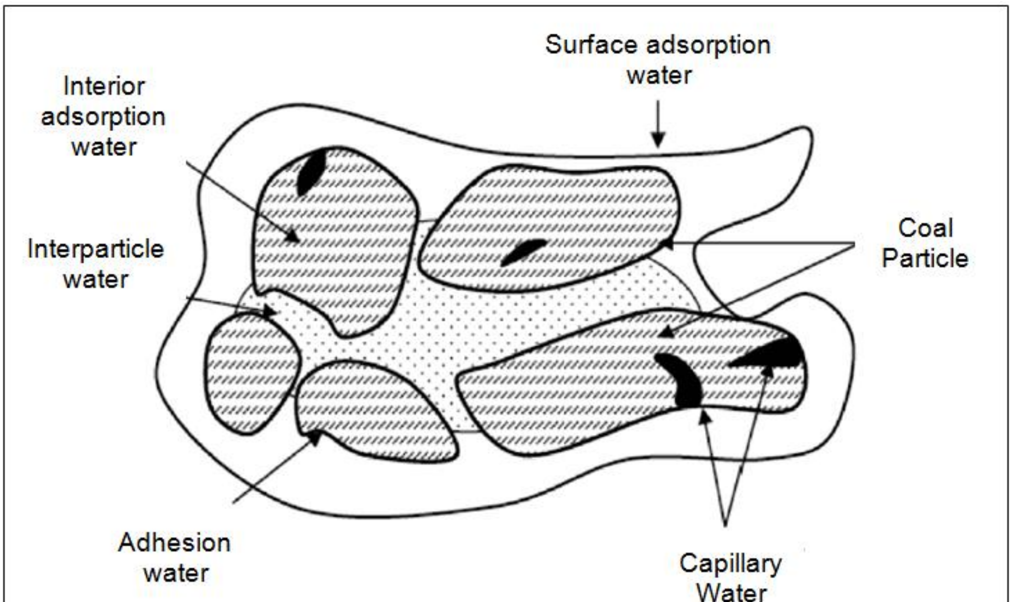

Figure 2.2.1: Different types of moisture associated with coal (Karr, 1978)

Table 2.2.1: Summary of coal moisture types and typical methods for removal (Karthikeyan *et al*., 2009:403-415)

Category	Location	Common name	Removal method
Interior adsorption water	Micropores and microcapillaries with each coal particle	Inherent moisture	Thermal or chemical
Surface adsorption water	Particle surface	Inherent moisture	Thermal or chemical
Capillary water	Capillaries in coal particles	Inherent moisture	Thermal or chemical
Interparticulate water	Small crevices found between two or more particles	Surface moisture	Mechanical or thermal
Adhesive water	Film around the surface of individual or agglomerated particles	Surface moisture	Mechanical or thermal

2.2.2 Factors affecting moisture content

There are various factors which influences the moisture content of coal. These factors are cursorily discussed in the sections below.

2.2.2.1 Mineral content

A general consensus is that water molecules are predominantly adsorbed at sites which contain either carbon-oxygen functional groups or hydrophilic inorganic minerals (Fuerstenau & Diao, 1992:1-17). Fuerstenau and Diao (1992:1-17) found that the hydrophobicity of coal particles (Laskowski, 2003) is negatively influenced by oxidation and that low-rank coals are more disposed to oxidation than high-rank coals.

Research shows that the coal dewatering efficiency is affected by the mineral content of the coal (Nkolele, 2004: 172; Pluzhnikov *et al*., 1993:18-20; Rozgonyi & Szigeti, 1985). The majority of the mineral matter contained in coal is defined as hydrophilic; consequently the presence of inorganic material at the coal particle surface would probably affect the dewatering efficiency in an adverse manner. Pyrite that has undergone limited oxidation, however, is the one significant exception to the rule as flotation response shows that the surface is hydrophobic (Buckley & Nicol, 1995:44).

Clay minerals, in particular, are expected to be intensely hydrophilic. Montmorillonitic clays – for example bentonite – will swell to a much larger volume when introduced to water, while kaolinitic and illitic clays are virtually entirely stable with regards to swelling behaviour (Buckley & Nicol, 1995:44). In the case of non-swelling clays, there is an insufficient amount of information obtainable on their influence on coal dewatering characteristics (Buckley & Nicol, 1995:44).

2.2.2.2 Heterodispersivity

A coal bed is comprised of rough, angular particles of heterodisperse size distribution – in contrast with idealised solutions of monodispersed, spherical particles. According to Harris and Smith (1957a; 1957b), the heterodispersivity of a coal bed can lead to the presence of continuous filaments of water in the surface crevices which, providing the capillary suction associated with these fine crevices is sufficiently high, may prolong the funicular state thereby depleting the moisture present at the particle contact points.

2.2.2.3 Porosity and density

Coal consists of pore systems interlinked with an uninterrupted coal structure (Karthiyekan *et al*., 2009:406). This porosity governs the degree of wetness (de Korte & Mangena, 2004:6). According to Karthiyekan *et al*. (2009:406), it is suspected that the pore network has transitional and micropore structures which branch off a larger macropore structure. An illustration of the water contained in the pore structure is given in Figure 2.2.2. The water contained in macropores is reasonably easily removed by heat treatment, while the water that is contained in the micropores is influenced by surface bonding forces and capillary action and is thus significantly harder to remove (Karthiyekan *et al*., 2009:406).

The density of a coal particle is directly related to the porosity of the said particle. Figure 2.2.3 shows a relationship – as obtained by Eckersley (1999:14) – between the moisture content and the density of a coal particle. A coal particle with a higher porosity will contain higher amounts of moisture.

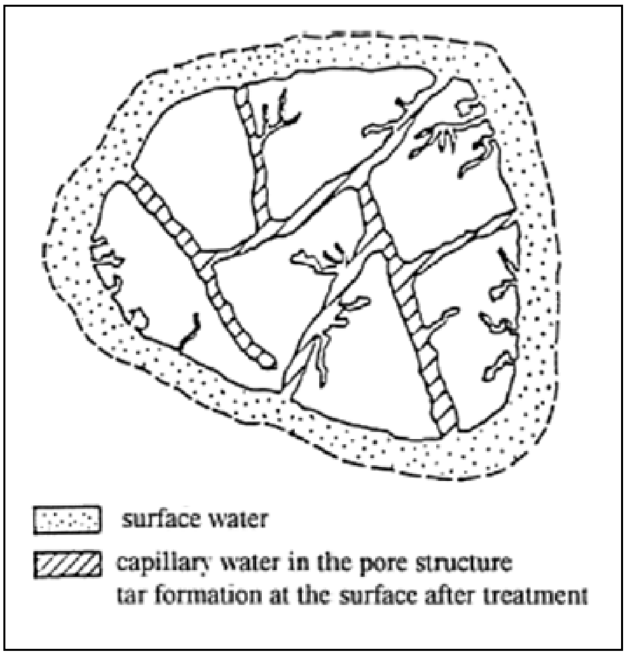

Figure 2.2.2: Water contained within the pore structure of a coal particle (Erdol *et al*., 1999)

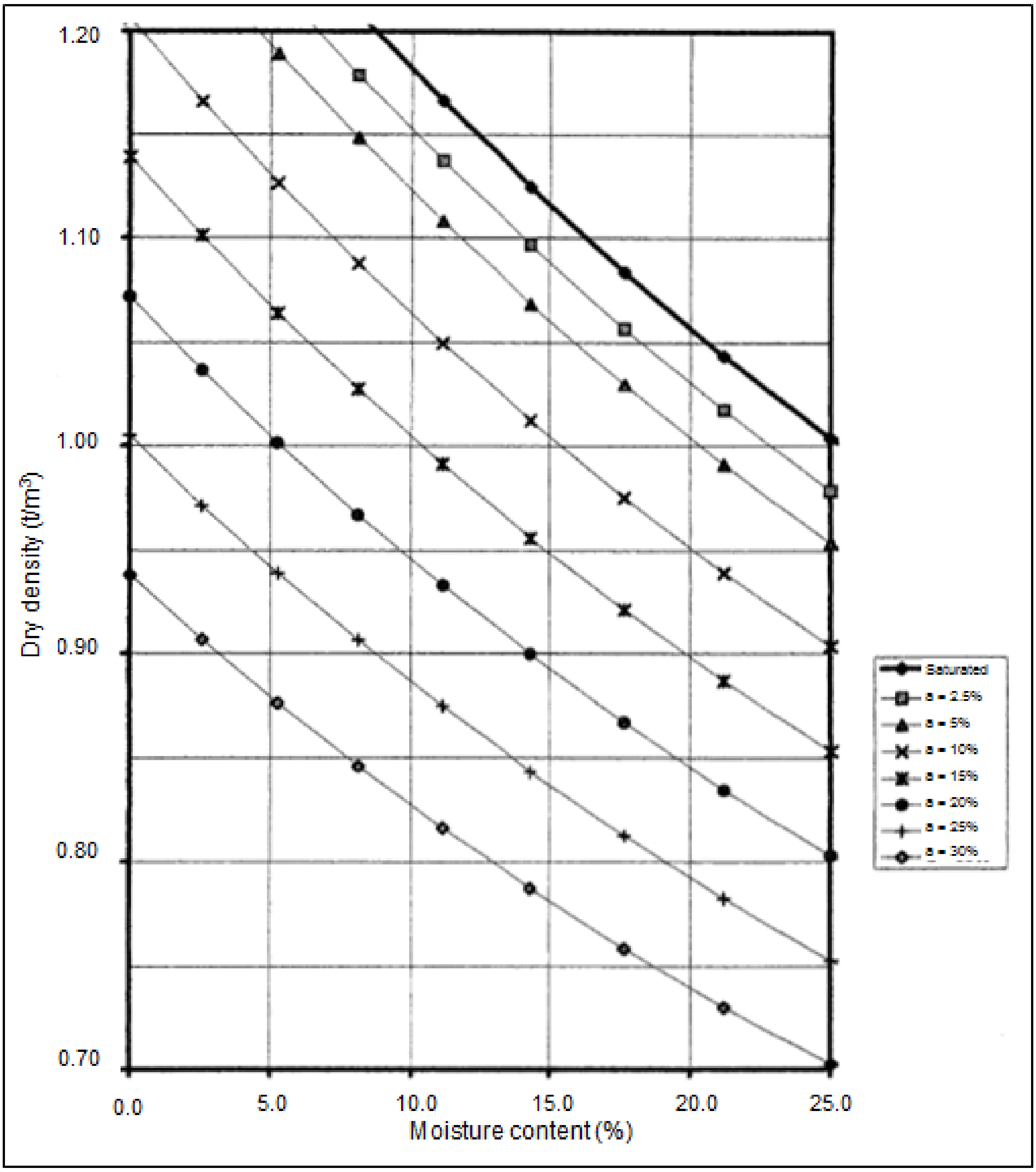

Figure 2.2.3: The relationship between the moisture content and the density of coal (Eckersley, 1999:14)

2.2.3 Effects of excess moisture

As previously mentioned, excess moisture in coal have various negative effects. Coal supply contracts generally contain strict limitations on the moisture content of the coal product. By not conforming to these specifications, the coal supplier risks paying substantial penalties or could even be required to provide an on-spec product at no additional cost. The calorific value of a coal sample is adversely affected by the moisture content of the sample (Karthikeyan, 2008:953). Karthikeyan (2008:954) obtained a typical relationship between the calorific values of coal samples and the moisture content of those samples as shown in Figure 2.2.4. Wakeman (1984) estimated that a 1% reduction in moisture content could result in an increase of 1.4% in calorific value.

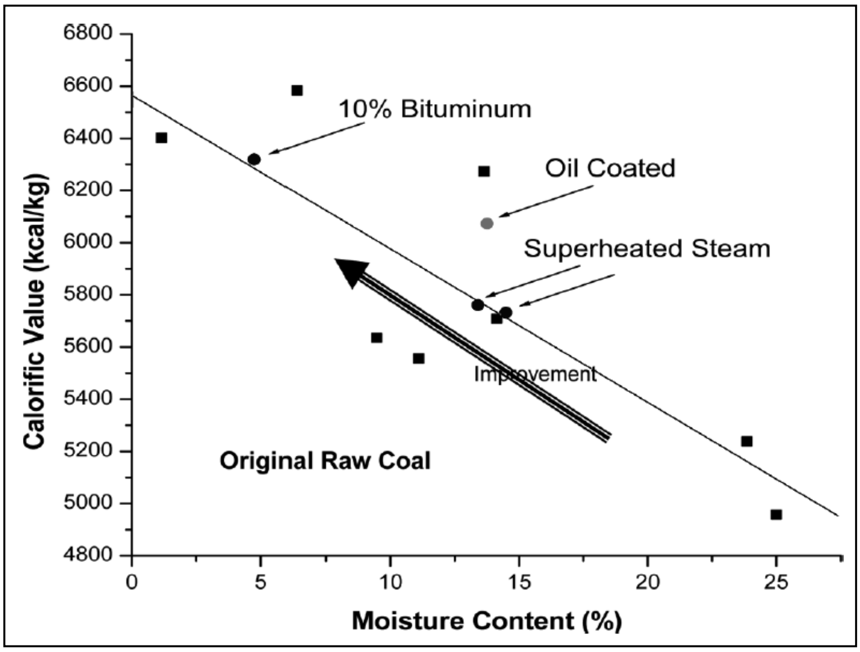

Figure 2.2.4: A typical relationship between coal moisture content and calorific values (Karthikeyan, 2008:954)

Excessive moisture does not only result in decreased coal quality, but can also lead to increased transportation costs as a result of the decreased calorific value (Firth *et al*., 1996; Hand, 2000:10; Rong, 1997:1; Williams, 2006:223) and handling problems (Firth *et al*., 1996; Leeder *et al*., 2011:1; Williams, 2006:223). Handling problems include the blocking of transfer chutes between conveyors and the obstruction of milling plants (Eskom, 2014).

Excessive moisture can also affect the stability of a coal stockpile by causing slabs of the stockpile to slip. If large sections of the stockpile should slip, a flow slide can occur (Eckersley, 1999:1). According to Eckersley (1999:1), the redistribution of initial moisture within a coal stockpile has a significant effect on the stability of the stockpile.

According to Spill-Sorb (s.a.) the effective heating value of wet coal can be estimated by [2.2.1] if the calorific value of the completely dry coal is known.

$$A = \frac{1}{100}[100B - X(B + 1120)] \quad [2.2.1]$$

In equation [2.2.1] A is the calorific value of the wet coal in BTU per pound, B is the calorific value of the absolutely dry coal in BTU per pound, X is the percentage of moisture contained in the wet coal. It takes 1120 BTU to raise one pound of water from 16.7 °C to 100 °C (Spill-Sorb, s.a.).

There are various equations which can estimate the gross calorific value of coal using ultimate analysis data. One of the oldest equations is the Dulong equation (SGS, s.a.), given in [2.2.2]:

$$GCV = 80.8C + 344.6H - 43.1O + 25S \quad [2.2.2]$$

2.2.3.1 Economic consequences in power stations

There are various economic consequences resulting from excess moisture in the coal feedstock. As the coal moisture content increases, its calorific value is decreased and more coal must be fired to produce a consistent power output. This increased amount of coal places strain on the coal handling system, conveyers and crushers. The additional strain increases maintenance costs and reduces the availability of the coal handling system. Furthermore, dryer coal requires less mill power to be pulverised and is easier to transport. Drier coal will also result in improved boiler efficiency and unit heat rate – this is mainly due to the lower stack loss and reduced station service power (Bullinger & Ness, 2002). An investigation conducted by Bullinger and Ness (2002) showed that – assuming a capacity factor of 0.8 – a 6 % reduction in coal moisture represented an annual savings of $1 300 000 for the two units at the power station.

2.3 Coal stockpiles

To ensure the efficient operation of coal consuming processes, a surge capacity in the form of stockpiles is essential. With the increased requirement for coal products, surge times are becoming briefer and good stockpile management is even more crucial (Keleher *et al*., 1998:422). Stockpiles are also used for blending and moisture control (Mahr, 2010).

Stockpiles can be used to dewater coal to the required moisture specification by means of gravity drainage and evaporation (Curran *et al*., 2002:2786; Williams, 2006:224). There are various factors which influence the effectiveness of using coal stockpiles for moisture control, such as PSD, weather conditions, stockpile height, and degree of compaction (Curran *et al*., 2002:2786; Williams, 2006:224). Depending on the season, the coal may be rewetted as a result of heavy rainfall. This can lead to an excessive increase in the moisture content of the coal (Williams, 2006:224).

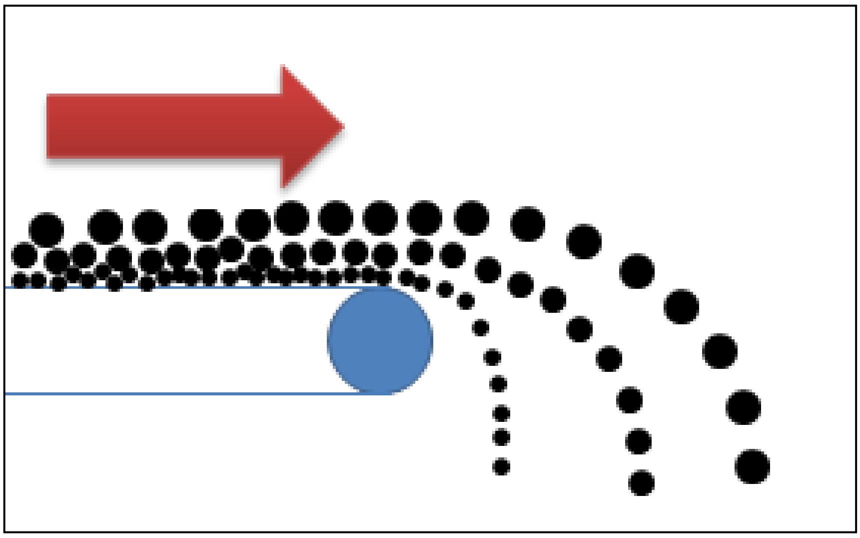

Figure 2.3.1: Particle segregation during transportation

2.3.1 Segregation

Coal particles of different sizes commonly segregate within the stockpile. The finer particles tend to accumulate at the crest and the coarser particles preferentially move to the base during the stockpile construction (Williams, 2006:224). Segregation can also occur during transportation, with the larger particles vibrating to the top and the smaller material to the bottom as illustrated by Figure 2.3.1. This results in a stockpile with larger particles on the one side, and smaller particles on the other side of the stockpile (McElwain & Fulford, 1995:60).

Segregation results in permeability contrasts within a stockpile (Eckersley, 1999) with zones containing fine particles inhibiting the drainage of water (de Korte & Mangena, 2004:5; Eckersley, 1999:6; Nkolele, 2004:171-172).

2.4 Mechanics of water movement in stockpiles

As seen in Figure 2.4.1, rainfall will either infiltrate the stockpile, or will directly run off the surface of the pile. The infiltrated water will either remain in the pile as coal moisture, or will percolate out the pile by means of gravity drainage (Brookman *et al*., 1981:2; Eckersley, 1999:1). The stockpile surface can be dried by means of evaporation. Each of these mechanisms is discussed in detail in this section.

2.4.1 Runoff versus infiltration

The relationship between coal stockpile runoff and infiltration is dependent upon factors such as PSD, rainfall intensity and duration, coal moisture content (Curran *et al*., 2000; Davis and Boegly, 1981; Kladias, 1993:13), and the degree of compaction of the stockpile surface (Curran *et al*., 2002). Various studies have found that the potential of correctly predicting the amount of run-off from coal storage facilities is restricted (Anderson & Youngstorm, 1976; Zelmanowitz et al., 1995).

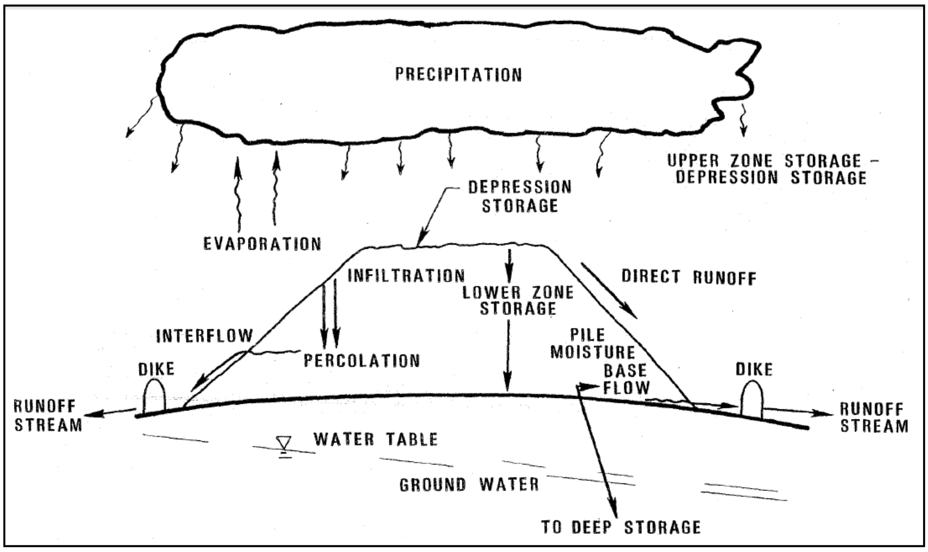

Figure 2.4.1: Hydrological cycle of a coal stockpile (Brookman *et al*., 1981:2)

Models which describe the quantity of coal-pile run-off – such as the one derived by TRC Environmental Consultants (1983) – are site-specific and cannot be applied to other coal stockpile systems. These models also generally make use of soil properties in order to attempt to describe coal-pile hydrodynamics (TRC Environmental Consultants, 1983; Williams, 2006). Depending on the rainfall intensity, the coal on the surface of the stockpile will become virtually saturated. Upon reaching saturation, the water will infiltrate vertically into the stockpile. The wetting front is defined as the margin between the wet coal and the coal at the initial moisture content. As more water is added to the pile – through rainfall for example – the wetting front will move deeper within the pile (Eckersley, 1999:23). According to Eckersley (1999:23), the water flow within a stockpile can concentrate in a central area under certain conditions – this would result in channelling with the water penetrating deeper and more quickly than anticipated. The infiltration process is controlled by the moisture properties of the saturated and unsaturated coal. As the water content increases, the suction in the water between the coal particles reduces. The movement of water is propelled by both moisture suctions and gravity (Eckersley, 1999:23). At many industrial coal field sites, coal stockpiles are often formed on compacted surfaces such as soil or concrete, which develops a pressure gradient within the stockpile. This pressure gradient may prevent rainwater infiltration by inhibiting the expulsion of air from the bottom of the stockpile (Curran *et al*., 2002:2786).

2.4.1.1 Rainfall intensity and duration

The proportion of rainfall which infiltrates a stockpile surface is a function of not only the rainfall intensity and duration (Wels *et al*., 2015:3), but also the infiltration capacity of the coal sample (TRC Environmental Consultants, 1983:3; Eckersley, 1999:35; Musy, 2001). This infiltration capacity is dependent on the sample's texture, structure and initial moisture content (Critchley *et al*., 1991). The infiltration capacity of a sample with low initial moisture content is higher than that of a sample containing high initial moisture content (Critchley *et al*., 1991; Musy, 2001). As the sample becomes saturated, a steady state value (defined as the final infiltration rate) is obtained (Critchley *et al*., 1991). The rainfall intensity and duration will thus determine whether this final infiltration rate will be reached. This rate is independent of the duration of the rainfall event, but will differ depending on the variability of the rainfall intensity. According to Huang *et al*. (2012), the high kinetic energy of raindrops in high intensity rainfall events will result in an increased amount of runoff water. This is supported by research conducted by Curran *et al*. (2002) as illustrated in Figure 2.4.2.

Runoff of water only occurs after the rainfall rate exceeds the infiltration capacity of the soil and all surface depressions (such as puddles and ditches) are filled (TRC Environmental Consultants, 1983:11; Critchley *et al*., 1991). According to Critchley *et al*. (1991), a high intensity rainfall event consists of raindrops which have substantial kinetic energy. This high kinetic energy can propel fine particles into the upper surface macropores – resulting in the obstruction of these pores and the establishment of a thin compacted layer at the surface which greatly decreases the infiltration capacity and increased the runoff proportion (Agassi *et al*., 1981; Curran *et al*., 2002:2785; Critchley *et al*., 1991; Huang *et al*., 2012:2). The extent to which this layer is formed is very dependent on the clay content of the sample (Agassi *et al*., 1981; Critchley *et al*., 1991).

It is generally assumed in soil mechanics that the runoff quantity is a function of the rainfall depth as described by equation 2.4.1, where the coefficient K relates the percentage of runoff to the rainfall quantity. K is, however, not constant and is dependent on surface and rainfall characteristics (Critchley *et al*., 1991).

$$Runoff\ (mm) = K \times Rainfall(mm) \qquad [2.4.1]$$

A specific quantity of rainfall – defined as the threshold rainfall value – is necessary before any runoff will transpire. The threshold rainfall value is dependent on sample specific surface characteristics (Critchley *et al*., 1991).

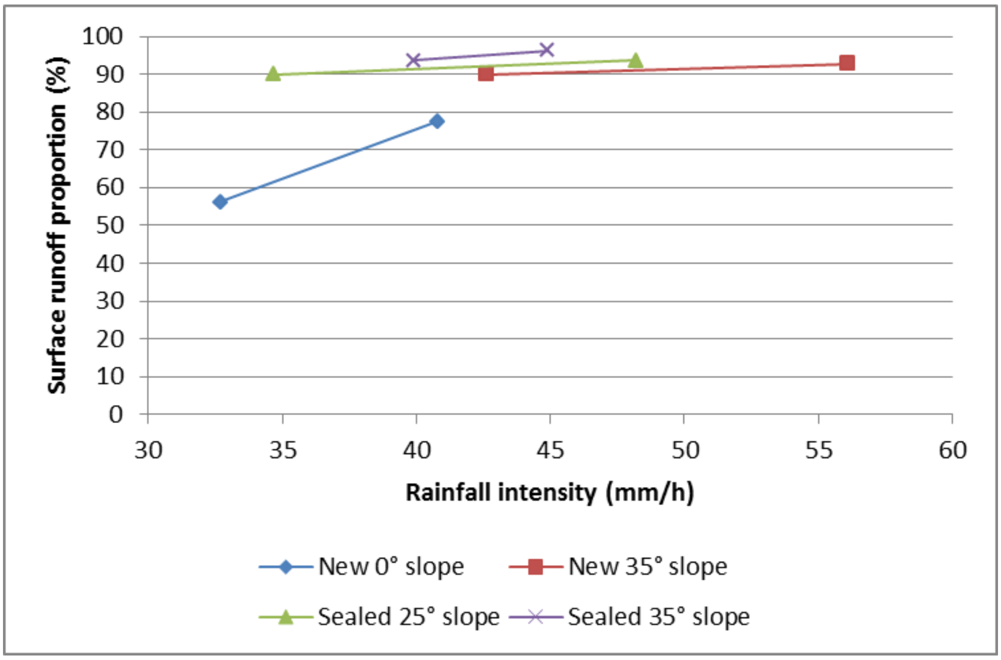

Figure 2.4.2: Influence of the rainfall intensity on the runoff proportion (adapted from Curran *et al.* (2002))

2.4.1.2 PSD

According to Curran *et al*. (2002:2785), water travels preferentially through the macropores formed between the particles in the stockpile. It is thought that the movement of water through micropores is hindered by the hydrophobic characteristics of coal (Soo & Radke, 1984). There is a positive relationship between the size of the particles and porosity of the sample (Critchley *et al*., 1991; Mahajan & Walker, 1978:136). Water will thus infiltrate a coarse coal stockpile with much more ease compared to a fine coal stockpile. It should be noted that the ability of rainfall to infiltrate a coal stockpile is related to its drainage characteristics – the infiltrated water will drain out of a coarse coal stockpile much faster and to a greater extent (Eckersley, 1999:30).

2.4.1.3 Coal moisture content

As mentioned in section 2.4.1.1, the infiltration capacity of a coal stockpile is influenced by its initial moisture content (Critchley *et al*., 1991). A dry coal stockpile will have a high initial infiltration capacity which will decrease over time until a constant value is achieved (Critchley *et al*., 1991; Musy, 2001). This value will remain constant only if the surface of the stockpile is undisturbed. As the infiltration capacity diminishes over time, the runoff proportion will increase as shown in Figure 2.4.3 (Musy, 2001). Surface runoff will only occur once the rainfall intensity is greater than the infiltration capacity.

2.4.1.4 Angle of repose

Research performed by Sharma (1986) on experimental runoff plots of soil showed that an increase in slope angle yields a greater surface runoff proportion. Similar results have been shown

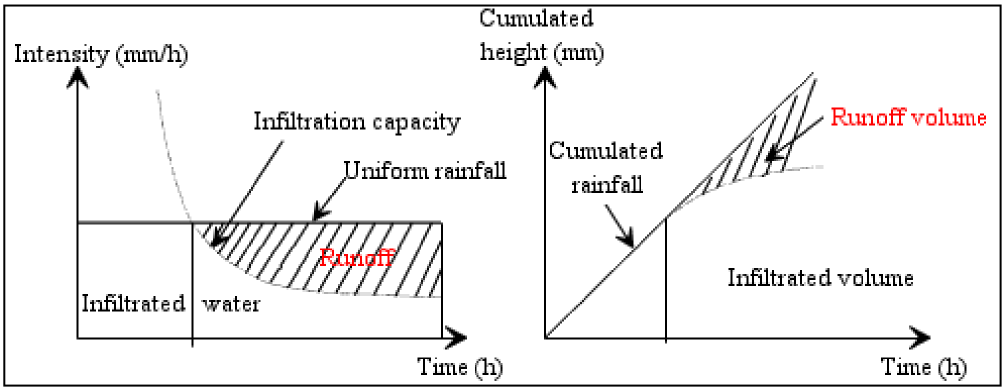

Figure 2.4.3: Change in infiltration capacity and runoff amount over time (Musy, 2001)

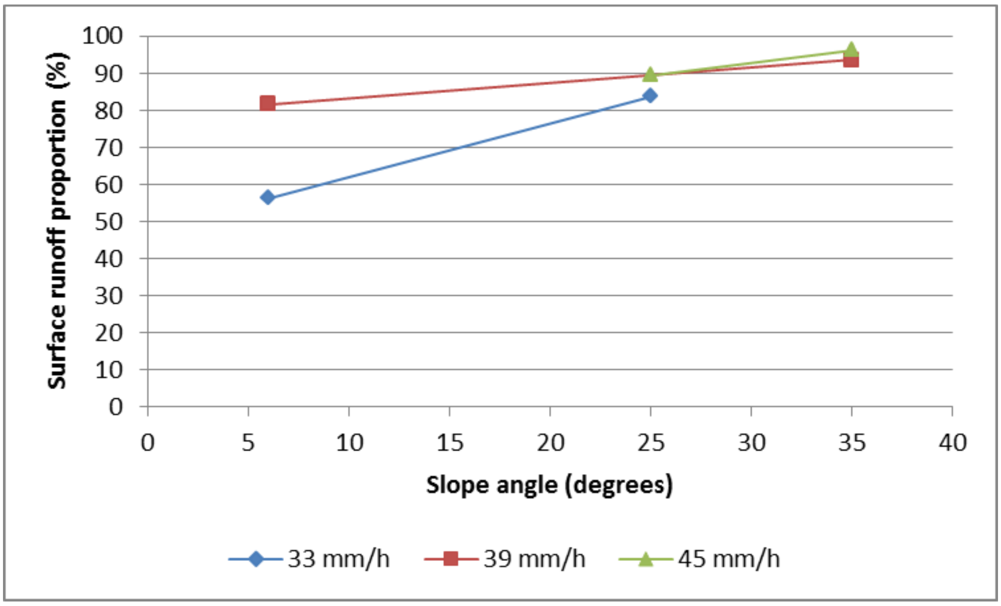

Figure 2.4.4: Influence of slope angle on the surface runoff proportion (Curran *et al*., 2002)

for coal stockpiles by researchers such as Curran *et al*. (2002) who constructed a coal-stockpile-rainfall simulator. Figure 2.4.4 illustrates the positive relationship between the surface runoff proportion and the slope angle as found by Curran *et al*. (2002:2784). In research performed by Wels *et al*. (2015:3), it was found that the probability of sidelong flows parallel to the surface was amplified when surfaces were slanted, which increased the proportion of runoff water.

Sharma (1986) observed that an increase in slope length lead to a decrease in the amount of runoff. This is attributed to the longer contact time between the surface and the runoff water which results in a greater probability of infiltration. Ekmann and Le (2014:18) suggested the construction of stockpiles with high angles of repose to reduce the proportion of infiltrated water.

2.4.1.5 Degree of compaction

The compaction of a coal bed results in the decrease of voids between the coal particles (McLean, 1998:406). As water is generally travels through the macropores formed between the coal particles (Curran *et al*., 2002:2785), the reduction of these pathways will lead to an increased resistance towards the infiltration of water (McLean, 1998:406). Compaction could also lead to the generation of additional fines (Bear, 1972:53), which will further inhibit the infiltration of water into the coal bed (de Korte & Mangena, 2004:5; Eckersley, 1999:6; Nkolele, 2004:171-172).

By compacting coal stockpile surfaces, the amount of water which infiltrates the stockpile can be minimised (Ekmann & Le, 2014; TRC Environmental Consultants, 1983).

2.4.1.6 Erosion

The probability of shallow erosion occurring increases once the surface of the coal stockpile is saturated (Eckersley, 1999:35). This is attributed to the fact that the stockpile's natural angle of repose is usually near the effective friction angle of the coal (36° to 40°), which means that only a slight positive pressure is needed to incite a slip (Eckersley, 1999:35). High intensity rainfall conditions will increase the extent to which erosion occurs (Huang *et al*., 2012:2: TRC Environmental Consultants, 1983). Erosion will also occur more readily on stockpile surfaces with high slopes (Brookman *et al*., 1981:3; Curran *et al*., 2002:2789).

2.4.2 Gravity drainage

Washed coal is regularly stockpiled with a high enough initial moisture content to facilitate gravity drainage towards the base of the stockpile (Eckersley, 1999:23). According to Eckersley (1999:23), the process of gravity drainage is controlled by the water flow properties of the unsaturated coal. These properties are influenced by factors such as PSD (de Korte & Mangena, 2004:5; Eckersley, 1999:6; Nkolele, 2004:171-172), stockpile height (Williams, 2006:224; Curran *et al*., 2002:2786), degree of compaction (Eckersley, 1999:15), and coal type (Eckersley, 1999), among others. Gravity drainage can result in a decrease in the moisture content of the upper 80% of the stockpile (Eckersley, 1999:23).

The stockpile is usually constructed on a subgrade (such as compacted coal, coal waste or soil) with a lower permeability than the coal which impedes the flow of water into the subgrade. As the water drains within the stockpile, the bottom coal layer becomes saturated with the excess water flowing along the low permeability boundary to eventually seep through the stockpile toe (Eckersley, 1999:22). Eckersley (1999:22) observed that the seepage from the stockpile toe commenced between 1 and 3 days following the construction of the stockpile. Once the seepage has begun, it can continue for weeks until there is no more water available for drainage. As the water is vertically redistributed by means of gravity drainage, the height of the saturated coal layer rises which results in a more rapid seepage rate through the toe of the stockpile. Eventually, the rate of drainage towards the base of the stockpile decreases, which results in a decrease in the height of the saturated layer as well as a decrease in the rate of seepage from the toe (Eckersley, 1999:22). According to Eckersley (1999:22), the flow within the saturated layer of the stockpile is managed by the moisture properties of the saturated coal – primarily the resaturated permeability.

2.4.2.1 Initial moisture content

In an investigation performed by Eckersley (1999:23), it was found that drainage column tests may be used to determine a moisture threshold which would give an indication of whether the amount of moisture redistribution which could take place would be significant. Stockpiles with initial moisture content below that of the moisture threshold would not experience significant vertical redistribution, while coal with an initial moisture content above that of the moisture threshold would experience significant drainage resulting an the formation of a saturated zone at the base (Eckersley, 1999:23). This is in agreement with the results obtained by Leeder (2011), which showed that drainage is a function of initial moisture content.

During the course of Eckersley's (1999:52) investigation, it was found that coal with higher initial moisture content also had higher moisture content at the end of the experiment. This manifestation is shown in Figure 2.4.5, where it can clearly be seen that coal sample LB-1 (initial total moisture content of 10.8%) had a final moisture content much lower than that of sample LB-3 (initial total moisture content of 14.8%). It is hypothesised by Eckersley (1999:52) that this occurrence might be a function of the amount of fine content within the coal as the effect was more pronounced at the samples containing more fines.

Results showed that an increase in initial moisture content at the same initial dry coal density resulted in an increase in both the maximum water level as well as an increase in the rate of drainage (Eckersley, 1999:52). This is clearly illustrated by Figure 2.4.6. Eckersley (1999:52) attributes this observation as a result of having less void space vacant which can be occupied by the redistributing moisture in the base of the column, as well as the positive relationship between higher moisture content and the permeability of the unsaturated coal (see section 2.2.2.3).

2.4.2.2 PSD

Curran *et al*. (2002:2785) found that water travels preferentially through the macropores formed between the particles in the stockpile. It is thought that the movement of water through micropores is hindered by the hydrophobic characteristics of coal (Soo & Radke, 1984). Large suspended particles can also function as plugs, which would result in sealing pore spaces (Curran *et al.*, 2002:2787). Pore spaces can also be clogged by fines, which would further reduced bed permeability.

The fineness of the coal particles has a big influence on the properties of coal – particularly on the coal-water interaction (de Korte & Mangena, 2004:5; Eckersley, 1999:6; Nkolele, 2004:171-172). Eckersley (1999:6) states that coal with less than 10% fines (generally defined as particles smaller than 0.5 mm) is usually free draining. Fine coal has a high surface area to which water can stick (de Korte & Mangena, 2004:5; Nkolele, 2004:171-172). With fine coal, the voids between the particles are so small that they act as capillary cavities which become filled with water. The capillary forces exerted on the water are so strong that mechanical dewatering will be unsuccessful (de Korte, 2000; Eckersley, 1999:12).

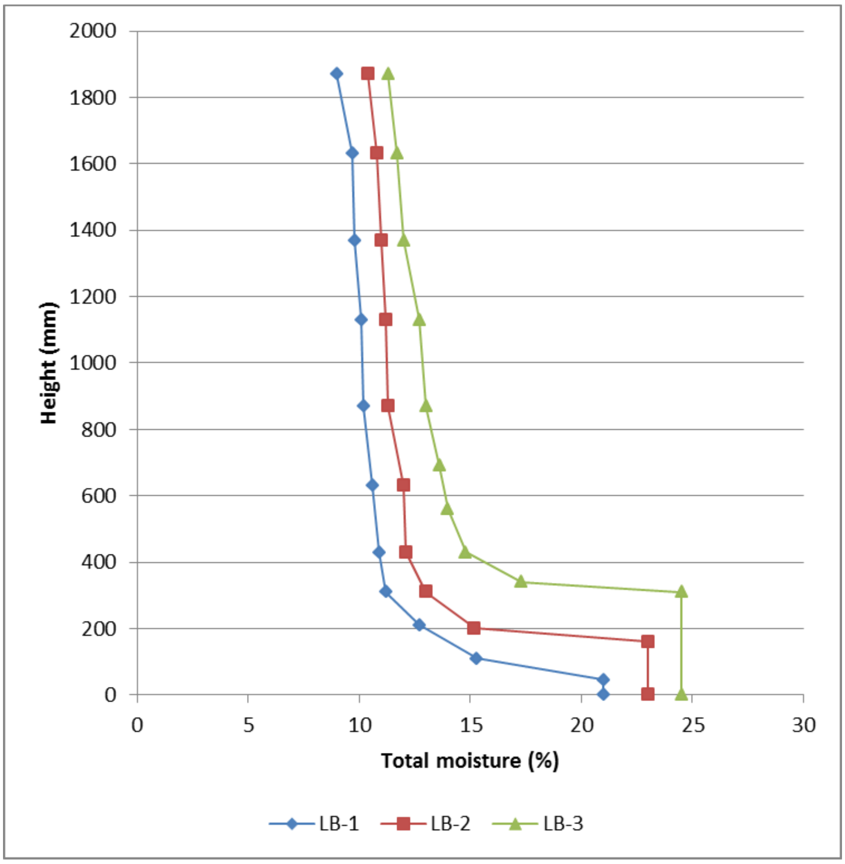

Figure 2.4.5: Final moisture distribution for coal sample LB (Eckersley, 1999:55)

A study was conducted by the Fuel Research Institute of South Africa (FRISA) in 1964 to investigate the static drainage of fine Elandsberg coal. During the course of the investigation, focus was placed on the establishing the size range which had the greatest influence on the drainage characterises.

It is shown in Figure 2.4.7 that the removal of the -0.5 mm coal particles has the most significant influence on the static drainage characteristics of a coal sample. By removing more -0.5 mm material, the amount of moisture which the coal samples retains is significantly lessened. It is indicated in Figure 2.4.8 that an increased amount of -0.5 mm fine content has a positive effect on the amount of water which is retained by the coal sample.

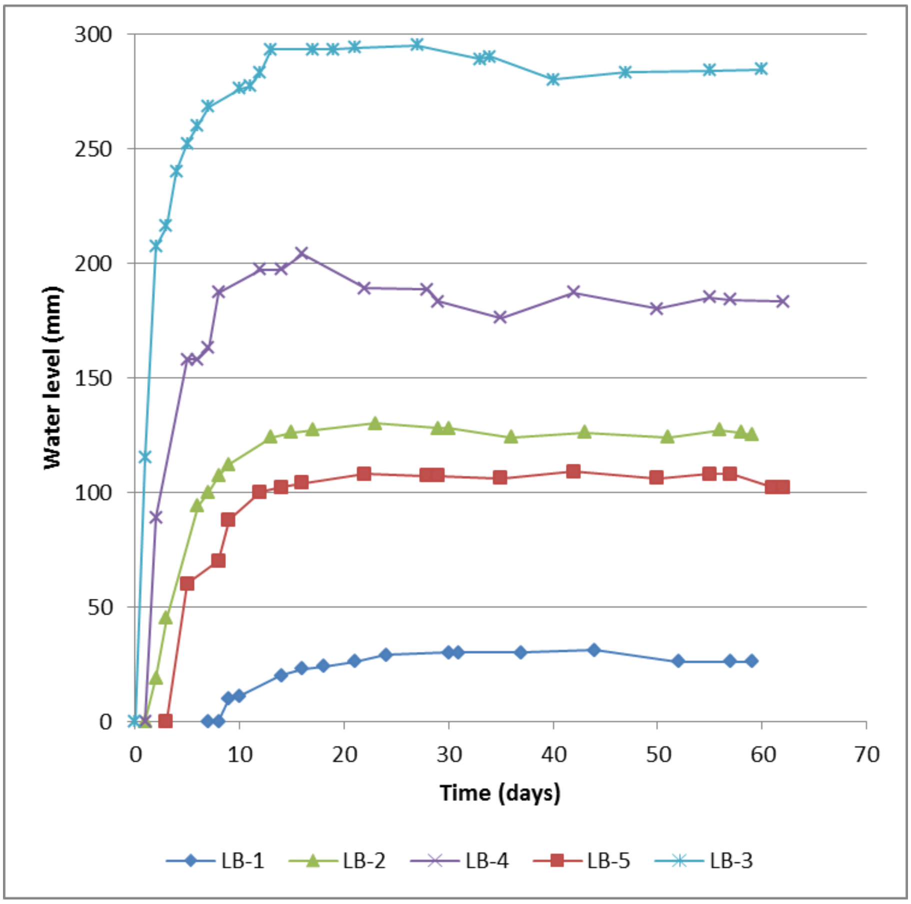

Figure 2.4.6: Column drainage water levels from coal LB (Eckersley, 1999:53)

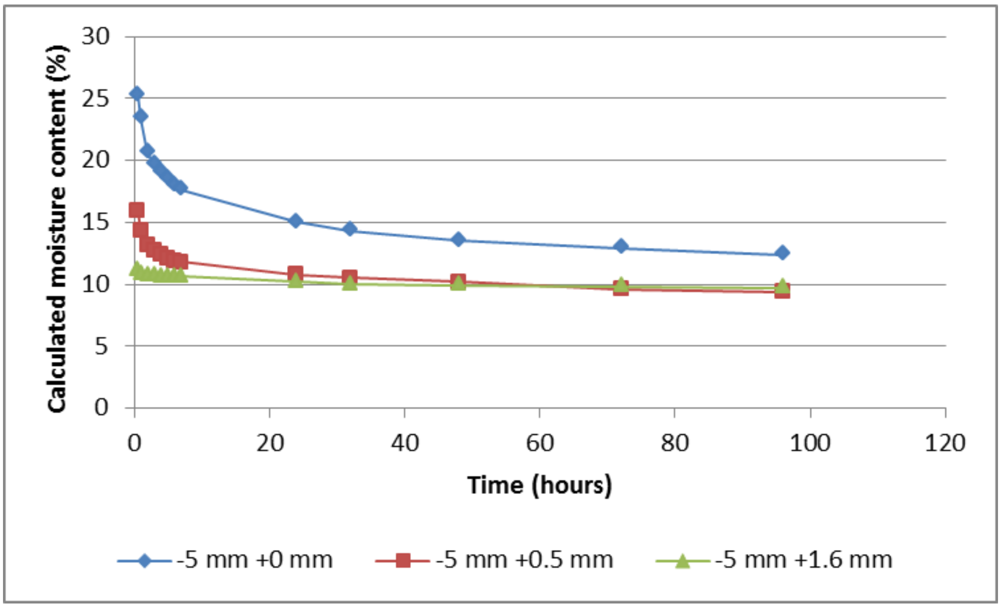

Figure 2.4.7: Effect of the elimination of lower size ranges on drainage characteristics (FRISA, 1964:8)

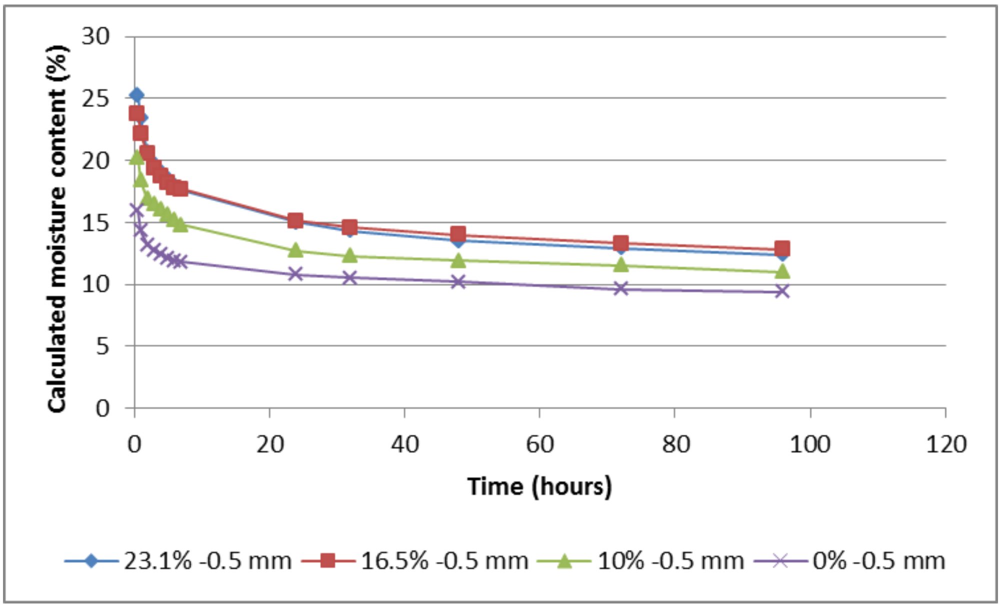

Figure 2.4.8: Effect of the percentage of -0.5 mm material on the drainage characteristics (FRISA, 1964:9)

2.4.2.3 Stockpile height

The extent of gravity drainage is largely determined by the height of the stockpile (Curran *et al*., 2002:2786, Eckersley, 1994; Leeder *et al*., 2011; Williams, 2006:224). Leeder *et al*. (2011:6) found that coal with a moisture content of 10.5% drained after two months in a 7.3 m high drainage pipe, while no drainage was experienced for coal samples with a moisture content of less than 14% in a 2 m high drainage pipe over the period of a months. Similar results were obtained by Eckersley (1999). As part of the investigation conducted by Leeder *et al*. (2011:7), it was found that the time taken to commence initial drainage can be directly related to the height of the column. This relationship is shown in Figure 2.4.9.

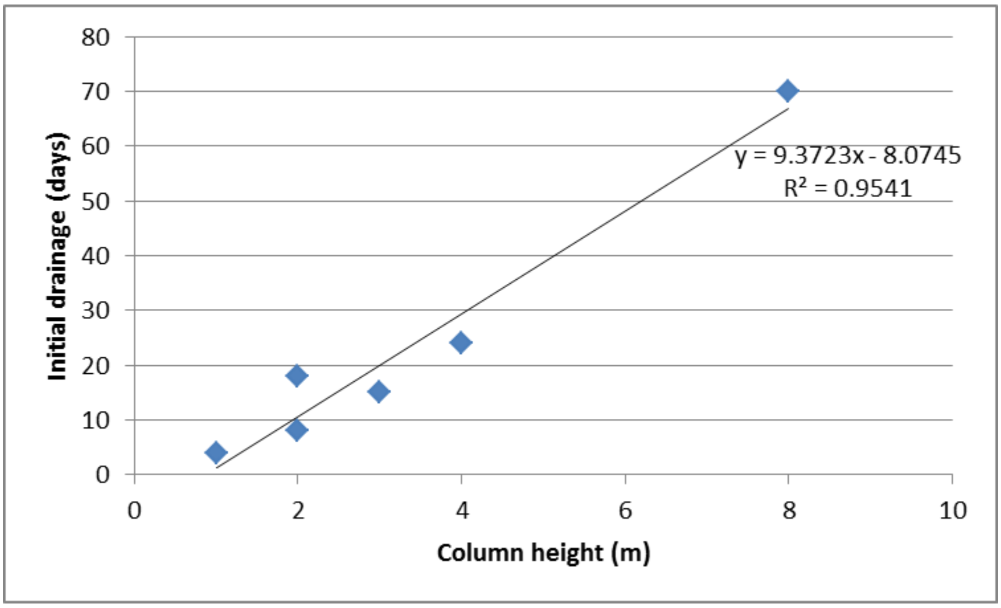

Figure 2.4.9: Days to drainage with Vancouver equivalent rainfall moisture added (coal moisture between 6.5 and 8%) (Leeder *et al*., 2011:7)

2.4.2.4 Vibration

Leeder *et al*. (2011:6) investigated the drainage and migration of moisture in a vibrated column. The aim of this investigation was to simulate vessel vibration during the shipment of the coal product. It was found that by vibrating the column, the rates of both moisture redistribution and drainage was increased six-fold when compared to that of a non-vibrated column (Leeder *et al*., 2011:6).

2.4.3 Evaporation

According to Williams (2006:224), evaporation by means of wind and solar action is reputed to be considerably more successful than gravity drainage, but only extends to a restricted depth from the exterior of the stockpile (Boyapati & Oates, 1994:687; TRC Environmental Consultants, 1983:76; Williams, 2006:224). The effectiveness of solar and wind action can be improved by angling the stockpile perpendicular to the predominant wind direction, maximizing the surface area of the pile and reclaiming the coal from the pile gradually in shallow cuts over a large area (Williams, 2006:224).

The extent of evaporation is mainly influenced by the weather – in particular solar radiation, temperature, wind strength and humidity (CSEM-UAE, 2010:1; Deodhar, 2008:25-29; Priyal & Toerien, 2010:3) – as well as by the porosity, heat conductivity and chemical nature of the coal particles (de Korte & Mangena, 2004:5).

During the formation of a mathematical model to describe the drainage of water from a coal stockpile in the United States (US), TRC Environmental Consultants (1983:13) derived a linear equation 2.4.2, which relates the evaporation of water from a pan of to the evaporation from the surface of a coal pile.

$$Cumulative\ Pile\ Evaporation = 0.293 * Cumulative\ Pan\ Evaporation + 0.177 \quad [2.4.2]$$

It was, however, noted that there are challenges between formulating a relationship between the rate of evaporation from a flat body of water and that from a coal stockpile surface (TRC Environmental Consultants, 1983). There are factors which influence the rate of evaporation from coal particles which do not affect the evaporation from a body of water. One of the factors is that attraction forces exist between the water and coal particles, which will reduce the rate of evaporation. Other factors which influence the rate of evaporation are that coal particles are generally black with a rough surface (TRC Environmental Consultants, 1983).

Primarily, two heat and mass transfer mechanisms describe the process of evaporation. These two mechanisms are diffusion and advection (Sartori, 1999). According to Sartori (1999), the influence of advection can be regarded as negligible at the water surface due to the low fluid velocity. McElwain and Fulford (1995:56) considered two mechanisms – diffusion and convection – to describe the loss of moisture from the stockpile surface by means of evaporation. It was concluded that diffusion alone cannot significantly decrease the moisture content of the stockpile in a reasonable period of time, while convection could be a feasible mechanism (McElwain & Fulford, 1995:56-57).

According to Fryer and Szladow (1973), moisture from a coal stockpile surface will evaporate until equilibrium is obtained between the ambient atmosphere and the coal particles. Once the relative humidity increases as the temperature decreases, the coal particles can reabsorb moisture to re-establish equilibrium (Fryer & Szladow, 1973; Karthikeyan *et al*., 2009). This process of desorption and reabsorption can be repeated on a daily cycle (Fryer & Szladow, 1973). This cycle can lead to the occurrence of slacking which will eventually result in an increased total coal surface area exposed to air (Fryer & Szladow, 1973).

2.4.3.1 Temperature

The ambient temperature of the atmosphere provides the heat required for the water molecules to reach the temperature at which evaporation occurs (Dama-Fakir & Toerien, 2010). An increase in temperature will lead to an increased rate of evaporation (Brown, 2014). As the temperature increases, the saturated partial pressure of the water vapour in the air will also increase (Headrick, 1967; Ryan, 2006). The water which evaporates from the coal surface will try to achieve this new partial pressure (Ryan, 2006).

2.4.3.2 Vapour pressure

The vapour pressure (water vapour partial pressure) at the surface of the water body or coal stockpile is generally higher than the atmospheric vapour pressure, which results in the water molecules moving from the high to the lower vapour pressure (Headrick, 1967), thus aiding the process of evaporation. There exists a positive relationship between the temperature and vapour pressure (Katsaros, 2001:874).

2.4.3.3 Relative humidity

High levels of relative humidity are associated with higher vapour pressures (Katsaros, 2001:871), which will lead to a lower rate of evaporation as the saturation level is reached faster (Dama-Fakir & Toerien, 2010).

2.4.3.4 Solar radiation

Solar radiation provides the energy required for the evaporation process to occur (Dama-Fakir & Toerien, 2010). An increase in the amount of solar radiation will thus translate into an increase in the rate at which evaporation occurs (Brown, 2014).

2.4.3.5 Wind action

The purpose of wind in the evaporation process is to remove the saturated air at the surface of the evaporating substance and replace it with unsaturated air (Dama-Fakir & Toerien, 2010). The rate of evaporation will thus increase if the windspeed increases (Brown, 2014; Headrick, 1967). According to Dama-Fakir and Toerien (2010), wind has a larger effect on the rate of evaporation at lower temperatures than temperature itself.

2.4.3.6 Surface area

An increase in surface area will lead to an increase in the rate of evaporation as this means that more moisture is exposed to the surrounding atmosphere. According to McElwain and Fulford (1995:55) a small particle should evaporate at a faster rate compared to a larger particle.

2.4.4 Suspended sediment

In the study conducted by Curran *et al*. (2002:2785), it was found that coal particles with certain characteristics were suspended in the runoff, infiltration and gravity drainage water. The suspended solid concentrations are dependent on the compaction and slope of the stockpile, and the extent of erosion which has occurred. A newly formed stockpile will have the highest concentration of solids suspended in the run-off as erosion and compaction has not yet taken place. An increase in the slope of the stockpile will result in an increase in suspended sediment concentration in the runoff, and a decrease in the suspended sediment concentration in the infiltration (Curran *et al*., 2002:2785). Both Hogg (1980) and Curran *et al*. (2002:2785) observed in their experiments that the suspended sediment samples do not aggregate within the runoff or infiltration.

CHAPTER 3: EXPERIMENTAL

In this chapter the experimental methodology used to perform the investigations required for this project is discussed. In section 3.1 the coal sample is characterised and discussed. A summary of the equipment used and the procedure followed for the experiments is given in section 3.2.

3.1 Coal

During this investigation two coals were studied. Coal A – a typical power station feedstock coal – was a mixture of washed Witbank No. 2 Seam and No. 4 Seam coals, while the coal B was export washed Witbank No. 2 Seam coal. Both coals were obtained directly from the source. Coal A was stored in 1 tonne bulk bags and coal B was stored on a stockpile covered with a tarpaulin. Both coal A and coal B had size ranges of -53 mm +0 mm. The total, surface and inherent moisture contents of each sample were obtained several times during this investigation. The procedure for these calculations is given in Appendix A.

3.1.1 Coal characterisation

To characterise the coal samples, three analyses were performed. These analyses were: proximate, calorific value (CV), and x-ray diffraction (XRD) analysis. The results of the proximate analysis and CV test are given in Table 3.1.1. These tests were performed on an air-dried (a.d.) basis by Bureau Veritas Testing and Inspections South Africa. It should be noted that the CV is not sulphur corrected.

According to Takarada *et al*. (1985), the inherent moisture content of a coal sample can be viewed as an indication of the porosity of coal. As both coal A and B had similar inherent moisture contents, it can be assumed that the coals had comparable porosities as well. It is shown in Table 3.1.1 that coal A is a high ash coal, which means that the coal was more likely to retain moisture (Nkolele, 2004: 172; Pluzhnikov *et al*., 1993:18-20; Rozgonyi & Szigeti, 1985) when compared to lower ash coals such as coal B.

Table 3.1.1: Proximate analysis of coal samples

	A (wt%) a.d.	B (wt%) a.d.	Standard
Inherent moisture content	2.5	2.6	ISO 11722: 1999
Ash content	35.6	15.9	ISO 1171: 2010
Volatile matter	19.0	25.2	ISO 562: 2010
Fixed carbon	42.9	56.4	By difference
CV (MJ/kg) a.d.	19.24	26.89	ISO 1928: 2009
Grade (based on a.d. CV)	Grade D-III	Grade B	CKS 561-1982

Table 3.1.2: XRD analysis of coal samples

Mineral	A		B	
	Weight (%)	Error	Weight (%)	Error
Calcite	0.43	0.10	1.14	0.17
Dolomite	0.42	0.17	0.97	0.19
Graphite	66.15	1.53	83.29	0.66
Gypsum	1.79	0.29	0.11	0.08
Hematite	0.33	0.14		
Kaolinite	21.85	1.02	12.66	0.48
Muscovite	2.25	0.27	0.79	0.29
Pyrite	0.71	0.11	0.17	0.06
Quartz	5.91	0.30	0.89	0.09
Siderite	0.16	0.12		

The XRD analysis results are given in Table 3.1.2. This analysis does not account for any species in the amorphous phase but only the crystalline phase. Large errors in the estimated values are due to possible crystallite size effects. Coal A has high kaolinite content, as shown in Table 3.1.2. This, coupled with coal A's high ash content, means that coal A will most likely retain much more moisture than coal B as kaolinite is clay mineral (Buckley & Nicol,1995:44).

3.2 Runoff versus infiltration

3.2.1 Experimental apparatus

The runoff versus infiltration experimental setup is shown in Figure 3.2.1. The dimensions of the coal container was 1.24 x 0.50 x 0.55 m and could be fastened at angles of 0°, 20°, 30° and 38°. The container was placed into different positions by the use of an overhead crane. Rainfall was simulated by use of the three containers seen at the top of the setup in Figure 3.2.1. Each container had several 0.1 mm holes drilled in at the bottom and was equipped with a float ball valve to regulate the water level. The water level controlled the rainfall intensity – a higher water level resulted in a more intense rainfall event. For each rainfall event a different level was thus maintained in the containers. Once the rain fell on the coal bed it either ran off or infiltrated the interior of the bed. The runoff water accumulated in the gutter and was removed through an outlet. The infiltrated water was removed by an outlet value at the bottom of the container. To prevent the loss of coal particles through the bottom outlet, a metal mesh layer was installed just before this valve. The runoff and surface water were collected in separate containers which were continuously weighed.

Figure 3.2.1: Runoff versus infiltration experimental setup

3.2.2 Experimental procedure

To perform experiments, a specific coal sample – as summarised in Table 3.2.1 – was loaded into the container shown in Figure 3.2.1. The coal bed was saturated with water to ensure that the experiments were conducted at steady state conditions to guarantee that the results were comparable. Water was added to the rainfall simulator containers to the required level and the coal container was placed on the correct angle. Once steady state conditions were established, the experiment was started. The amounts of rain which ran off the surface and infiltrated the coal bed within a certain time period was collected separately and weighed. This procedure was repeated three times for each experimental condition as summarised in Table 3.2.1. As it is impossible to replicate a coal bed due to variabilities in particle size and packing, the same coal bed was used for all experiments using the same particle size range or compaction. It should be noted that structural changes occurred within the coal bed during the experiments due to fine particles being washed out and the surface of the bed being compacted due to rainfall.

The compacted coal beds were prepared by loading a certain amount of coal into the container and decreasing the sample volume until a certain degree of compaction (defined by the bulk density of the sample) was obtained. To ensure that the degree of compaction was homogeneous throughout the coal bed, the bed was compacted layer by layer. The thickness of each layer was measured, where after mechanical pressure was applied to compact the layer to a predetermined fraction of the initial thickness.

Table 3.2.1: Summary of the runoff versus infiltration experimental conditions

RI (mm/h)	Slope angle	Size range	Compacted	No. of repeats
174	20°	-53 mm +6.7 mm	No	3
174	30°	-53 mm +6.7 mm	No	3
174	38°	-53 mm +6.7 mm	No	3
220	20°	-53 mm +6.7 mm	No	3
220	30°	-53 mm +6.7 mm	No	3
220	38°	-53 mm +6.7 mm	No	3
290	20°	-53 mm +6.7 mm	No	3
290	30°	-53 mm +6.7 mm	No	3
290	38°	-53 mm +6.7 mm	No	3
174	20°	-53 mm +0 mm	No	3
174	30°	-53 mm +0 mm	No	3
174	38°	-53 mm +0 mm	No	3
220	20°	-53 mm +0 mm	No	3
220	30°	-53 mm +0 mm	No	3
220	38°	-53 mm +0 mm	No	3
290	20°	-53 mm +0 mm	No	3
290	30°	-53 mm +0 mm	No	3
290	38°	-53 mm +0 mm	No	3
174	20°	-6.7 mm +0 mm	No	3
174	30°	-6.7 mm +0 mm	No	3
174	38°	-6.7 mm +0 mm	No	3
220	20°	-6.7 mm +0 mm	No	3
220	30°	-6.7 mm +0 mm	No	3
220	38°	-6.7 mm +0 mm	No	3
290	20°	-6.7 mm +0 mm	No	3
290	30°	-6.7 mm +0 mm	No	3
290	38°	-6.7 mm +0 mm	No	3
174	20°	-53 mm +0 mm	Yes – to 1069 kg/m^3	3
174	30°	-53 mm +0 mm	Yes – to 1069 kg/m^3	3
174	38°	-53 mm +0 mm	Yes – to 1069 kg/m^3	3
220	20°	-53 mm +0 mm	Yes – to 1069 kg/m^3	3
220	30°	-53 mm +0 mm	Yes – to 1069 kg/m^3	3

RI (mm/h)	Slope angle	Size range	Compacted	No. of repeats
220	38°	-53 mm +0 mm	Yes – to 1069 kg/m^3	3
290	20°	-53 mm +0 mm	Yes – to 1069 kg/m^3	3
290	30°	-53 mm +0 mm	Yes – to 1069 kg/m^3	3
290	38°	-53 mm +0 mm	Yes – to 1069 kg/m^3	3
174	20°	-53 mm +0 mm	Yes – to 1157 kg/m^3	3
174	30°	-53 mm +0 mm	Yes – to 1157 kg/m^3	3
174	38°	-53 mm +0 mm	Yes – to 1157 kg/m^3	3
220	20°	-53 mm +0 mm	Yes – to 1157 kg/m^3	3
220	30°	-53 mm +0 mm	Yes – to 1157 kg/m^3	3
220	38°	-53 mm +0 mm	Yes – to 1157 kg/m^3	3
290	20°	-53 mm +0 mm	Yes – to 1157 kg/m^3	3
290	30°	-53 mm +0 mm	Yes – to 1157 kg/m^3	3
290	38°	-53 mm +0 mm	Yes – to 1157 kg/m^3	3
290	38°	-53 mm +0 mm	Yes – to 1157 kg/m^3	3

3.3 Drainage

3.3.1 Experimental apparatus

To simulate the drainage process which occurs within a stockpile, two drainage columns (2 m and 0.48 m) were constructed and are pictured in Figure 3.3.1. The columns had an interior diameter of 0.385 m and were fitted with mesh at the bottom which supported the packed coal bed and facilitated the drainage process. A perforated plate was added to the top of the 2 m high column and this acted as a water distribution system. The drained water was collected at the bottom and, in the case of the 2 m high column, continuously weighed by a scale connected to a data logger. The 2 m high drainage column was equipped with two sampling methods. The first method consisted of three sampling ports at the back of the column. These sampling ports could only be accessed by lowering the column to a horizontal position, opening the ports at the back and sampling the coal with a ground auger. The second method involved sampling the coal while the column was vertical through one of four sampling ports shown in Figure 3.3.1.

3.3.2 Experimental procedure

Coal samples with specific characteristics (as summarised in Table 3.3.1) were loaded into the columns. In all cases 20 L of water was added to the top of the column, allowed to percolate through the coal bed, and collected at the bottom. The amount of water which percolated through the packed bed in the 2 m high column was continuously weighed and the data was logged. The water drained from the 0.48 m high coal bed was weighed only after all drainage had ceased.

Figure 3.3.1: : Drainage column experimental setup (left: 2m high, right: 0.48 m high)

Table 3.3.1: Summary of the drainage experimental conditions

Coal type	Column height (m)	Size range	ρ_B	Layer of fines	No. of repeats
A	0.48	-53 mm +0 mm	1073	No	2
A	0.48	-53 mm +0 mm	1198	No	3
A	0.48	-53 mm +0 mm	1288	No	3
A	0.48	-53 mm +0.5 mm	-	No	2
A	0.48	-53 mm +0 mm	-	Yes (3 cm)	2
A	0.48	-53 mm +0 mm	-	Yes (6 cm)	2
A	2	-53 mm +0 mm	-	No	2
A	2	-53 mm +0.5 mm	-	No	2
A	2	-53 mm +1 mm	-	No	2
B	2	-53 mm +0 mm	-	No	3
B	2	-53 mm +6.7 mm	-	No	3
B	2	-6.7 mm +0 mm	-	No	3

Samples were taken from the 2 m high column every other day to track the migration of moisture and fine coal content over time. The coal bed in the 0.48 m drainage column was only sampled during the deconstruction of the bed once drainage has come to an end. In the experiments where coal A was used, a new coal sample was used for each repeat, while for experiments in which coal B was used, water was added to the same coal samples to constitute repeats.

3.4 Evaporation from stockpile surfaces

3.4.1 Rate of evaporation

3.4.1.1 Experimental apparatus

To determine the rate at which water evaporates from a coal stockpile surface, the setup shown in Figure 3.4.1 was constructed. Three plastic containers were positioned on scales and placed on the frame. To prevent the ingress of actual rain, the frame was equipped with a perspex roof. A weather station was located near the experimental setup.

3.4.1.2 Experimental procedure

To investigate the factors which have an impact on the rate of evaporation from coal stockpile surfaces, coal with different size ranges was loaded into the containers shown in Figure 3.4.1. The weight of the coal samples and the weather conditions were continuously recorded. The different experimental conditions are summarised in Table 3.4.1. Each coal bed was sampled at the start and end of each experimental run to determine the exact amount of moisture which was lost through evaporation. A fresh coal sample was used for each experimental run. The coal sample was separated into the required size ranges before being loaded into the experimental apparatus.

Figure 3.4.1: Evaporation rate experimental setup

Table 3.4.1: Summary of evaporation rate experimental conditions

Date	Coal type	Size range
20/06/2014 – 04/07/2014	A	-50 mm +0 mm
20/06/2014 – 04/07/2014	A	-26.5 mm +0.5 mm
20/06/2014 – 04/07/2014	Water	-
15/07/2014 – 29/07/2014	A	-50 mm +0 mm
15/07/2014 – 29/07/2014	A	-26.5 mm +0.5 mm
15/07/2014 – 29/07/2014	Water	-
29/08/2014 – 12/08/2014	A	-50 mm +0 mm
29/08/2014 – 12/08/2014	A	-26.5 mm +0.5 mm
29/08/2014 – 12/08/2014	Water	-
12/08/2014 – 26/08/2014	A	-50 mm +0 mm
12/08/2014 – 26/08/2014	A	-26.5 mm +0.5 mm
12/08/2014 – 26/08/2014	Water	-
26/08/2014 – 09/09/2014	A	-50 mm +0 mm
26/08/2014 – 09/09/2014	A	-26.5 mm +0.5 mm
26/08/2014 – 09/09/2014	Water	-
28/04/2015 – 12/05/2015	B	-13.2 mm +6.7 mm
28/04/2015 – 12/05/2015	B	-13.2 mm +0 mm
28/04/2015 – 12/05/2015	B	-6.7 mm +0 mm
12/05/2015 – 23/05/2015	B	-13.2 mm +6.7 mm
12/05/2015 – 23/05/2015	B	-13.2 mm +0 mm
12/05/2015 – 23/05/2015	B	-6.7 mm +0 mm
02/06/2015 – 16/06/2015	B	-13.2 mm +6.7 mm
02/06/2015 – 16/06/2015	B	-13.2 mm +0 mm
02/06/2015 – 16/06/2015	B	-6.7 mm +0 mm
14/07/2015 – 24/07/2015	B	-13.2 mm +6.7 mm
14/07/2015 – 24/07/2015	B	-13.2 mm +0 mm
14/07/2015 – 24/07/2015	B	-6.7 mm +0 mm
04/08/2015 – 18/08/2015	B	-13.2 mm +6.7 mm
04/08/2015 – 18/08/2015	B	-13.2 mm +0 mm
04/08/2015 – 18/08/2015	B	-6.7 mm +0 mm

3.4.2 Depth of evaporation

3.4.2.1 Experimental apparatus

The depth to which evaporation occurs was investigated by using the experimental apparatus showed in Figure 3.4.2. The frame consisted of a grid which served to keep the pipes in place and a perspex roof which prevented rain from intruding on the experiment. Each pipe consisted out of 7 segments with a height of 0.1 m. These segments were taped together to form a cohesive pipe with a length of 0.7 m. There were a total of 36 pipes – 12 pipes were used for each sample.

3.4.2.2 Experimental procedure

Dry coal samples were loaded into the pipes shown in Figure 3.4.2. There were 12 pipes per sample, three samples (or 36 pipes) in total for each run. Water was added to each pipe to saturate the coal within and the free water was allowed to drain out at the bottom. Once drainage has ceased, the bottom of the pipes were sealed. Each pipe was lined with filter cloth to prevent fine and ultrafine particles from exiting with the free water. The filled pipes were placed in the frame as indicated in Figure 3.4.2. One pipe of each sample was sampled every day and its contents were analysed for moisture content and PSD. The first pipe was sampled before any evaporation could occur to establish the initial moisture profile. All experimental conditions are summarised in Table 3.4.2. A fresh coal sample was used for each experimental run. This sample was separated into the respective sizes and loaded into the pipes.

Figure 3.4.2: Evaporation depth experimental setup

Table 3.4.2: Summary of evaporation depth experimental conditions

Date	Coal type	Size range
28/04/2015 – 09/05/2015	B	-10 mm +6.7 mm
28/04/2015 – 09/05/2015	B	-10 mm +0 mm
28/04/2015 – 09/05/2015	B	-6.7 mm +0 mm
12/05/2015 – 23/05/2015	B	-10 mm +6.7 mm
12/05/2015 – 23/05/2015	B	-10 mm +0 mm
12/05/2015 – 23/05/2015	B	-6.7 mm +0 mm
26/05/2015 – 06/06/2015	B	-10 mm +6.7 mm
26/05/2015 – 06/06/2015	B	-10 mm +0 mm
26/05/2015 – 06/06/2015	B	-6.7 mm +0 mm

3.5 Experimental stockpile

3.5.1 Experimental apparatus

A 6 x 6 m solid floor steel platform, covered with a corrugated iron roof, was constructed and mounted on four load cells as shown in Figure 3.5.1. The platform floor was inclined 5° to 8° from the horizontal in the two ordinal directions.

The platform was equipped with garden-type sprays 3 m above the platform floor which served to simulate rainfall events. The used water was received from a municipal water line with the rate measured by a flow meter. The total amount of water from each rainfall event was measured by a volume counter. Gutters ran around the platform and collected runoff water. The runoff water was collected in drums which were located on scales. The data from both the load cells and scales was continuously logged to track the addition and removal of moisture from the stockpile.

A weather station was attached to the platform as seen in Figure 3.5.1 and recorded the temperature, relative humidity, wind speed and direction.

3.5.2 Experimental procedure

The platform shown in Figure 3.5.1 was loaded with approximately 9 tonnes of coal B (-50 mm +0 mm) by means of a 12 m conveyer which discharged directly onto the platform. This resulted in a stockpile with a natural angle of repose and allowed for the segregation of particles. After the construction, the stockpile was observed over a period of three days before the first rainfall event was initialised. The addition of water was started at the chosen flow rate and continued for the required duration.

Figure 3.5.1: Experimental stockpile platform

The amount of water which drained from the stockpile was measured by scales and recorded by the data logger. The stockpile weight was also continuously recorded. Each test was concluded after a number of days (generally between 7 and 10) when no more water loss could be detected. The test conditions are given in Table 3.5.1. Weather conditions such as temperature, relative humidity, wind speed and direction was measured at set time intervals by the weather station. After the completion of the final experiment, the stockpile was destructed and samples were taken at certain points for moisture and PSD analysis. These samples were used to convert and correct the recorded data in terms of moisture percentages.

Table 3.5.1: Summary of experimental stockpile test conditions

Test	Rainfall	Rain duration	Total water added
1	68 mm/h	30 min	1226 L
2	36 mm/h	145 min	3110 L
3	69 mm/h	90 min	3740 L

CHAPTER 4: RESULTS AND DISCUSSION

The results obtained for all experiments are given in this chapter. The relationship between the proportions of water which runs of the surface versus the amount which infiltrates a stockpile is discussed in section 4.1. Section 4.2 contains a discussion of the results obtained for the rate and depth of evaporation experiments. Drainage is discussed at length in section 4.3. In section 4.4 the results from the individual experiments are discussed and compared to the results obtained by from the experimental stockpile. Over the course of this investigation it was found that the inherent moisture content remained constant for both coals investigated. Focus was thus placed on the total moisture content – which changed as a result of the fluctuations in the surface moisture content.

4.1 Runoff versus infiltration

During this investigation, four factors which influence the amount of water which runs off the surface of a stockpile were investigated. These factors are: stockpile angle, size range, degree of compaction and rainfall intensity .A detailed discussion of the results obtained by these experiments can be found in the next sections, with the additional experimental results shown in Appendix B.

4.1.1 Rainfall intensity

In this study, the coal bed was saturated to ensure that the coal sample had reached its final infiltration capacity (see section 2.4.1.1). This was done to guarantee repeatable results. According to Critchley *et al*. (1991), it is commonly assumed in the soil mechanics field that the amount of runoff is determined by the rainfall depth and these values are related by coefficient *K* in equation 4.1.1.

$$Runoff = K \times Rainfall \qquad [4.1.1]$$

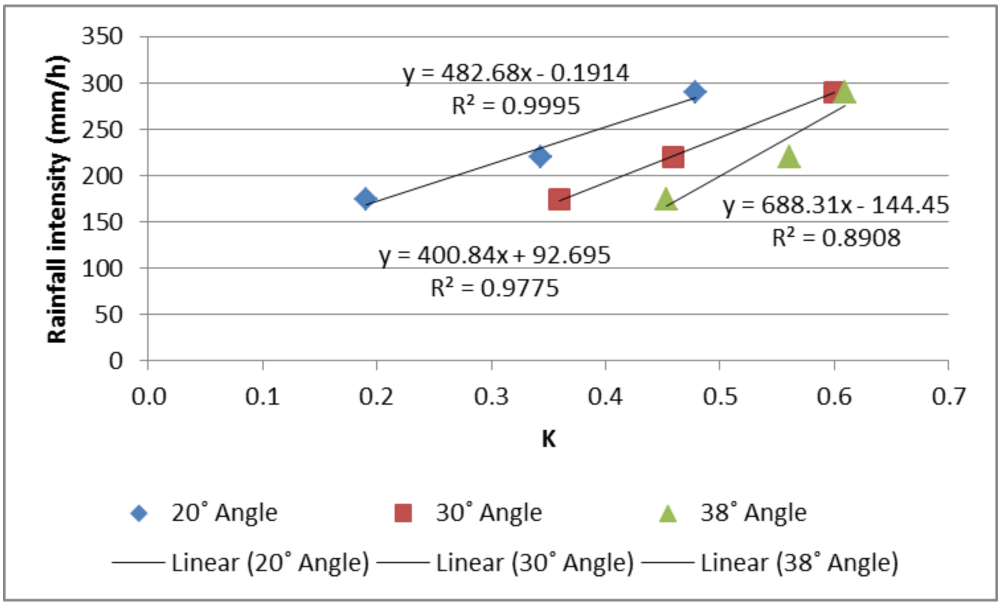

Figure 4.1.1: Relationship between the rainfall intensity and K (-53 mm +0 mm, ρ_B = 1069 kg/m^3)

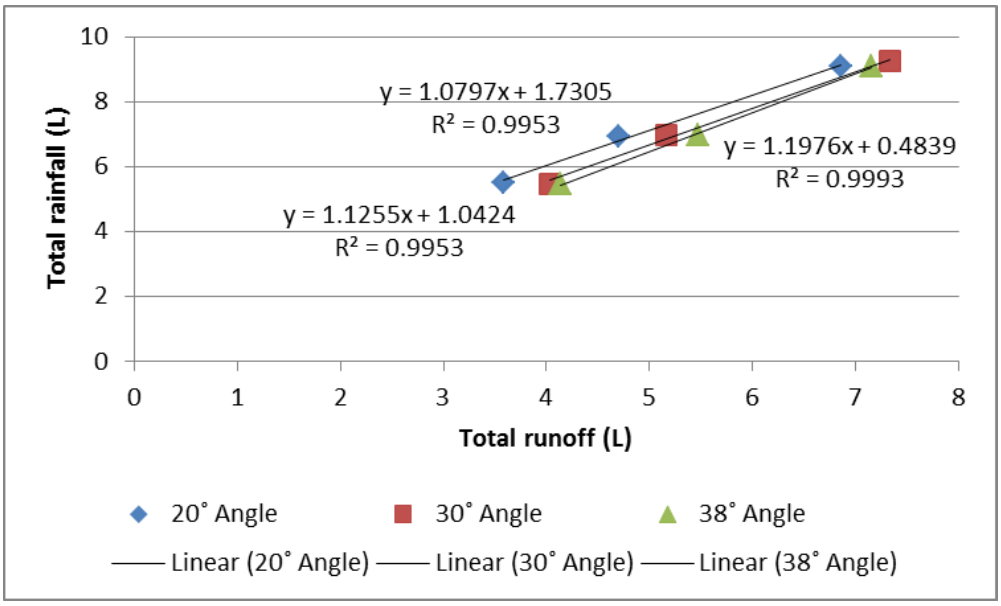

Figure 4.1.2: Relationship between the total rainfall and the total runoff (-53 mm +0 mm, ρ_B = 1157 kg/m^3)

As noted in section 2.4.1.1, the value of *K* is not constant and very much surface dependent. There should be a good linear relationship between the calculated *K* coefficient and the rainfall intensity (Critchley *et al*., 1991), which proved to be true in this study as shown by Figure 4.1.3. A good linear relationship was also found between the total rainfall and the total amount of runoff, as illustrated in Figure 4.1.2.

Various researchers have found that an increase in rainfall intensity will translate into an increase in the proportion of runoff (Agassi *et al*., 1981; Curran *et al*., 2002:2785; Critchley *et al*., 1991; Huang *et al*., 2012:2). The trends in Figure 4.1.1 and Figure 4.1.2 show that this holds true for this investigation – an increase in rainfall intensity will lead to a greater the runoff proportion. All experimental runs showed the same tendency as shown in Appendix B.

As mentioned in sections 2.4.1.1 and 2.4.1.3, each sample will have its own infiltration capacity which is independent of the rainfall intensity and is determined by the sample's texture, structure and initial moisture content (Critchley *et al*., 1991). Once the final infiltration rate has been achieved after the sample has been saturated, an increase in rainfall intensity will only result in an increase in the amount of surface runoff (if the sample remains undisturbed). As seen in Figure 4.1.3, the infiltration rate was relatively constant, with a slight increase as the bed surface was disturbed between experimental runs. This slight variation in the infiltration rate was seen throughout the results obtained for the experimental work (Appendix B). The disturbance can be attributed to the method of adjusting the slope angle during experimentation. Some surface disturbance also occurred with the increase in rainfall intensity (see section 4.1.5), which lead to the manifestation of erosion and the creation of holes in the bed surface.

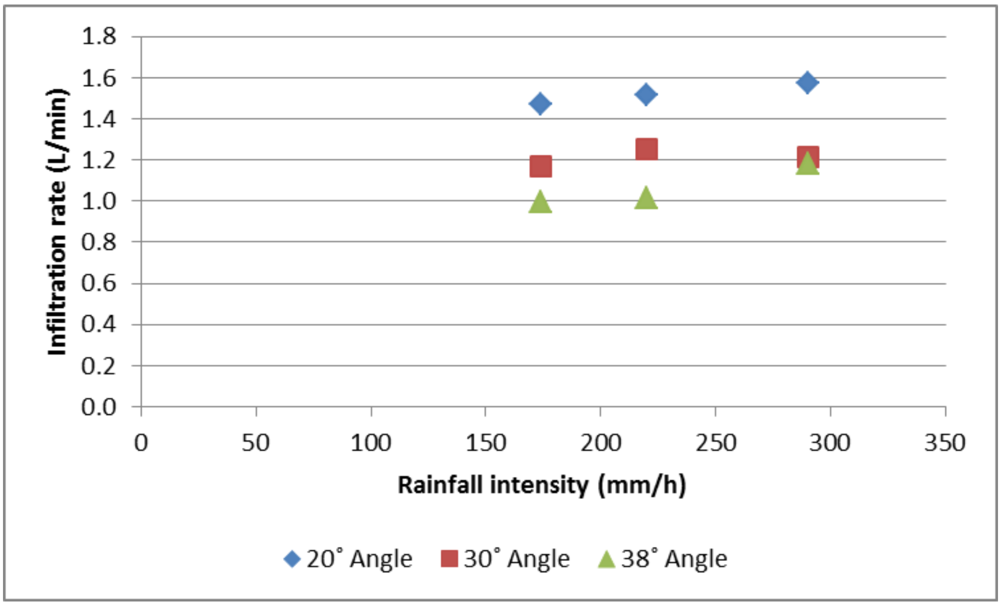

Figure 4.1.3: Infiltration rate versus rainfall intensity (-53 mm +0 mm, ρ_B = 1069 kg/m^3)

Research showed that the rainfall intensity could lead to the formation of a sealed surface layer which would decrease the amount of infiltration into the coal bed and thus increase the runoff proportion (Agassi *et al*., 1981; Curran *et al*., 2002:2785; Critchley *et al*., 1991; Huang *et al*., 2012:2). This layer was not seen during this investigation. According to Agassi *et al*. (1981) and Critchley *et al*. (1991), the extent to which this layer would form is dependent on the clay content of the sample. For this experiment coal B was used which, as seen in section 3.1.1 has a relatively small amount of clay minerals present.

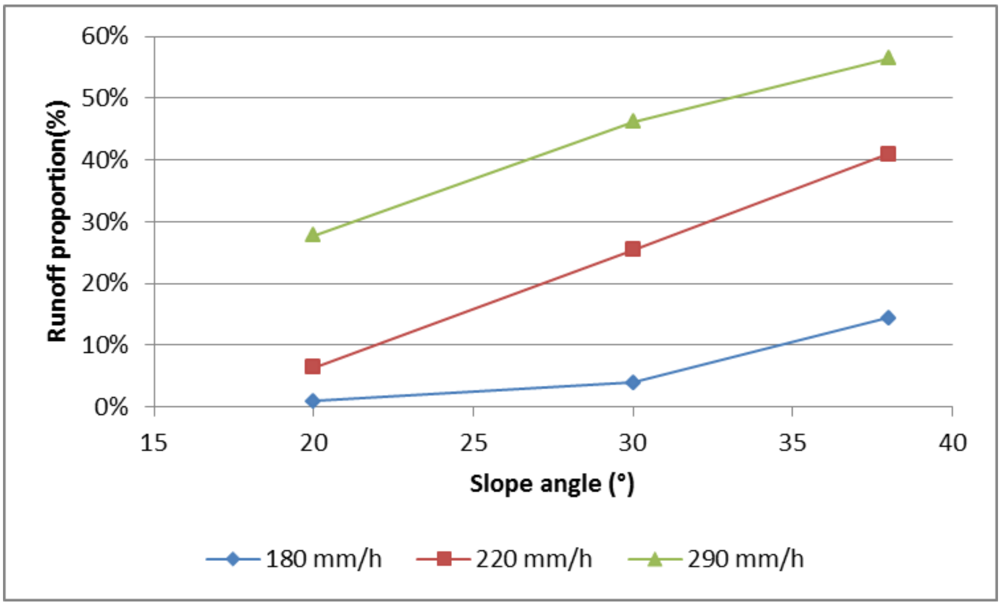

Figure 4.1.4: Runoff proportion versus slope angle (-53 mm +0 mm, ρ_B = 997 kg/m^3)

4.1.2 Stockpile angle of repose

Three angles (20°, 30° and 38°) were investigated and, as expected (Curran *et al*., 2002; Sharma, 1986), an increase in slope angle lead to an increased runoff proportion as shown in Figure 4.1.4. This trend was seen for all experiments (Appendix B). By increasing the slope angle, the contact time between the coal and the water is decreased, thus limiting the opportunity for infiltration. According to Wels *et al*. (2015:3), the probability of sidelong flows parallel to the surface is amplified when surfaces are slanted, which increases the proportion of runoff water. This effect was much less pronounced for extremely porous coal beds or coal beds with minimal interparticulate spacing, as seen in sections 4.1.3 and 4.1.4 respectively.

4.1.3 Particle size distribution

According to literature (Critchley *et al*., 1991; Mahajan & Walker, 1978:136) there is a positive relationship between the size of the particles and porosity of the sample. Water will thus infiltrate a coarse coal stockpile to a greater extent compared that of a fine coal stockpile. As seen in Figure 4.1.5, the coarse coal bed (-53 mm +6.7 mm) had a runoff proportion of approximately 0%, while the samples containing fine content experienced surface runoff. The sample with the highest fraction of fines (-6.7 mm +0 mm) showed the highest runoff proportions. These results were constant for all the experiments which were performed (Appendix B).

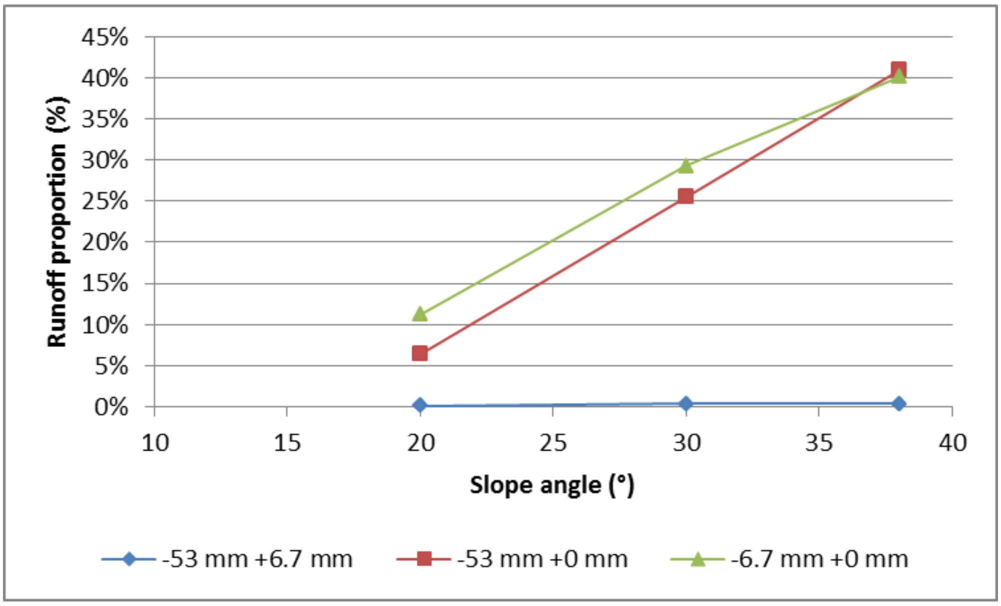

Figure 4.1.5: Proportion of runoff versus slope angle as a function of size range at 220 mm/h

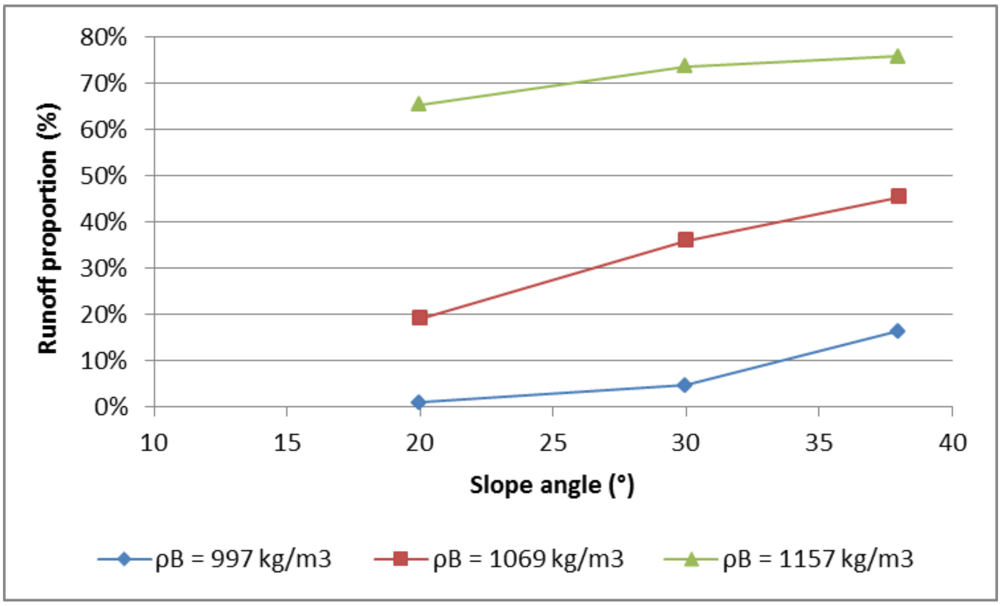

Figure 4.1.6: Proportion of runoff versus slope angle as a function of compaction at 174 mm/h

4.1.4 Degree of compaction

As compaction decreases the spacing between particles in the coal bed, it is expected that an increase in the degree of compaction will result in an increased runoff proportion (McLean, 1998:406). Figure 4.1.6 illustrates that this is supported by this investigation, with the highest compacted coal bed showing the largest runoff proportions. Similar results were found at other rainfall intensities as shown in Appendix B. By the compaction of a stockpile surface, the majority of rainfall ingress can be prevented. This is in accordance with recommendations by Ekmann and Le, (2014) and TRC Environmental Consultants (1983).

4.1.5 Surface disturbance

As the rainfall event progresses, there are surface disturbances which can take place. One of these is erosion. The probability of erosion increases with an increase in slope angle, rainfall intensity and the amount of fine content. Other surface disturbances which can occur are ponding and channelling. All three of these disturbances were seen during this investigation as shown in Figure 4.1.7.

The mixed coal sample (-53 mm +0 mm) had the tendency to form channels, while the fine coal sample (-6.7 mm +0 mm) had a predisposition toward pooling. The fine coal sample experienced a significant amount of erosion at high angles and high rainfall intensities. The coarse coal sample did not shown any major form of surface disturbance. According to Roberts *et al*. (1998), this can be explained by the different behaviour seen between large and small particles. Larger particles behave in a non-cohesive manner with particles eroding individually, while smaller particles tend to perform cohesively and will eventually consolidate to erode in masses.

Figure 4.1.7: Surface disturbance

4.2 Drainage

According to various literature sources (see section 2.4.2) the drainage characteristics of a coal stockpile are primarily influenced by the coal type, particle size, extent of compaction, and the height of the stockpile. These factors were investigated over the course of this project and the results obtained by the experiments are discussed in detail in the following sections.

4.2.1 Influence of stockpile height on drainage characteristics

To investigate the influence of stockpile height on drainage characteristics, two drainage columns with heights of 0.48 m and 2 m were loaded with coal. These drainage columns had the same ID of 0.38 m. Table 4.2.1 gives a summary of the experimental conditions and the results which were obtained. In each experiment, 20 kg of water was added to the top of the column.

If the column height had no influence on the amount of water which is retained by the coal sample, it would be expected that the amount of water retained by the sample in the 2 m high column would be around four times that of the amount of water retained by the coal in the 0.48 m high column. As seen by the averaged values in Table 4.2.1, this is not the case. An expected average moisture retention value for the coal sample in the 2 m high drainage column would be around 15.8 kg of the added 20 kg of water for the similar coal sample. A comparison between the actual and the expected values shows that there is a difference between the two values, with the actual value being substantially less than that of the expected amount. This shows that the height of a stockpile has an influence on the amount of added water which drains out of the coal, which is in agreement

Table 4.2.1: Influence of stockpile height on drainage characteristics experimental results

Coal type	Test no.	Column height (m)	Size range	ρ_B (kg/m^3)	Water retained (kg)
A	1	0.48	-53 mm +0 mm	1073	3.63
A	2	0.48	-53 mm +0 mm	1073	4.27
				Average	**3.95**
A	1	2	-53 mm +0 mm	1019	9.29
A	2	2	-53 mm +0 mm	1044	9.51
				Average	**9.40**

with literature (Carpenter, 1999; Curran *et al*., 2002:2786; Eckersley, 1994; Leeder *et al*., 2011; TRC Environmental Consultants Inc., 1983; Williams, 2006:224). As the height of a stockpile increases, the weight of the coal above the bottom layer increases. This leads to an increase in the pressure, which in turn aids the drainage of water from the stockpile (Williams, 2006:224).

4.2.2 Influence of compaction on drainage characteristics

Compaction is known to have a negative influence on the drainage characteristics of a coal sample. This is attributed to the fact that compaction decreases the amount of interstitial voids which are available for percolation (TRC Environmental Consultants Inc., 1983; Kuyumcu & Sander, 2014). Compaction of a stockpile surface is commonly used to prevent the infiltration of moisture into the interior of the stockpile and increase the amount of runoff water. In this experiment, runoff is eliminated – thus forcing the added water (20 kg) to percolate through the packed coal bed. The experimental results are summarised in Table 4.2.2.

As seen in Figure 4.2.1, there was a difference between the total moisture content at the top and at the bottom of the non-compacted coal bed (ρ_B = 1073 kg/m^3). The same cannot be said of the compacted coal beds (ρ_B = 1198 kg/m^3 and ρ_B = 1288 kg/m^3) – indicating that the compaction of the samples deterred the percolation and movement of water. The compaction of the coal bed from a bulk density of 1073 kg/m^3 to a bulk density of 1198 kg/m^3 resulted in an average increase of 1.9% in the amount of moisture retained. By compacting the bed further to a bulk density of 1288 kg/m^3, the amount of moisture retained is increased by another 0.8%.

It is noted by researchers such as Williams (2006) and TRC Environmental Consultants Inc. (1983) that the bottom layer of a coal stockpile is more compacted than that of the coal above – this is attributed to the weight of the coal above. As a result of this, as well as the influence of gravity, it is expected that the bottom layer of the coal stockpile would be wetter than the coal above. Figure 4.2.1 shows that this hypothesis holds true.

As water percolates through the coal bed, some fine particles migrate downwards with the flow of water. The size distribution of these migrating particles depends on the void size between the larger particles. As the degree of compaction increases, the void size between the particles decreases – thus allowing fewer fine particles to migrate downwards with the added water. This is confirmed by the amount of fine particles which was washed out along with the drained water – as illustrated by Figure 4.2.2.

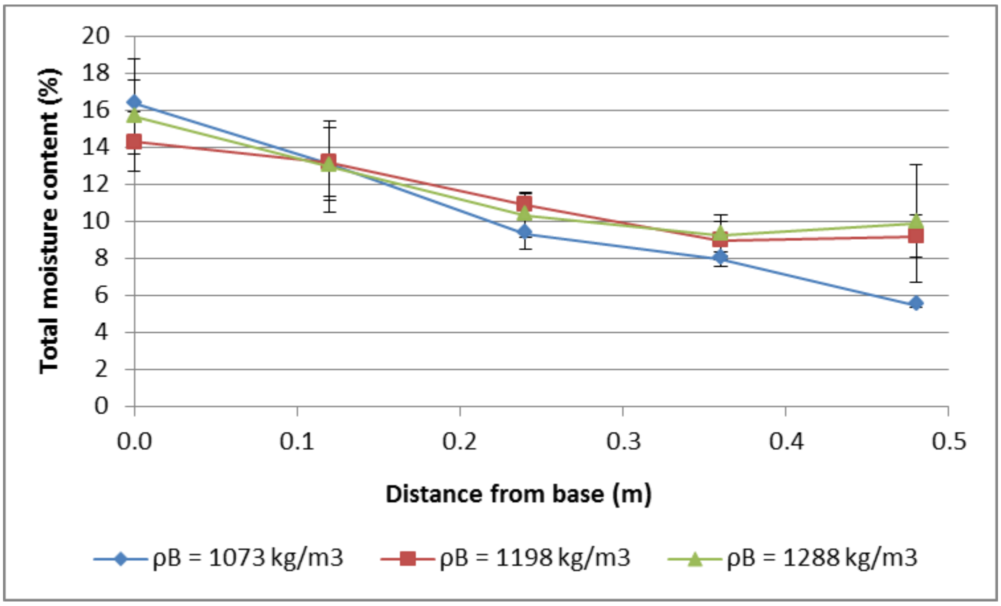

Figure 4.2.1: Moisture profile over 0.48 m high drainage column for different compactions

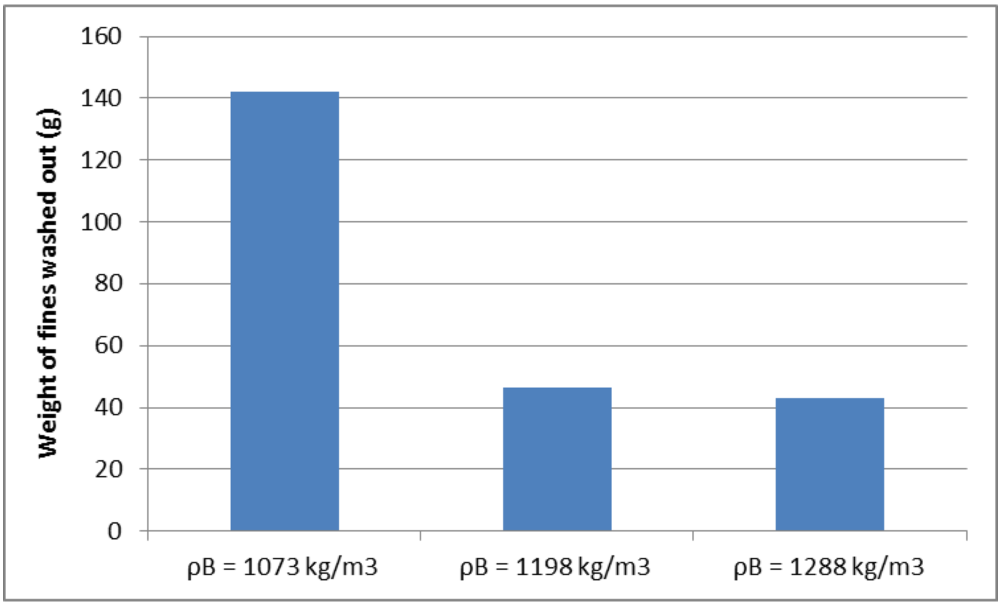

Figure 4.2.2: Weight of fines washed out of 0.48 m high drainage column

Table 4.2.2: Influence of compaction on drainage experimental results

Coal type	Test no.	Column height (m)	Size range	ρ_B (kg/m^3)	Water retained (kg)
A	1	0.48	-53 mm +0 mm	1073	3.63
A	2	0.48	-53 mm +0 mm	1073	4.27
				Average	**3.95**
A	1	0.48	-53 mm +0 mm	1198	4.17
A	2	0.48	-53 mm +0 mm	1198	4.63
A	3	0.48	-53 mm +0 mm	1198	4.20
				Average	**4.33**
A	1	0.48	-53 mm +0 mm	1288	4.51
A	2	0.48	-53 mm +0 mm	1288	4.06
A	3	0.48	-53 mm +0 mm	1288	4.93
				Average	**4.50**

4.2.3 Influence of fines on drainage characteristics

Two drainage columns (0.48 and 2 m) were used to investigate the extent to which the PSD influences the drainage characteristics of a specific coal stockpile, as well as to investigate the migration of fines.

4.2.3.1 0.48 m high drainage column

In order to investigate the influence of fines on the drainage characteristics, various coal samples were loaded into the 0.48 m drainage column. These samples ranged from samples from which fines (-0.5 mm) were removed to samples which were loaded with an additional layer of fines. The experimental conditions and results are summarised in Table 4.2.3.

Results show that the removal of fines translated into a decrease in the amount of water which was retained by the coal bed. This indicated that the presence of fines inhibited the drainage of moisture from the coal bed. This is further supported by the fact that the addition of a fines layer to the middle of the drainage column resulted in an increase in the amount of moisture retained by the coal bed. The influence which the layer of fines has on total moisture content profile of the column is illustrated in Figure 4.2.3. The addition of the fines layer in the centre of the packed bed inhibited the drainage of water through the column, resulting in a higher total moisture content at the centre of the column where the layer is located and impeding the drainage into the lower part of the packed bed. This resulted in a lower moisture content at the base of the samples with the high fines content compared to that of the raw coal. It is speculated that the moisture was held up in the fines-containing centre of the coal sample and was unable to drain through to the base of the column, thus resulting in the coal sample with the highest fines content having the lowest base moisture content.

A downwards migration of fines were seen for all experiments, which is illustrated by Figure 4.2.4. This is a further explanation for the increase in moisture content towards to bottom of the drainage column. An increase in the amount of fine particles results in an increased surface area to which water particles can adhere to (Falcon & Ham, 1988; Leeder *et al*., 2011). An increased amount of fines also translates in less void space within the packed bed through which water can drain (Kuyumcu & Sander, 2014) – similar to the way in which compaction decreases void space in a packed bed.

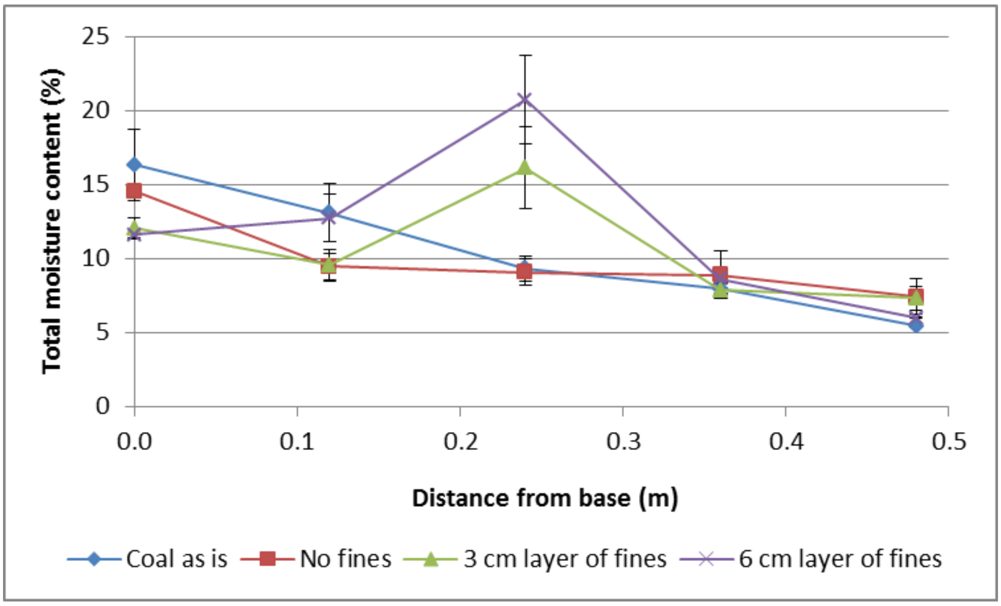

Figure 4.2.3: Moisture profile over 0.48 m high drainage column for different fine content

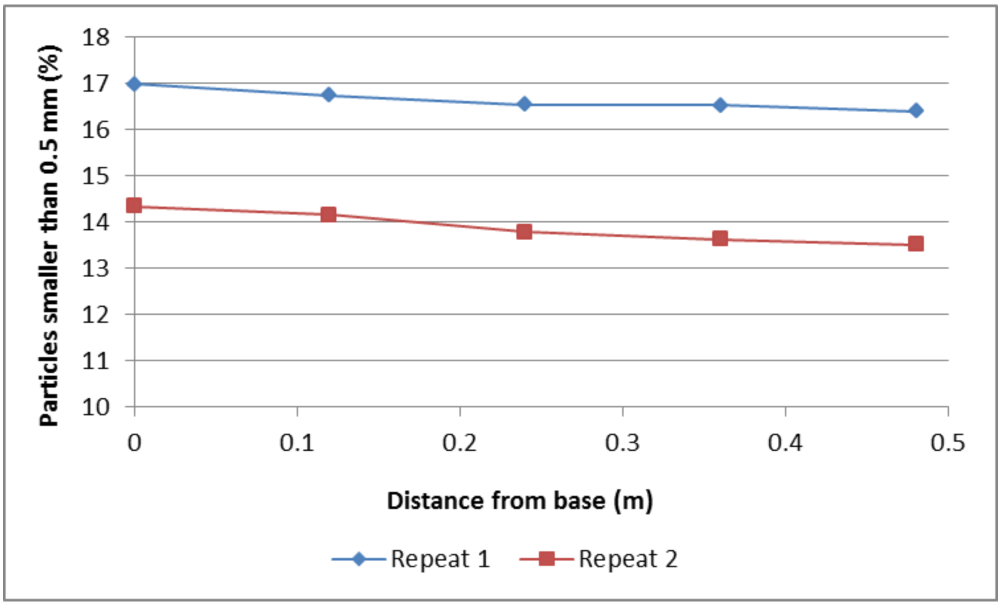

Figure 4.2.4: Amount of particles smaller than 0.5 mm for the fines containing coal bed

Table 4.2.3: Influence of fines on the 0.48 m drainage column experimental results

Coal type	Test no.	Column height (m)	Size range	Layer of fines	Water retained (kg)
A	1	0.48	-53 mm +0 mm	No	3.63
A	2	0.48	-53 mm +0 mm	No	4.27
				Average	**3.95**
A	1	0.48	-53 mm +0.5 mm	No	2.99
A	2	0.48	-53 mm +0.5 mm	No	2.37
				Average	**2.68**
A	1	0.48	-53 mm +0 mm	Yes (3 cm)	3.86
A	2	0.48	-53 mm +0 mm	Yes (3 cm)	3.34
				Average	**3.60**
A	1	0.48	-53 mm +0 mm	Yes (6 cm)	4.41
A	2	0.48	-53 mm +0 mm	Yes (6 cm)	5.99
				Average	**5.20**

4.2.3.2 2 m high drainage column

Two different coals with several different size ranges were loaded into the 2 m high drainage column to further investigate the influence of PSD on the water drainage characteristics of a coal stockpile. The experimental conditions and results are summarised in Table 4.2.4. In each experiment 20 kg of water was added to the drainage column. By comparing the results obtained for coal A, it can be seen that a packed bed containing less fine particles will retain less added water. This is similar to what was seen in the 0.48 m high drainage column. In Figure 4.2.5 the average drainage profiles which were determined for each coal A sample is shown.

It is shown in Table 4.2.4 that coal A retained a larger portion of the added 20 kg of water when compared to the amount retained by coal B – even though coal B samples generally had a higher proportion of coal fines. It can be seen in Figure 4.2.5 that the removal of the -0.5 mm particle sizes had a much larger effect than the removal of the -1 mm particle sizes on the final amount of moisture retained by the packed coal bed. The same phenomenon was seen during an investigation done by the Fuel Research Institute of South Africa in 1964. This is attributed to the fact that the majority of drainage related problems seem to be dependent on the amount of -0.5 mm coal particles within a stockpile (Cummings, 2003; Eckersley, 1999:6).

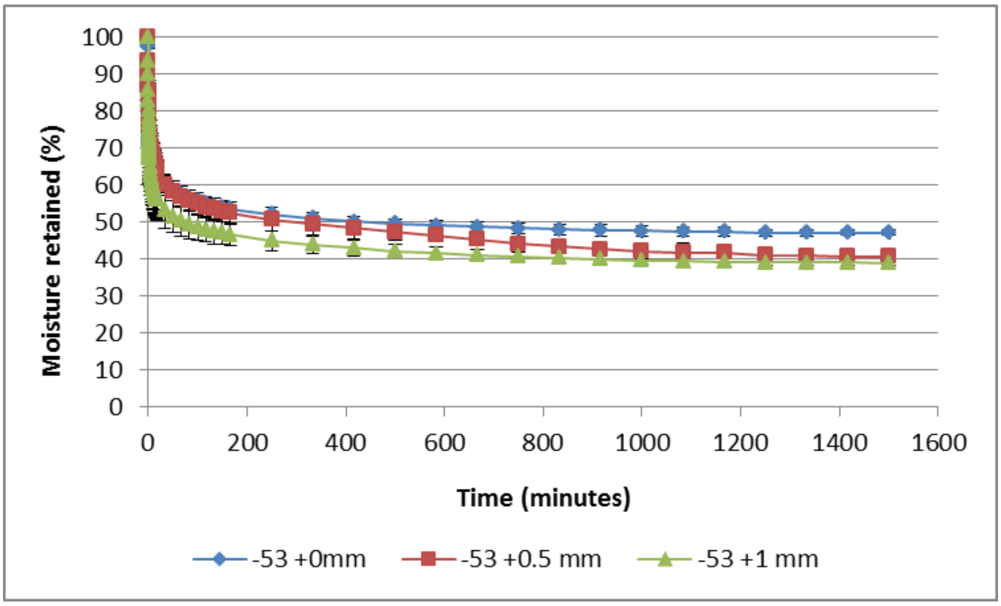

Figure 4.2.5: Average drainage profiles of the 2 m drainage column for coal A

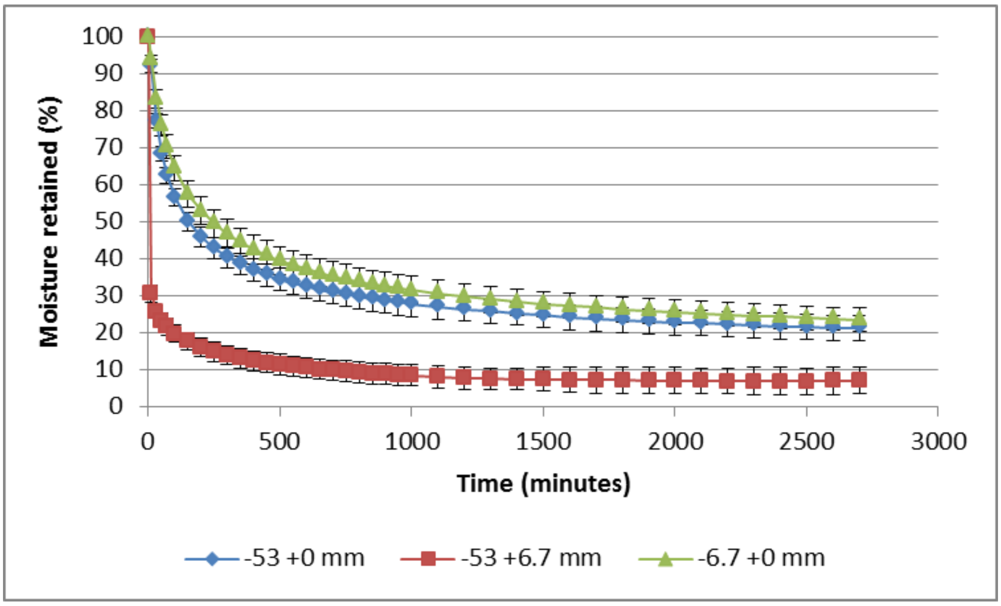

Figure 4.2.6: Average drainage profiles of the 2 m drainage column for coal B

The coal B sample was split into two particle size ranges (-53 mm +6.7 mm and -6.7 mm +0 mm) to represent the interior of the experimental coal stockpile (see section 4.4). The drainage profiles obtained for these samples is given in Figure 4.2.6, which shows that profile for the coal as is sample (-53 mm +0 mm) and the fines sample (-6.7 mm +0 mm) is very similar. This is attributed to the high fines content of the original sample. Only the drainage over the first two days is shown as no further drainage after this period was observed. As seen in Figure 4.2.7, the coarse coal sample (-53 mm +6.7 mm) drained almost instantaneously and retained very little of the added 20 kg of water. In contrast to this, the as-is sample (-53 mm +0 mm) and the fines sample (-6.7 mm +0 mm) retained approximately 20% of the added water. A comparison between the initial drainage rates show that the as is sample (-53 mm +0 mm) and the fines sample (-6.7 mm +0 mm) drained at a much slower rate than the coarse sample (-53 mm +6.7 mm). The difference in both drainage rates and moisture retained is once again attributed to the void spaces within the packed bed. As mentioned in literature (de Korte & Mangena, 2004:5; Eckersley, 1999:6; Nkolele, 2004:171-172), a decrease in PSD translates into less interstitial voids which inhibit the movement of moisture. Figure 4.2.7 is a good example of the water which builds up in the packed bed over time (the same coal sample is rewetted each time).

Table 4.2.4: Influence of fines on the 2 m high drainage column experimental results

Coal type	Test no.	Column height (m)	Size range	ρ_B (kg/m^3)	Water retained (kg)
A	1	2	-53 mm +0 mm	1019	9.29
A	2	2	-53 mm +0 mm	1044	9.51
				Average	**9.40**
A	1	2	-53 mm +0.5 mm	1012	8.00
A	2	2	-53 mm +0.5 mm	985	8.20
				Average	**8.10**
A	1	2	-53 mm +1 mm	969	7.88
A	2	2	-53 mm +1 mm	1024	7.67
				Average	**7.77**
B	1	2	-53 mm +0 mm	879	3.85
B	2	2	-53 mm +0 mm	879	3.78
B	3	2	-53 mm +0 mm	879	5.08
				Average	**4.24**
B	1	2	-53 mm +6.7 mm	659	0.88
B	2	2	-53 mm +6.7 mm	659	1.20
B	3	2	-53 mm +6.7 mm	659	2.16
				Average	**1.41**
B	1	2	-6.7 mm +0 mm	743	8.41
B	2	2	-6.7 mm +0 mm	743	5.07
B	3	2	-6.7 mm +0 mm	743	4.21
				Average	**5.90**

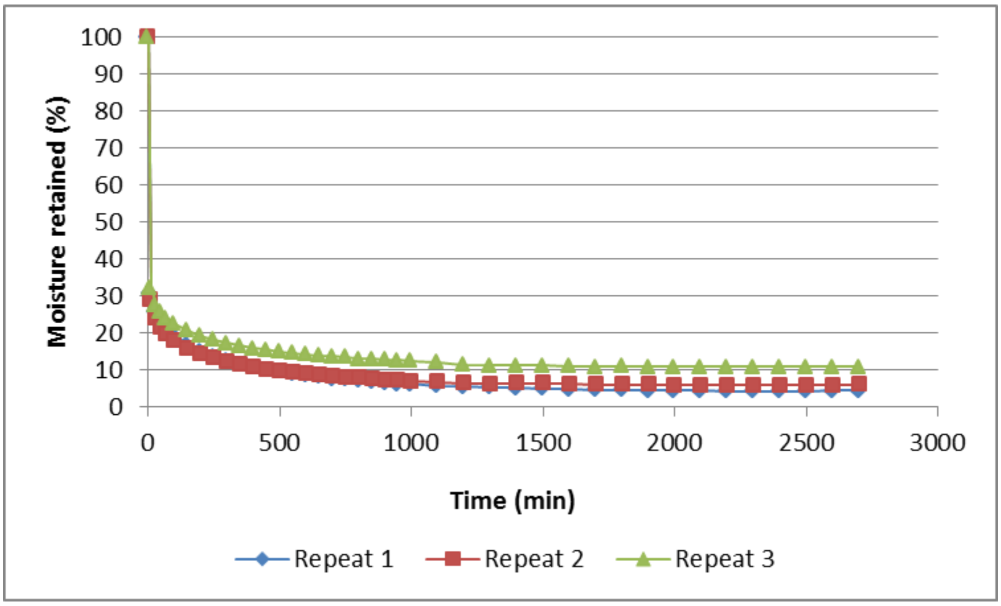

Figure 4.2.7: Average drainage profiles of the 2 m drainage column for coal type B (-53 mm +6.7 mm)

Moisture profiles

To track the migration of water and fines within the packed coal bed, samples were taken at specific time intervals over the length of the column. Coal A was sampled at three points and coal B was sampled at four points. The drainage column was lowered to a horizontal position for the sampling of coal A experiments (see section 3.3.2 for the sampling method) to investigate the effect which the disturbance of the packed bed would have on the moisture profile and fines migration of a packed bed. An investigation performed by Leeder *et al*. (2011:6), it was found that by vibrating the column, the rates of both moisture redistribution and drainage was increased six-fold when compared to that of a non-vibrated column.

During this investigation it was found that the disturbance of the coal bed had a positive influence on both the moisture and fines migration. As seen in Figure 4.2.8, there was a clear correlation between the fines and moisture migration over time within the packed bed. As previously mentioned, the proportion of fine particles and moisture content are usually related. It is shown in Figure 4.2.8 that while the moisture steadily migrated downwards over time, the fine content at the highest sampling point in the column remained relatively constant. This is attributed to the fact that the water added to the column instantly washed the fines downwards into the lower sections of the column. It can be seen that the moisture and fines content in the lower section of the column also remained moderately constant. This can be credited to the insufficient void spaces at the base of the column, which is a result of the pressure from the coal above. There was a steady migration of both moisture and fines content from the middle section – which is ascribed to the movement of the column for sampling.

Coal B was sampled with minimum disturbance of the packed bed to enable the investigation of the moisture and fines migration over time in an undisturbed bed (see section 3.3.2 for the sampling method). Figure 4.2.9 shows that there was essentially no migration of fines over time – which is expected as the bed is not disturbed as with the experiments containing coal A. Even though there was no fines movement, there was a steady migration of moisture over time which can be attributed to the effects of gravity drainage.

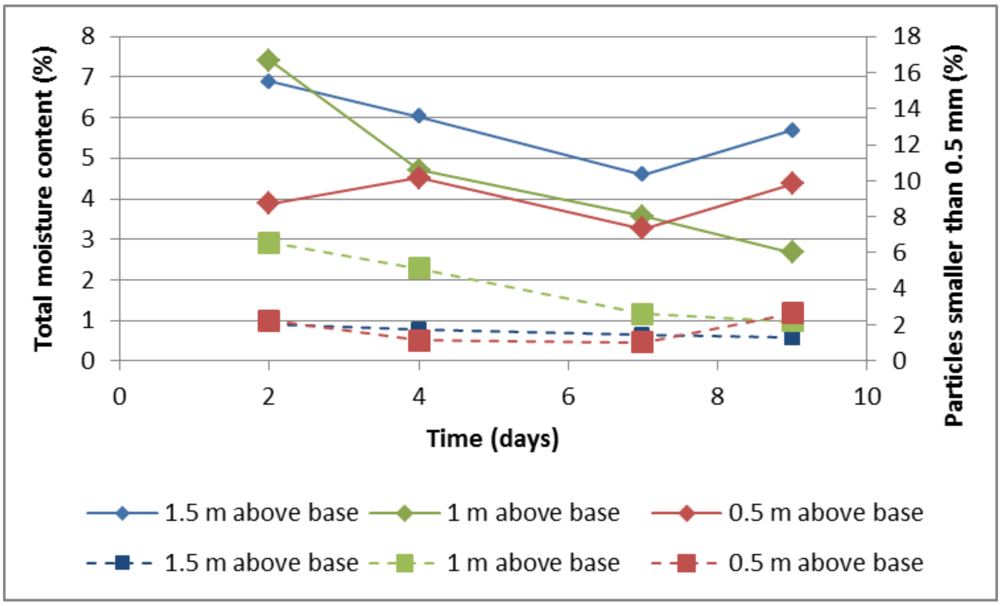

Figure 4.2.8: Migration of moisture content and fines over time for coal A 2 m packed bed (♦ - moisture content, ■ – fine content) (PSR -53 mm +0 mm)

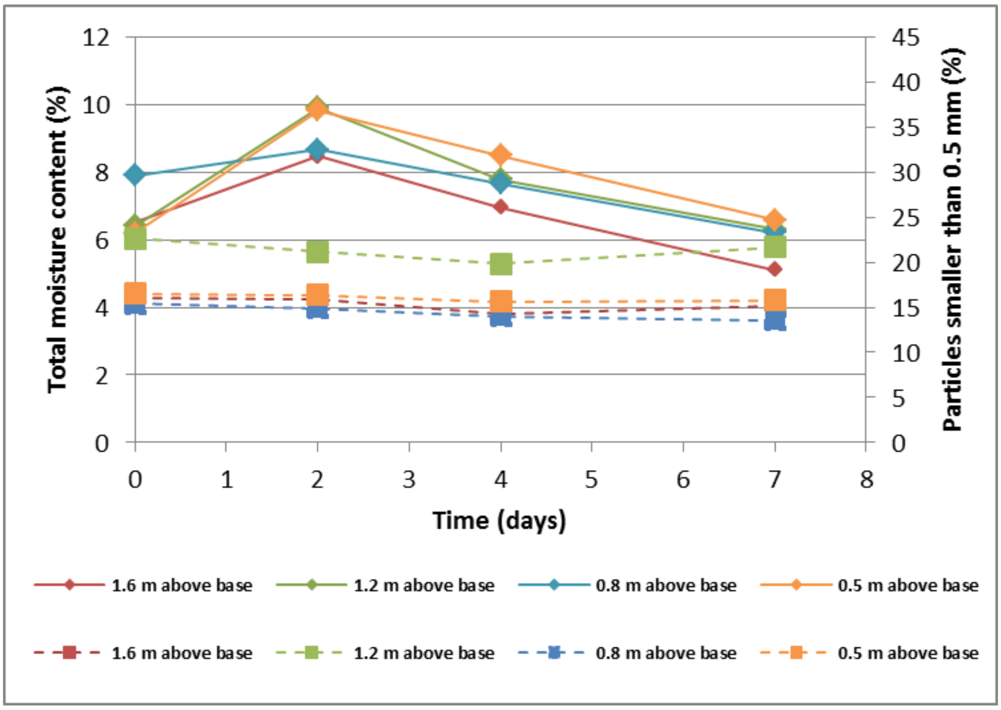

Figure 4.2.9: Migration of moisture content and fines over time for coal B 2 m packed bed (• - moisture content, ■ – fine content) (PSR -6.7 mm +0 mm)

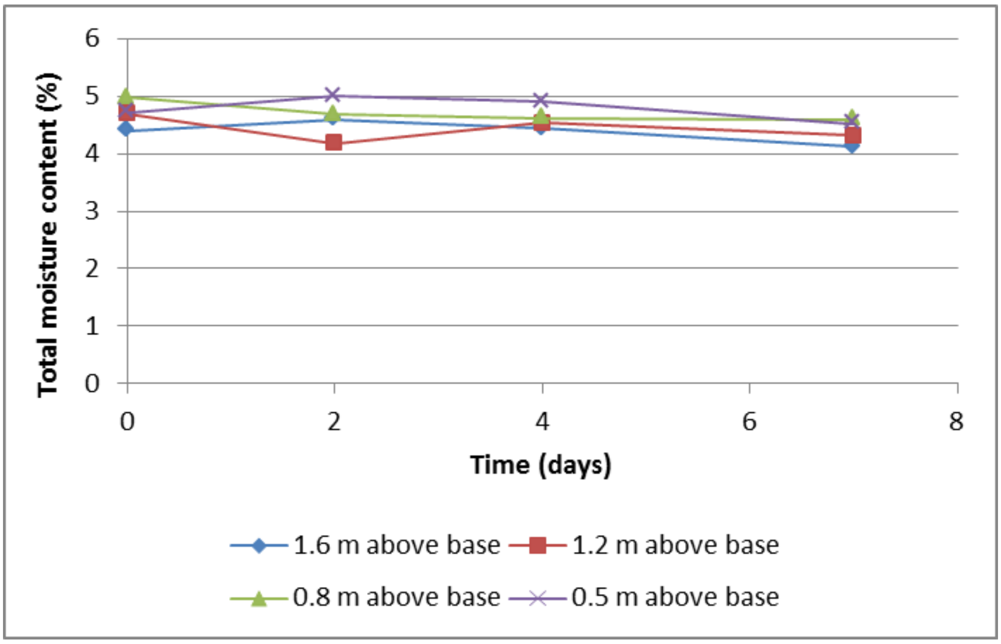

Figure 4.2.10: Moisture profile of the coarse (-53 mm +6.7 mm) coal type B sample in the 2 m drainage column

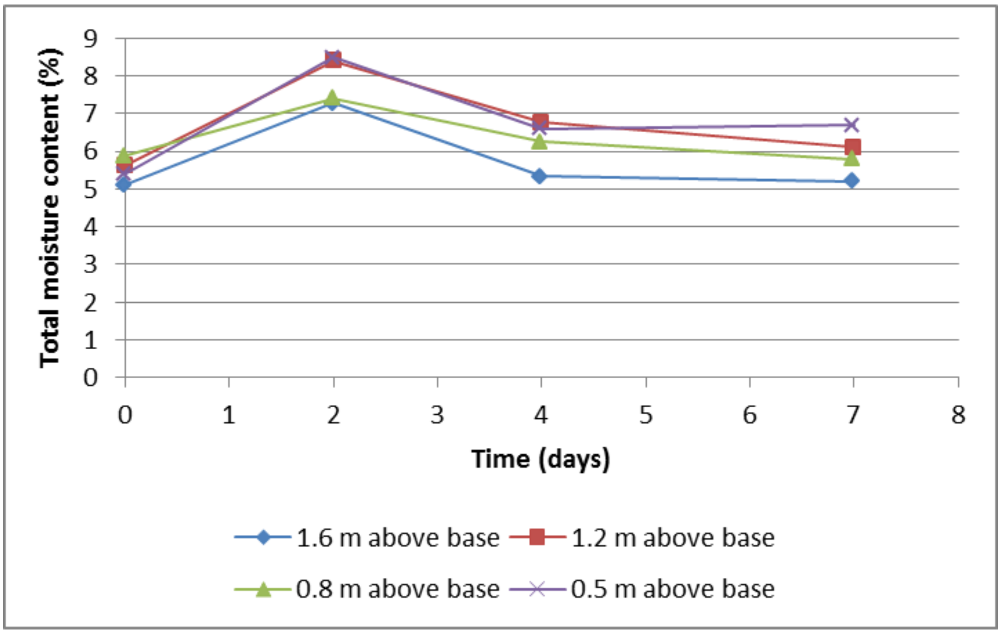

Figure 4.2.11: Moisture profile of the fine (-6.7 mm +0 mm) coal type B sample in the 2 m drainage column

The average moisture profile of the coarse (-53 mm +6.7 mm) coal B is given in Figure 4.2.10. The profile shows that the packed bed retained a negligible amount of added water, which was in accordance with the amount of water drained out as shown in Figure 4.2.6. This is in contrast to the profile obtained for the fine (-6.7 mm +0 mm) coal B as illustrated in Figure 4.2.11. An initial sample was taken on day 0 before water was added, and the second sample was taken after drainage has ceased on day 2. As seen by the increase in moisture content from day 0 to day 2, some water was retained by the coal bed, which slowly migrated downwards over time towards the bottom section of the drainage column. It should be noted that while there was a downwards migration of moisture, no water exited the column after the second day. This finding is in accordance with research conducted by Leeder *et al*. (2011), who performed a similar experiment on Canadian coking coals in drainage columns with heights ranging from 2 to 7.3 m. During the investigation, the impact of initial coal moistures, the effect of rain and the impact of vibration were studied. Figure 4.2.12 clearly shows the influence of the initial moisture content on the drainage of water from the packed bed. Higher initial moisture content resulted in higher final moisture content – also shown by Eckersley (1999:55).

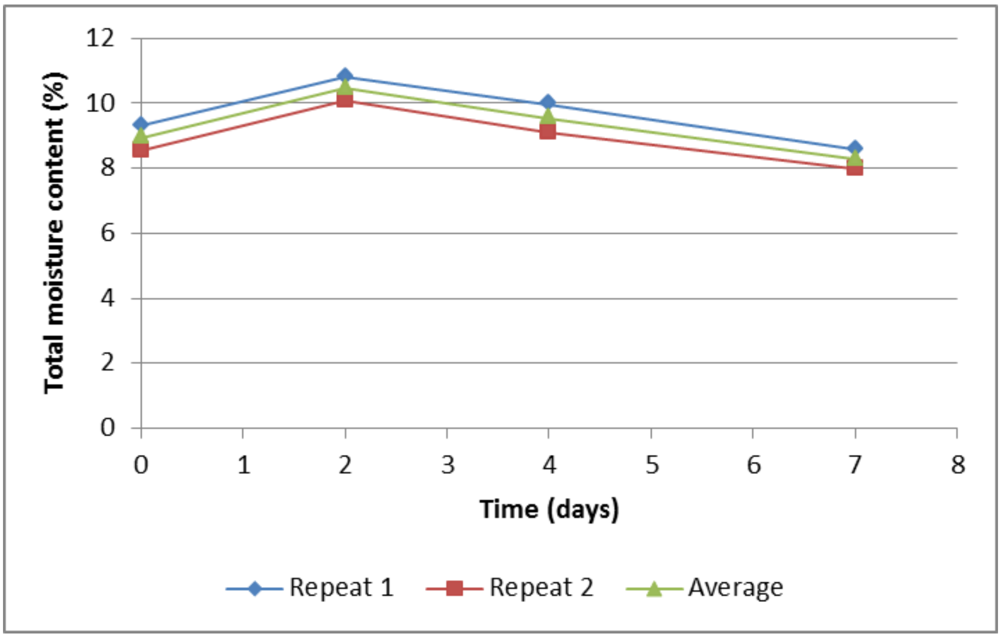

Figure 4.2.12: Average moisture content at 0.8 m above the base of the 2 m drainage column for the -53 +0 mm coal type B

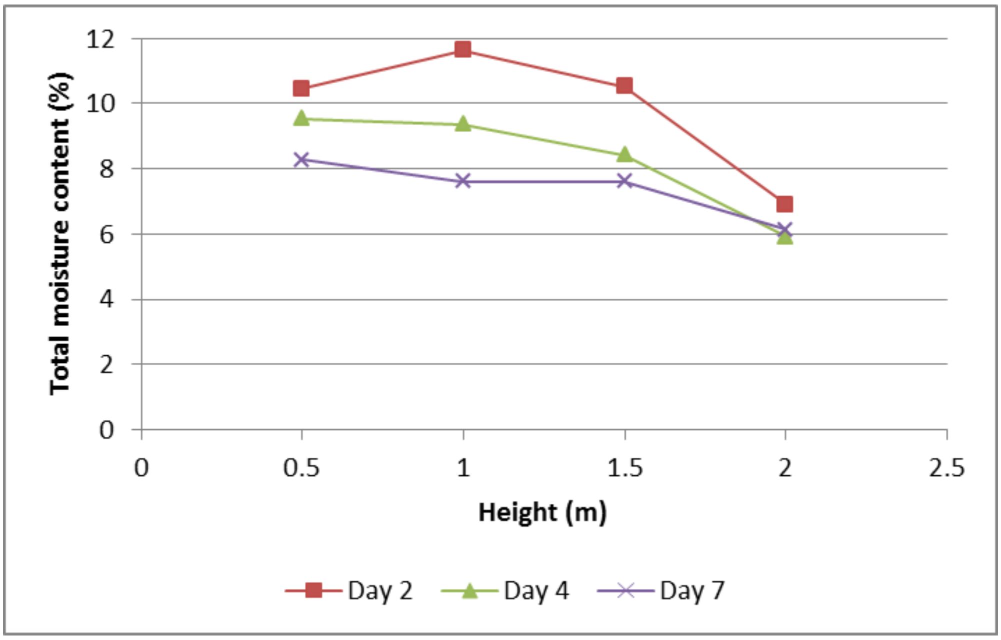

Figure 4.2.13: Moisture content as a function of height for coal type B (-53 mm +0 mm)

Eckersley (1999:55) loaded various Australian coals into 2 to 4 m high segmented drainage pipes. The objective of the investigation was to establish the effects of stockpile height, initial moisture content and fines content. Campbell & le Roux (2014) also observed during an experimental stockpile investigation that the initial moisture content also played a role in determining the final moisture content. The stockpile investigation consisted of a 15 tonne stockpile loaded onto a weighed platform – the same platform which was used in this investigation (see section 3.5).

As shown in section 4.2.1, stockpile height has an influence on its drainage characteristics. Figure 4.2.13 supports this statement – the water slowly drained from the top to the bottom sections of the packed bed over time. It is shown that there was a significant difference between the moisture content at the top compared to that of the bottom sections – similar to the drainage profiles determined by Leeder *et al*. (2011).

Data validation

The variability within a packed coal bed means that representative sampling is difficult. The coal sample consists of heterodisperse particles, meaning that there is no uniform structure within the drainage column. This complicates sampling, as no sample will be truly representative of a section of the column. It is thus necessary to validate the moisture profiles obtained by this investigation.

To validate the data obtained by this investigation, the moisture profiles are tested against the drainage profiles by means of mass balances. This was done by transforming the moisture percentages into mass values. The drainage pipe was divided into four sections and the assumption was made that each sample was representative of its section as a whole. The initial moisture content of the sections and the decrease in total coal mass over time as a result of sampling was taken into account.

A mass balance over each section is given by equations 4.2.1 and 4.2.2:

$$(Water\ mass\ flow\ out) = (Water\ mass\ flow\ in) - (Water\ mass\ accumulated) \qquad [4.2.1]$$

where

$$(Water\ mass\ accumulated) = (Water\ mass\ before) - (Water\ mass\ after) \qquad [4.2.2]$$

Table 4.2.5 gives the mass balance obtained for the first repeat of the -53 mm + 0 mm coal B sample experiment and a mass balance schematic is given in Figure 4.2.14.

It is shown in Table 4.2.5 that there is a slight difference between the calculated amount of water which exits the drainage pipe and the actual amount which was measured. This can be attributed to the fact that accurate sampling is difficult in such an experimental setup. The difference in values can also be attributed to how the mass balance was performed. According to the mass balance, 3.45 kg of water should exit the column by the end of the 4th day, which was not seen in the measured values. This discrepancy could be because the bottom sampling port is 0.5 m from the base of the column, which means that the calculated 3.45 kg of water could have drained undetected into the bottom section of the column – unable to exit as a result of the increased fines content at the base of the packed bed.

While it is assumed that each sample is a decent indication of the moisture content of a certain section, it is by no means exact. Some inconsistencies between the samples are expected due to the variant nature of coal. In spite of this, the moisture and drainage profiles are very comparable. The mass balances for the other experimental runs are given in Appendix C. Generally, the mass balances over the first two days of all experiments showed the lowest errors. This is attributed to the coal sample being close to saturated just after the water was initially added. The highest error over the first two days was 12.3%. An experimental error of around 10% is usually considered extremely good for experimental setups such as this. These results confirm the validity of the moisture profiles and the method of sampling.

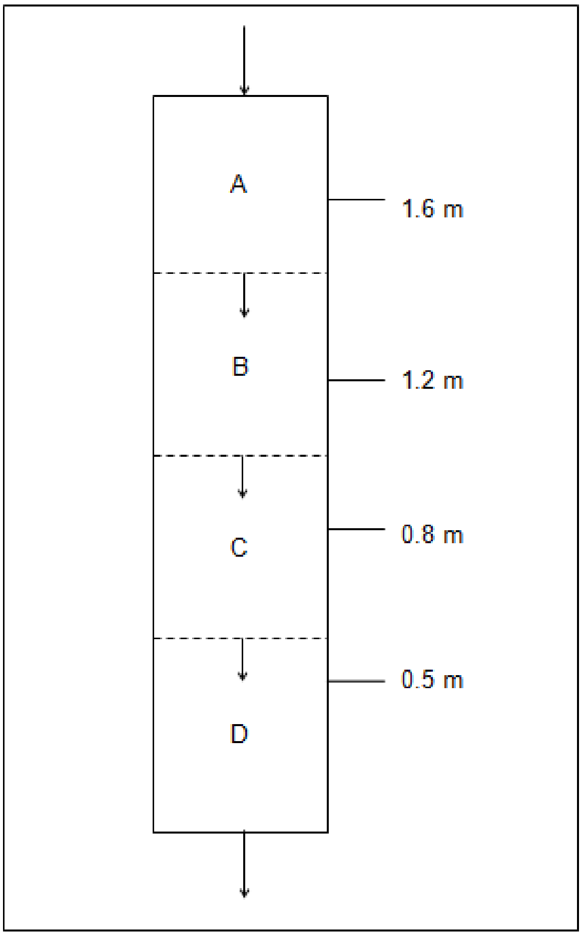

Figure 4.2.14: Illustration of the mass balance over the 2 m drainage column

Table 4.2.5: Mass balance for -53 mm + 0 mm coal B repeat 1 in the 2 m high drainage column

Time period		In (kg)	Initial mass (kg)	Final mass (kg)	Accumulated (kg)	Out (kg)	Actual out (kg)	Difference (kg)
Day 0	**A**	20.00	20.07	3.13	-0.07	20.07		
to	**B**	20.07	3.97	5.73	1.76	18.32		
day 2	**C**	18.32	4.03	5.63	1.60	16.72		
(2 days)	**D**	16.72	4.24	5.00	0.76	15.96	14.92	1.04
Day 2	**A**	0.00	3.13	2.74	-0.39	0.39		
to	**B**	0.39	5.73	4.14	-1.59	1.98		
day 4	**C**	1.98	5.63	4.65	-0.98	2.96		
(2 days)	**D**	2.96	5.00	4.51	-0.50	3.45	0.00	3.45
Day 4	**A**	0.00	2.74	2.65	-0.09	0.09		
to	**B**	0.09	4.14	3.55	-0.59	0.68		
Day 7	**C**	0.68	4.65	3.50	-1.15	1.83		
(3 days)	**D**	1.83	4.51	3.96	-0.55	2.38	0.00	2.38

Empirical modelling

An empirical model (equation 4.2.3) was derived for each experiment performed in the 2 m high drainage column. This was done by fitting an approximating curve to the drainage data in MATLAB. The model predicts the percentage of moisture retained in a packed coal bed with a height of 2 m and a diameter of 0.38 m as a function of time when 20 kg of water added.

$$R_m = a * t^{-b} \qquad [4.2.3]$$

In equation 4.2.3 R_m represents the mass of added water which the packed bed would retain in %, *a* and *b* are constants specific to a coal sample with a certain PSD, and *t* is the time since drainage initialised in minutes. The constants for each sample are summarised in Table 4.2.6. The R^2 values show that the empirical model and its calculated constants are a very good fit for the drainage profiles. This is confirmed by the comparison drawn between the experimental data and model output as shown in Figure 4.2.15. As seen in Table 4.2.5, *a* seems to be a function of the fines content of the coal sample (see Figure 4.2.16), while *b* appears to be related to the coal type – as illustrated by Figure 4.2.17. There is a strong positive relationship between the value of *a* and the amount of fine coal content. By comparing the values obtained for coals A and B, it appears that coal type also has an influence on the constant *a* – although this is much more evident in the *b* constant values. Further investigation is necessary to identify the effect which other coal properties have on the *a* and *b* values.

Table 4.2.6: Summary of empirical model parameters

Exp.	Coal type	Test no.	Size range	a	b	R^2
A-1	A	1	-53 mm +0 mm	128.3	0.09383	0.9934
	A	2	-53 mm +0 mm	89.77	0.05837	0.8409
			Average	108.5	0.0774	0.9783
A-2	A	1	-53 mm +0.5 mm	124.8	0.09401	0.9865
	A	2	-53 mm +0.5 mm	120.7	0.09398	0.997
			Average	122.8	0.0940	0.9952
A-3	A	1	-53 mm +1 mm	121.7	0.1003	0.9981
	A	2	-53 mm +1 mm	109.5	0.1004	0.9614
			Average	115.6	0.1004	0.9894
B-1	B	1	-53 mm +0 mm	189.4	0.2797	0.9830
	B	2	-53 mm +0 mm	190.5	0.2869	0.9861
	B	3	-53 mm +0 mm	170.2	0.2422	0.9898
			Average	187.9	0.2731	0.9889
B-2	B	1	-53 mm +6.7 mm	81.5	0.3530	0.9405
	B	2	-53 mm +6.7 mm	66.07	0.3101	0.9691
	B	3	-53 mm +6.7 mm	57.28	0.2172	0.9826
			Average	66.53	0.2869	0.9689
B-3	B	1	-6.7 mm +0 mm	181.0	0.2397	0.9381
	B	2	-6.7 mm +0 mm	186.4	0.2664	0.9345
	B	3	-6.7 mm +0 mm	183.4	0.2524	0.9369
			Average	194.3	0.2586	0.9729

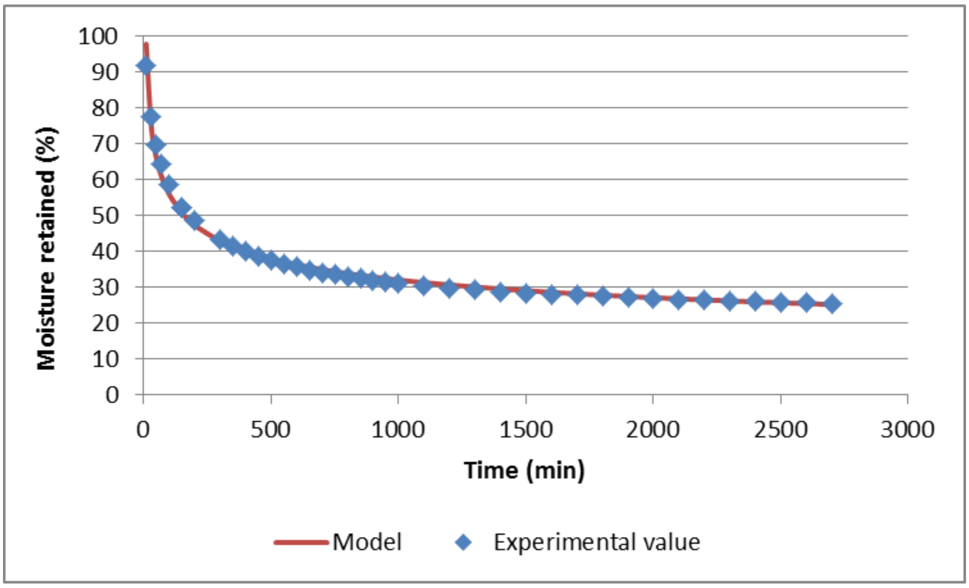

Figure 4.2.15: Comparison between empirical model and experimental data for coal type B (-53 mm +0 mm) repeat 3

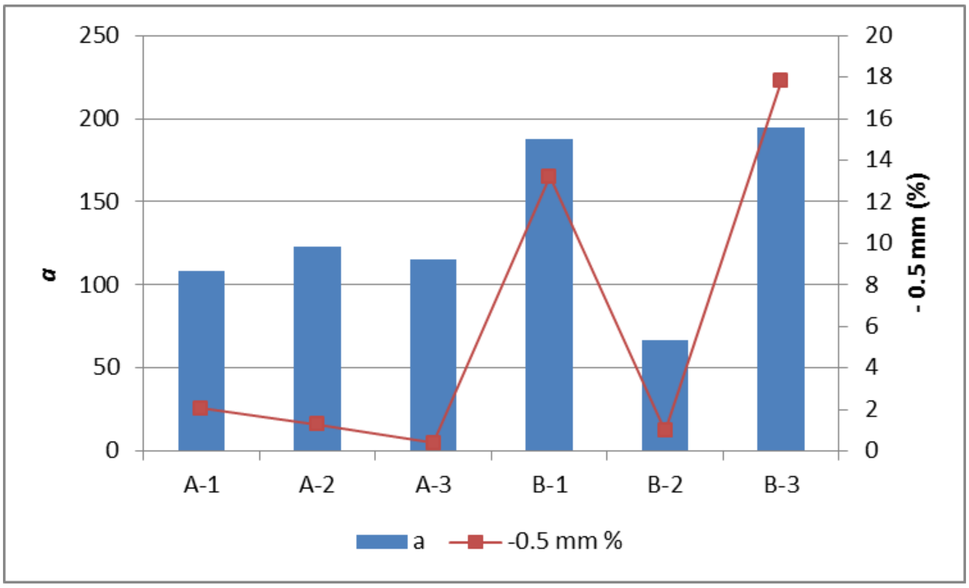

Figure 4.2.16: Comparison between average *a* and amount of particles smaller than 0.5 m

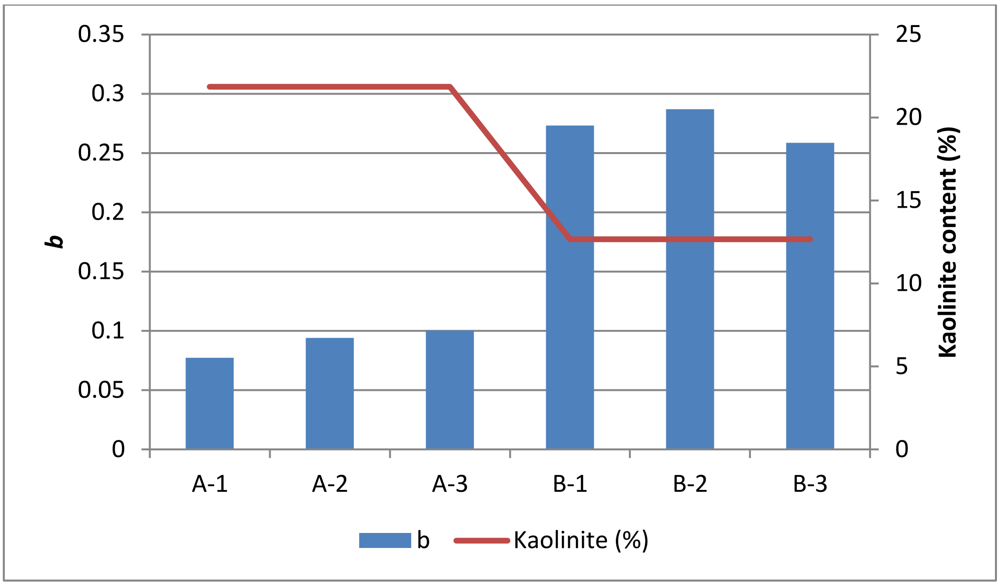

Figure 4.2.17: Comparison between average *b* and coal kaolinite content

4.3 Evaporation

Evaporation is known to be the more effective method (compared to drainage) of dewatering stockpiles, but the effect only extends to a certain depth below the surface (Boyapati & Oates, 1994:687; TRC Environmental Consultants, 1983:76; Williams, 2006:224). The effect of PSD and weather conditions such as relative humidity, temperature and wind speed on the evaporation rate and depth was investigated. These results are discussed in detail in the next sections.

4.3.1 Rate of evaporation

The rate of evaporation from stockpile surfaces is greatly dependent on the weather conditions (CSEM-UAE, 2010:1; Deodhar, 2008:25-29; Priyal & Toerien, 2010:3). In this study the influence of temperature, relative humidity, wind strength, and PSD was investigated. The weather station was not equipped to record solar radiation and the surface temperature of the coal bed was not measured.

4.3.1.1 Evaporation from coal stockpile surfaces

As illustrated in Figure 4.3.1, the evaporation from coal particles is a cyclic event. Moisture evaporated during the day when the temperature was high and the relative humidity low (see section 4.3.1.2). As evening fell, the temperature decreased and the relative humidity increased, resulting in the reabsorption of moisture into the porous coal particles. This is in accordance with research conducted by Fryer and Szladow (1973). The cyclic behaviour is attributed to the coal particles attempting to remain in equilibrium with the surrounding atmosphere. For example, if the relative humidity increases, the coal particles will absorb moisture to remain in equilibrium with the atmosphere. It can be seen in Figure 4.3.1 that the coal bed did not experience a large amount of

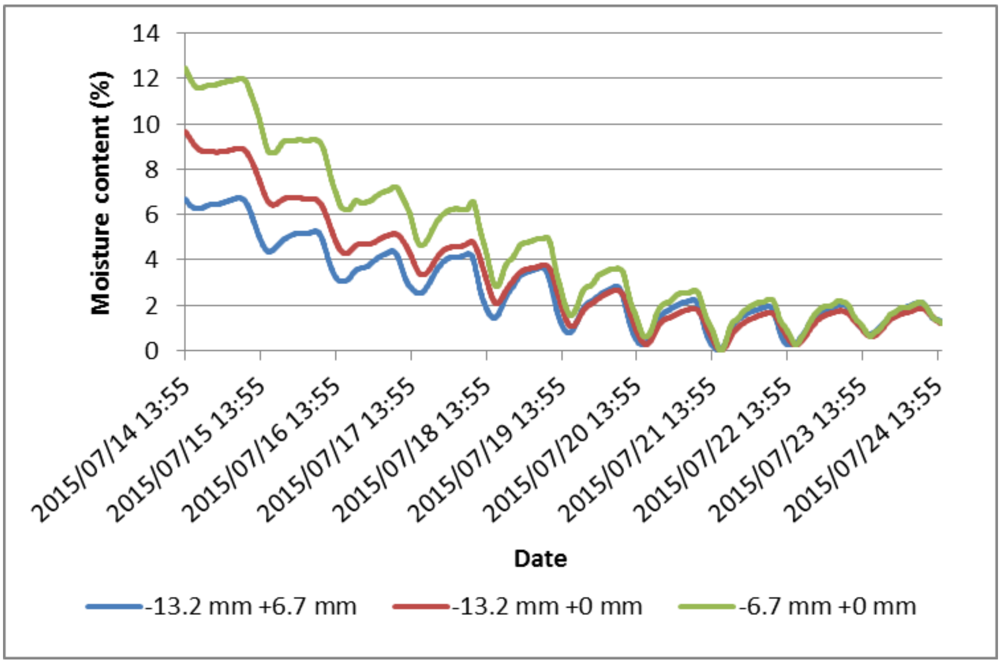

Figure 4.3.1: Decrease in moisture content for coal B

evaporation on the first day (2015/07/14) and thus experienced less reabsorption at night as the bed was still somewhat saturated. A high rate of evaporation during the day will lead to drier coal particles, meaning that the reabsorption capacity of the coal bed will be higher. This is demonstrated by the evaporation and adsorption cycle between 2015/07/19 and 2015/07/20. Evaporation generally occurred from 09:00 to 15:00 or from 09:00 to 17:00 depending on the season. Similar trends were obtained for all experimental runs.

4.3.1.2 Influence of weather conditions

Three weather elements – temperature, relative humidity, and wind speed – were investigated. It is known that an increase in temperature will lead to an increase in the rate of evaporation (Brown, 2014). This positive correlation is illustrated by Figure 4.3.2 and can be attributed to the fact that there is a positive relationship between the thermal conductivity coefficient and the temperature (Xie, 2015). Evaporation generally occurs from 09:00 to 17:00, with the highest rate of evaporation occurring at around 12:00 – depending on the moisture available for evaporation. Once the sun has set, the temperature falls and there is an increase in the relative humidity. The troughs seen in Figure 4.3.2 occurred when the temperatures were low and the relative humidity was high – leading to the coal particles absorbing moisture from the atmosphere. This resulted in a negative rate of evaporation.

There is a negative correlation between the rate of evaporation and the relative humidity as shown by Figure 4.3.3. Relative humidity is a factor of the temperature – as the temperature increases the saturated partial pressure of the air will also increase, which means that the relative humidity will decrease. A decrease in the relative humidity will lead to an increase in the rate of evaporation as the saturation level of the air is reached faster (Dama-Fakir & Toerien, 2010). Relative humidity is a function of the partial vapour pressure. The vapour pressure (water vapour partial pressure) at the surface of the coal stockpile is generally higher than the atmospheric vapour pressure, which results in the water molecules moving from the high to the lower vapour pressure (Headrick, 1967), thus aiding the process of evaporation as shown in Figure 4.3.4.

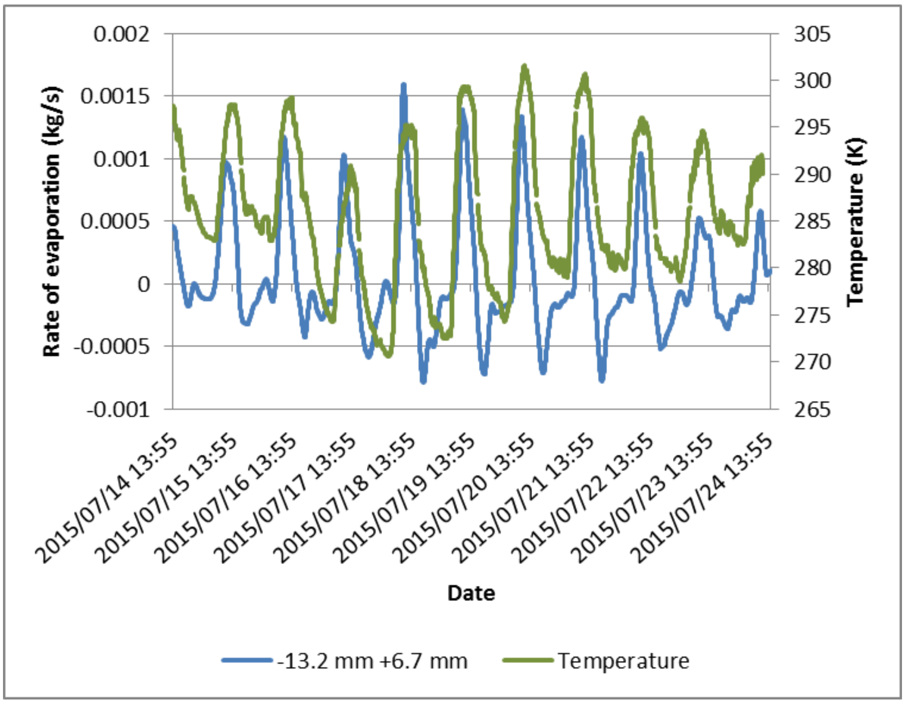

Figure 4.3.2: Comparison between the rate of evaporation and temperature (Coal B -13.2 mm +6.7 mm)

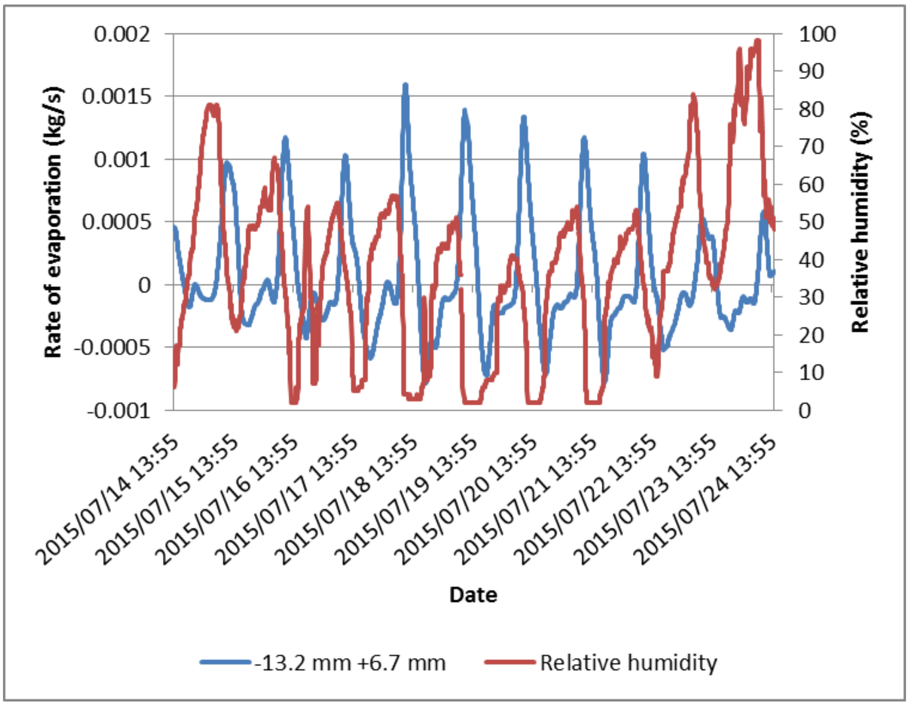

Figure 4.3.3: Comparison between the rate of evaporation and relative humidity (Coal B -13.2 mm +6.7 mm)

It can be seen in Figure 4.3.5 that no distinct correlation could be established between the wind speed and the rate of evaporation. This is due to the high variability associated with wind speed. As mentioned in section 2.4.3.5, wind serves to remove the saturated layer of air above the stockpile surface and replace it with an unsaturated air layer. In this investigation the weather conditions were only recorded every 5 minutes, which means that important wind speed data was not documented. Results were similar for all coal types and seasons.

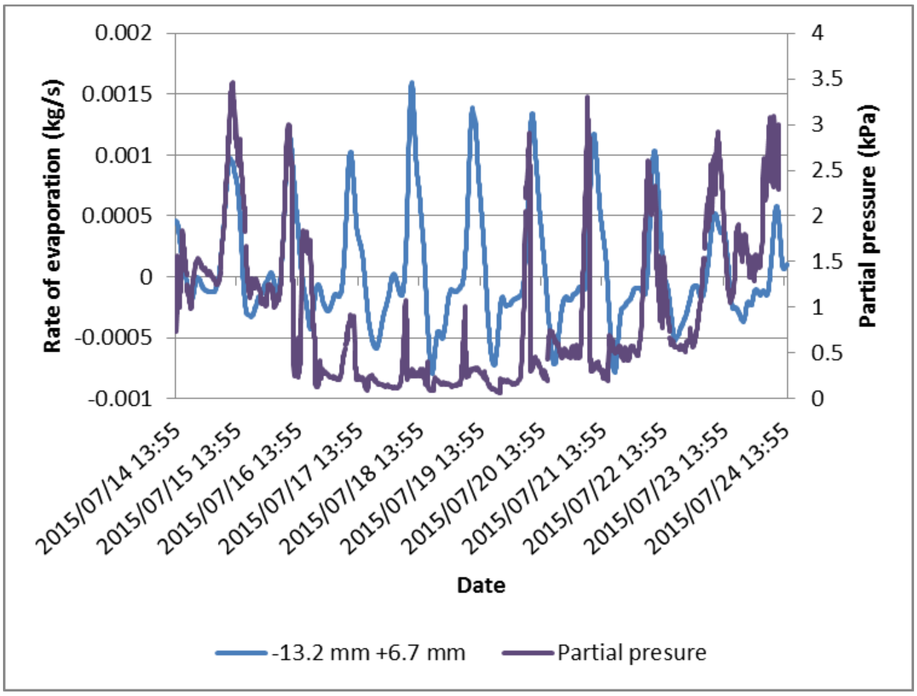

Figure 4.3.4: Comparison between the rate of evaporation and partial pressure (Coal B -13.2 mm +6.7 mm)

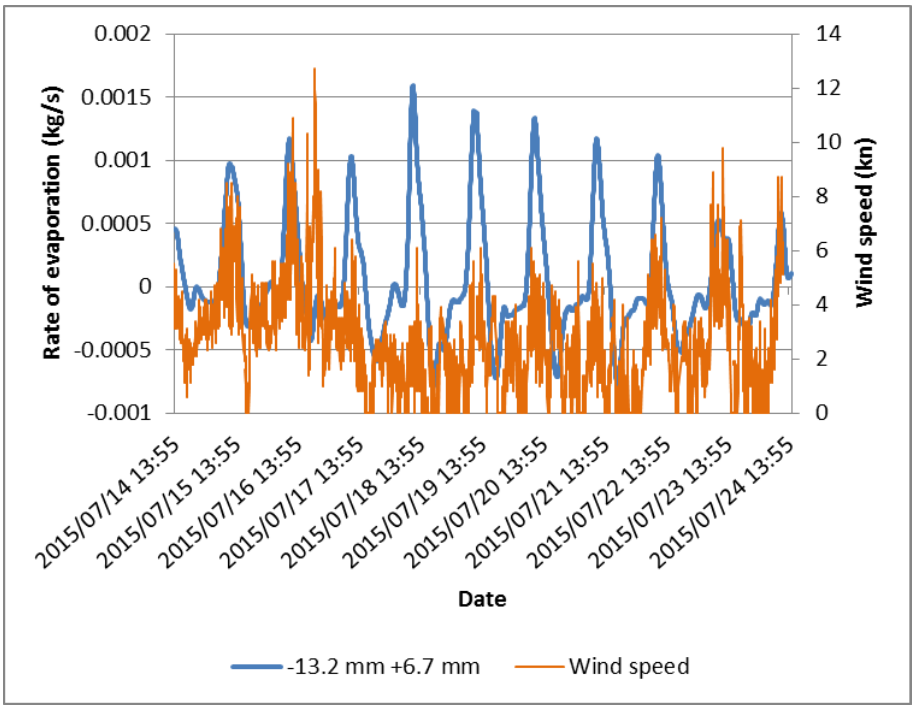

Figure 4.3.5: Comparison between the rate of evaporation and wind speed (Coal B -13.2 mm +6.7 mm)

As a result of the many factors which influence the rate of evaporation, it is difficult to establish the exact weather conditions at which evaporation commenced. The temperatures at which evaporation commenced on a daily basis ranged from 16 °C to 24 °C, while relative humidity ranged from 4% to 53%. The moisture content available for evaporation played a large role in determining the rate of evaporation. It is known that there is a positive relationship between the thermal conductivity coefficient and the moisture content (Xie, 2015). As seen in Figure 4.3.6, the rate of evaporation increased as the temperature increased up to a maximum, from whereon it decreased until no further evaporation occurred. This decrease is attributed to the decline of moisture content available for evaporation as the day progressed. It is shown in Figure 4.3.7 that the maximum rate of evaporation occurred earlier at the start of a run than at the end. The maximum rate of evaporation also decreased as the coal bed becomes drier over time.

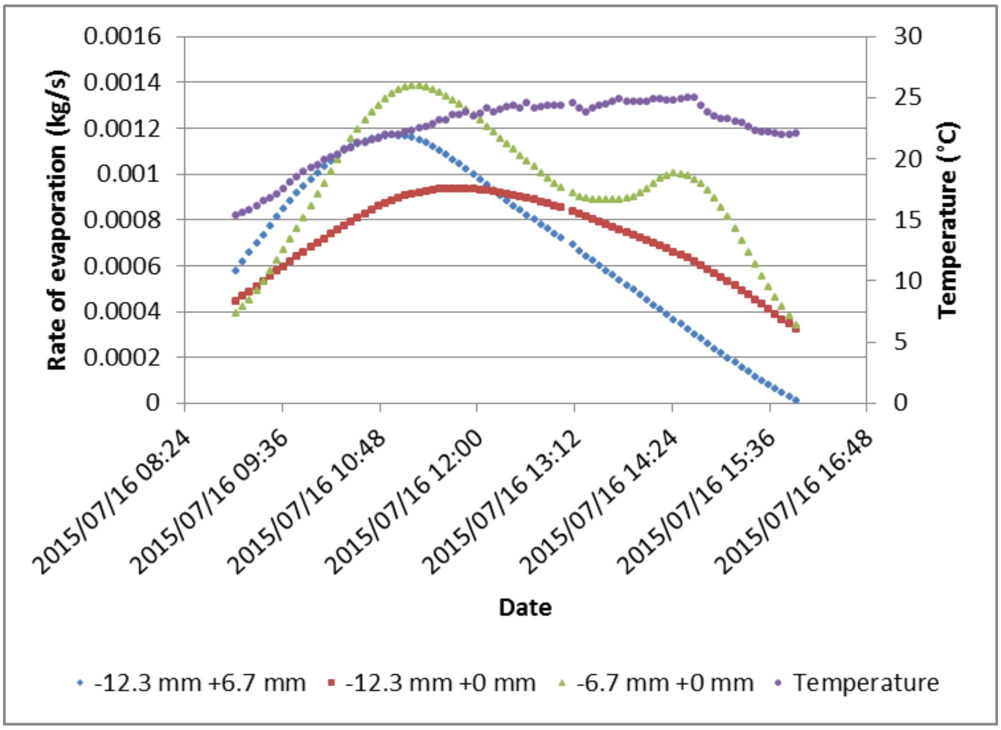

Figure 4.3.6: A daily cycle of the rate of evaporation from a coal B surface

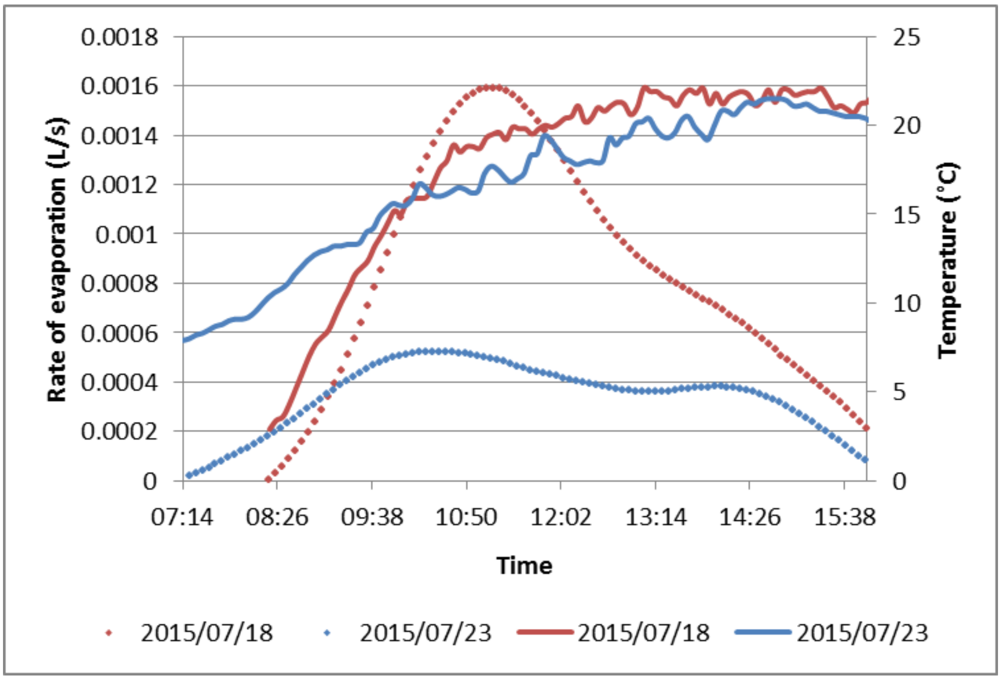

Figure 4.3.7: A comparison between the daily rate of evaporation for a coal B -13.2 mm +0 mm surface (♦ - rate of evaporation, ─ - temperature)

4.3.1.3 Influence of PSD

As seen in Figure 4.3.8, the coal bed consisting of fine particles (-6.7 mm +0 mm) initially evaporated at a higher rate than the other coal samples. However, after a couple of days the coarse coal (-13.2 mm +0 mm) started to evaporate at a higher tempo compared to that of the fine coal bed. This was seen throughout all experiments (Appendix D). This occurrence is attributed to the fact that the fine coal sample has a larger surface area which leads to a higher rate of evaporation. As the drying front moved downwards, and went deeper into the coal bed, the expulsion of the water vapour from the bed was hindered by the small spacing between the particles. This resulted in a decrease in the rate of evaporation.

The coarse coal bed was more porous, which means that the removal of water vapour is less obstructed and this aided the evaporation process. It can thus be derived that the surface of a fine coal stockpile will evaporate faster than a coarse stockpile, but that a coarse stockpile will experience evaporation more effectively as a result of its porous structure.

The mixed (-13.2 mm +0 mm) coal bed generally experienced the slowest rate of evaporation. This is attributed to the combination of the decreased surface area due to the larger particles and the minimal void spacing between the smaller particles.

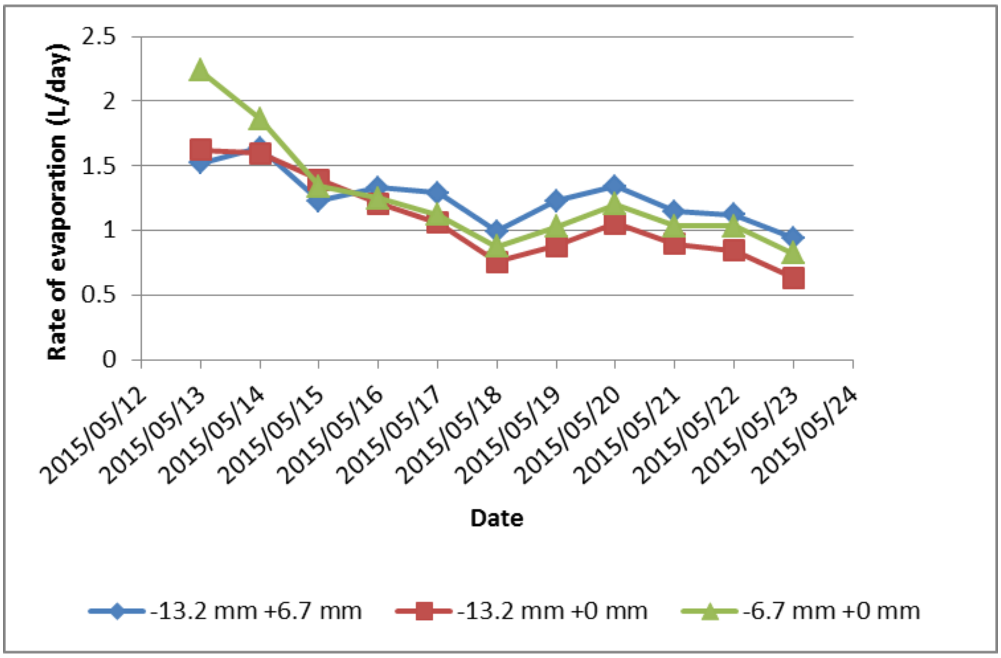

Figure 4.3.8: Influence of PSD on the daily rate of evaporation for coal B

4.3.1.4 Comparison between the two different coal types

It is known that there is a positive correlation between the thermal conductivity of coal and its moisture and mineral content (Xie, 2015). As the two coal types have similar inherent moisture contents, this will not have a large effect on the thermal conductivity characteristic to each coal type. Coal A, however, has a much higher ash content than that of coal B – meaning that coal A will have a higher mineral content than coal B. It is thus predicted that coal A will evaporate faster than coal B due to its likely higher thermal conductivity.

Experimental results were, however, not conclusive with regards to which coal type experienced a higher rate of evaporation. This is attributed to the different PSD ranges of the two coals as well as the fact that the two coals were investigated under different weather conditions.

4.3.1.5 Correlation between the evaporation of water and that from coal

As mentioned in section 2.4.3, it is difficult to establish a correlation between the rate of evaporation from a coal stockpile surface and that from a flat body of water. The mean rates of evaporation obtained for the flat body of water and that from coal surfaces over the same period of time is summarised in Table 4.3.1. Moisture generally evaporates faster from the flat surface of water, but an exact correlation between the rate of evaporation from a stockpile surface and that from body of water cannot be determined due to other factors which influence this rate such as PSD and the moisture available for evaporation within the coal beds. As the thermal conductivity of water is around three times that of dry coal (Speight, 1994), it was expected that the flat body of water will evaporate faster than the coal beds. There are also some attractive forces which exist between the coal particles their moisture content which must be overcome before evaporation will start.

Table 4.3.1: Summary of the rates of evaporation obtained between the coal A bed and the flat water surface

	Rate of evaporation (L/m²/day)		
	-50 mm +0 mm	**-26.5 mm +0.5 mm**	**Water**
20/06/2014 – 04/07/2014	0.12	0.10	0.10
15/07/2014 – 29/07/2014	1.38	1.14	1.26
29/07/2014 – 12/08/2014	1.29	1.05	1.38
12/08/2014 – 26/08/2014	1.52	1.04	1.52
26/08/2014 – 09/09/2014	1.66	1.29	1.94
Average	**1.20**	**0.92**	**1.24**

In Figure 4.3.9 the decrease in moisture content of both the coal samples and the flat water surface is illustrated. This figure shows the flat water surface experienced the largest amount of evaporation. This can be credited to the fact that the coal samples have a limited amount of moisture available for evaporation and regain some of the evaporated moisture during night time through the reabsorption process. The body of water, however, does not have such a limited moisture content. In Figure 4.3.10 it is shown that the flat body of water generally experiences the highest rate of evaporation.

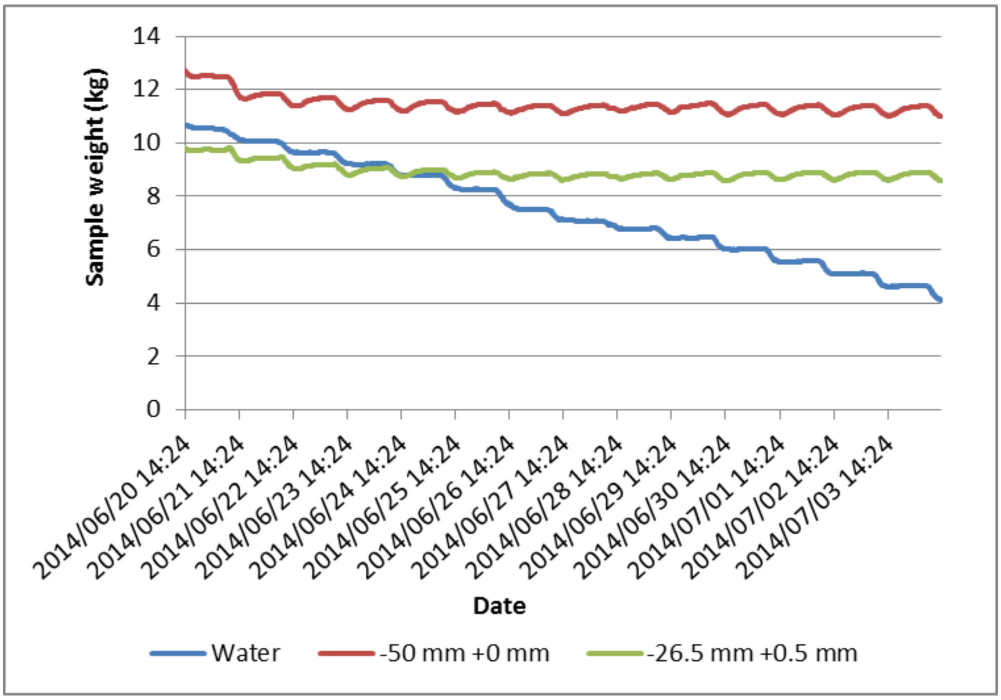

Figure 4.3.9: Decrease in sample weight over time for coal A

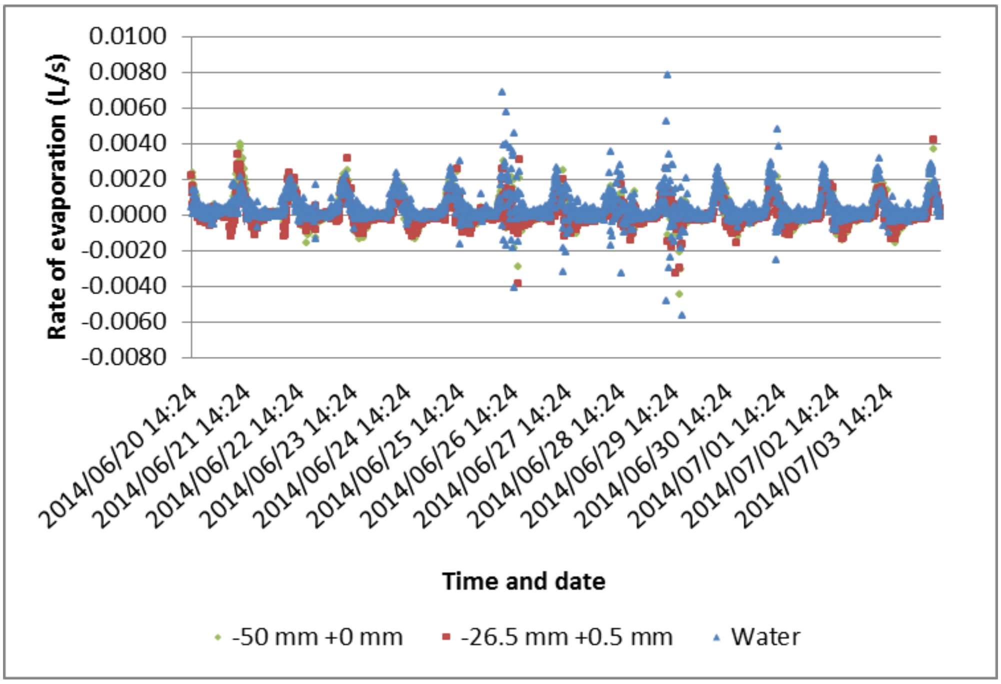

Figure 4.3.10: Rate of evaporation from a flat body of water and coal A surfaces

4.3.2 Depth to which evaporation extends

As discussed in section 4.3.1, the surface of a coal stockpile will experience significant evaporation. However, the question of the depth to which evaporation will extent remains. To investigate this, several segmented pipes were constructed and used to track the migration of moisture through evaporation as explained in section 3.4.2.

It is shown by Figure 4.3.11, Figure 4.3.12 and Figure 4.3.13 that the total moisture content decreased over time for all coal samples as the moisture evaporated from the surface of the coal containers. The same trends were seen throughout the investigation, as summarised in Appendix D. Some drainage occurred within the samples, shown by the steady increase in moisture towards the bottom of the container. Some discrepancies can be seen in the moisture analysis (e.g. the variability in the moisture content 0.6 m below the surface as shown in Figure 4.3.11). This is attributed to the imperfect experimental procedure – pipes containing dissimilar coal samples were analysed on a daily basis as explained in section 3.4.2.2.

From Figure 4.3.11 it can be seen that the surface of the coarse coal sample (-10 mm +6.7 mm) reached a final total moisture content of approximately 3% after two days of evaporation. It is assumed that some drainage also occurred within the first day (similar to the drainage experiments performed in section 4.2), but the amount was not measured. This would account for the large decrease in moisture content. The coarse sample (-10 mm +6.7 mm) experienced evaporation up to 0.4 m below the coal surface. As mentioned in section 4.3.1.3, the act of evaporation is aided by the porous structure of a coarse coal sample.

The surface of the mixed (-10 mm +0 mm) coal bed reached a final total moisture content of around 4% within a period of 2 days as indicated by Figure 4.3.12. This figure shows that the mixed coal bed experienced drainage in a similar manner to the coarse coal sample. The decrease in moisture content 0.2 m and below the surface on the first day is attributed to the manifestation of drainage. The surface of the stockpile experienced a decrease of 4% total moisture within the first two days, while evaporation 0.2 m below the surface only commenced after two days. No evaporation deeper than 0.2 m below the surface was observed.

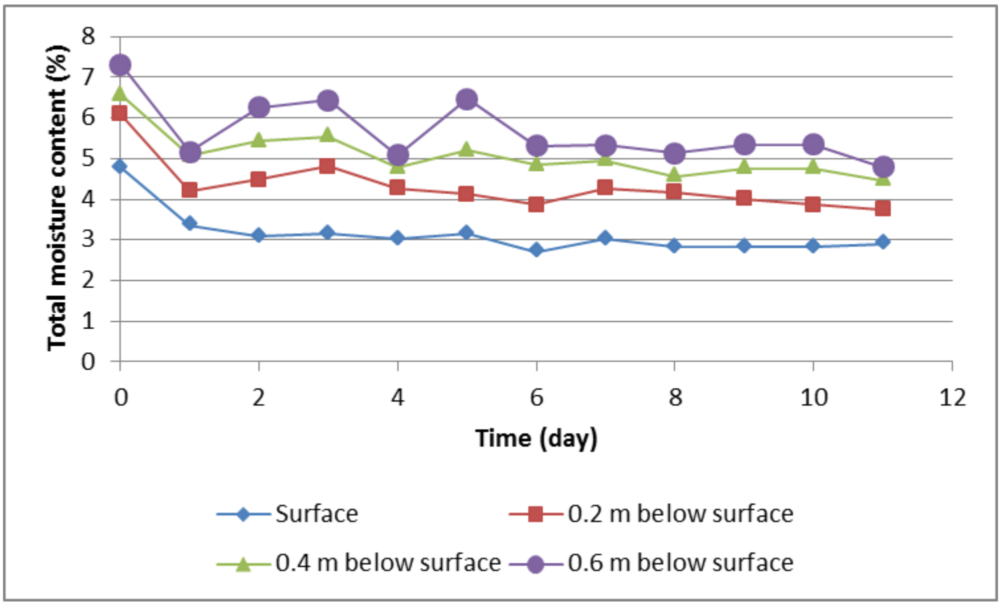

Figure 4.3.11: Moisture profile over time (coal B -10 mm +6.7 mm)

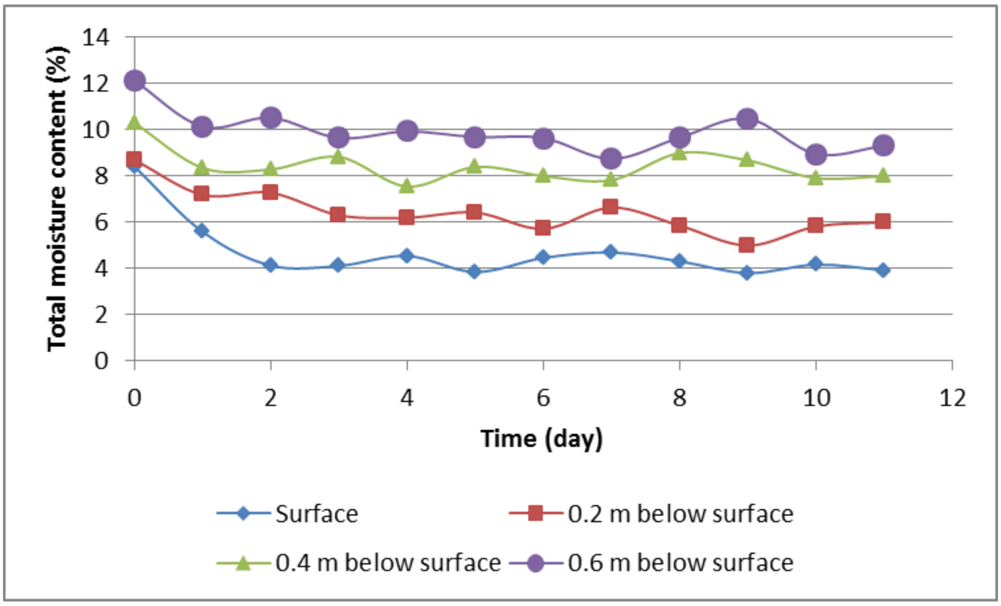

Figure 4.3.12: Moisture profile over time (coal B -10 mm +0 mm)

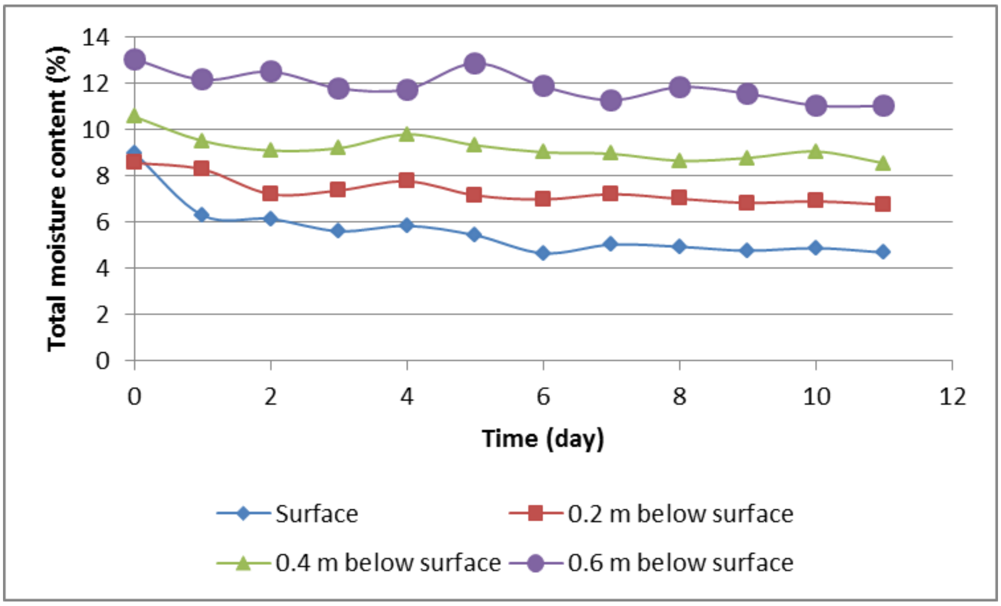

Figure 4.3.13: Moisture profile over time (coal B -6.7 mm +0 mm)

It is indicated by Figure 4.3.13 that the surface of the fine (-6.7 mm +0 mm) coal bed dried from 8.5% to a total moisture content of around 5% over the course of this experiment. Less drainage was seen in this coal bed, which is explained by the high fines content (section 4.2.3). No significant evaporation deeper into the coal bed was observed. This is attributed to the low porosity of the coal bed as explained in section 4.3.1.3.

4.3.2.1 Sample volume decrease

During the investigation, a decrease in sample volume was observed as showed in Figure 4.3.14. The fine coal sample (-6.7 mm +0 mm) experienced the largest volume decrease, while the coarse sample (-10 mm +6.7 mm) showed the smallest decrease. There are two explanations for this occurrence. Firstly, the evaporation of interparticulate water formed pressure gradients which lead to a decrease in volume as the moisture was removed. Secondly, the desorption of moisture occurred more rapidly from the surface of a coal particle than from its interior, which may have resulted in internal stresses which could have caused the particle to disintegrate (Fryer & Szladow, 1973).

Figure 4.3.14: Sample displacement for coal B (-10 mm +6.7 mm, -10 mm +0 mm, -6.7 mm +0 mm)

4.4 Stockpile dewatering

A stockpile consisting of approximately 9 tonnes (Figure 4.4.1) of coal B was constructed on the experimental platform as explained in section 3.5. The properties of the stockpile is summarised in Table 4.4.1.

Table 4.4.1: Experimental stockpile properties

Property	Value
Calculated dry coal mass	8628 kg
Calculated water content after loading	454 kg
Experimental total moisture after loading	5.5%
Height	2.4 m
Base diameter	5.7 m
Angle of repose	40°
Size range	-50 mm +0 mm

Figure 4.4.1: Experimental stockpile

4.4.1 Equilibrium results

In this section, the surface runoff water and the water which drained out of the bottom of the stockpile are collectively referred to as drainage. This is due to the fact that the experimental setup was not able to differentiate between the two types of water.

The data – summarised in Table 4.4.2 – indicates that the final moisture content of the stockpile was independent of the rainfall conditions. This suggests that the fines content determines the final moisture content, which is supported by the results obtained in sections 4.2.3 as well as by research conducted by Rong (1997), Eckersley (1999) and Campbell and le Roux (2014). As shown in Figure 4.4.2, the rate at which water initially drained from the stockpile in run 3 is much higher than that of run 2. This is a consequence of the fact that run 3 consisted of a more intense rainfall event as summarised in Table 4.4.2. After a while, water drained at similar rates for the two runs, supporting the conclusion that the final moisture content of the stockpile is not dependent on the rainfall intensity.

The difference between the initial and final moisture contents of runs 1 and 2 shown in Table 4.4.2 indicates that the initial moisture content of the stockpile is a deciding factor in determining the amount of moisture retained by the stockpile. It appears that the effect of evaporation was considerable and continued long after all drainage has ceased as indicated by the water balance in Figure 4.4.3. An interesting observation is the mass loss and gain cycles through which the stockpile went – it appears that the stockpile absorbed moisture from the atmosphere as the relative humidity increased and the temperature fell through the night similar to the evaporation experiments discussed in section 4.3.1. The results shown in Figure 4.4.3 are typical for all experiments – thus only the result of run 2 is shown. The drainage showed an exponential decay, ceasing within the first 2 days after the rainfall event has concluded. In contrast to this, the evaporation showed a more linear rate and appeared to be very dependent on the weather conditions such as temperature, wind speed and relative humidity.

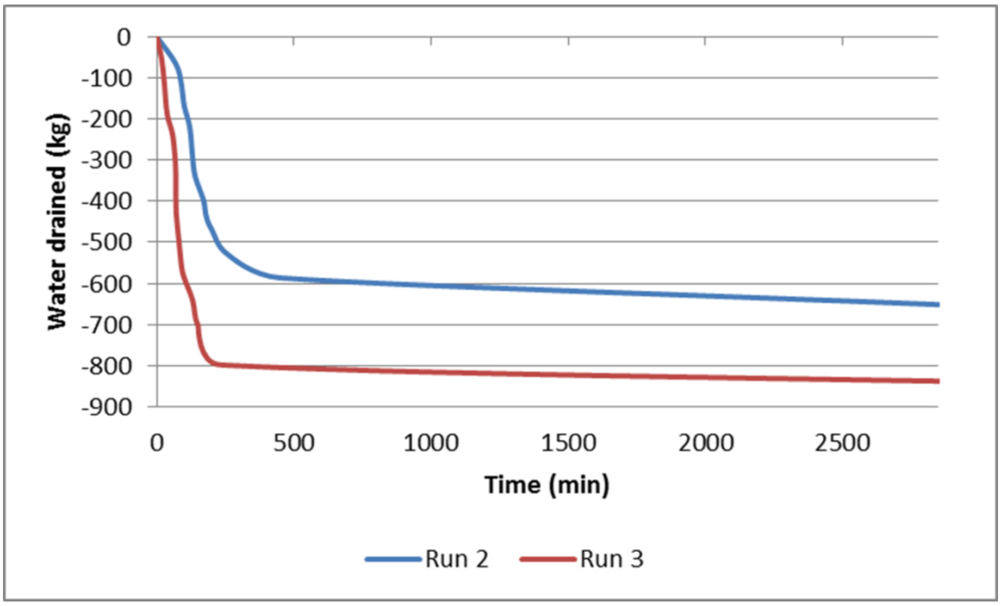

Figure 4.4.2: Comparison between the total amount of water drained of runs 2 and 3 over time

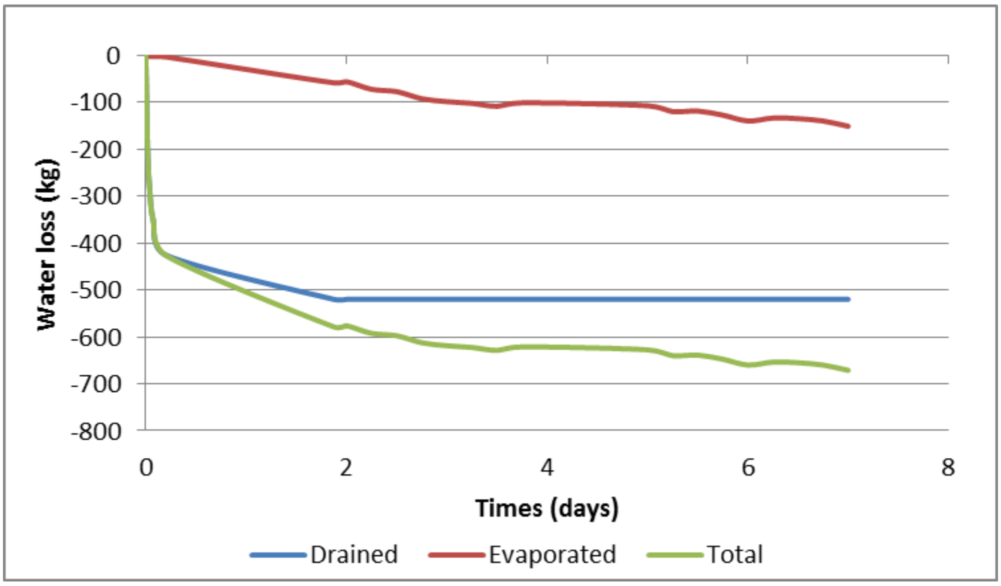

Figure 4.4.3: Water balance of run 2 over time

Table 4.4.2: Summary of stockpile test results

	Test 1	Test 2	Test 3
Total test period (minutes)	10041	10250	28894
Initial moisture (%)	5.5	6.6	6.5
Wetting period (minutes)	30	145	90
Rainfall rate (mm/h)	68	36	69
Total water added (L)	1226	3110	3740
Maximum moisture (%)	11.6	12.9	16.3
Rain addition rate (L/min)	40.9	21.5	41.2
Drainage rate during wetting (L/min)	20.4	16.3	29.4
Drainage period after wetting (min)	3941	2740	8164
Water drained (L)	1047	3056	3394
Water evaporated (L)	134	109	346
Final water retained (L)	609	598	649
Final moisture (%)	6.6	6.5	7.0
Evaporation rate (kg/day/m^2)	0.57	0.46	0.52

4.4.2 Final moisture distribution

As seen in Figure 4.4.4, evaporation and gravity drainage both had a significant influence on the moisture movement within a coal stockpile. Gravitational forces pulled the water within the stockpile towards the base of the stockpile, while evaporation dried the surface. The water at the base of the sample was unable to be removed by drainage or evaporation, which explains why this part of the stockpile has the highest moisture content. The inherent moisture of the samples remained constant at around 2.6%, which is expected as it is dependent of the surface and pore properties of the coal.

The segregation of particles which occurred during the construction of the stockpile is shown in Figure 4.4.5. The finer particles accumulated at the crest of the stockpile and the coarser particles formed a layer at the bottom of the stockpile. This is in accordance to segregation patterns observed by Williams (2006:224). It is shown in Figure 4.4.4 that the highest moisture content was found at point O. This is attributed to the fact that the O sample contained a larger proportion of fines content compared to the surrounding samples. The outskirts of the stockpile (sample S) contained the lowest fines content. This is attributed to the fact that the larger particles had a higher momentum due to their greater mass. This is also shown in Figure 4.4.1, where it can clearly be seen that the coarser particles formed the outskirts of the stockpile.

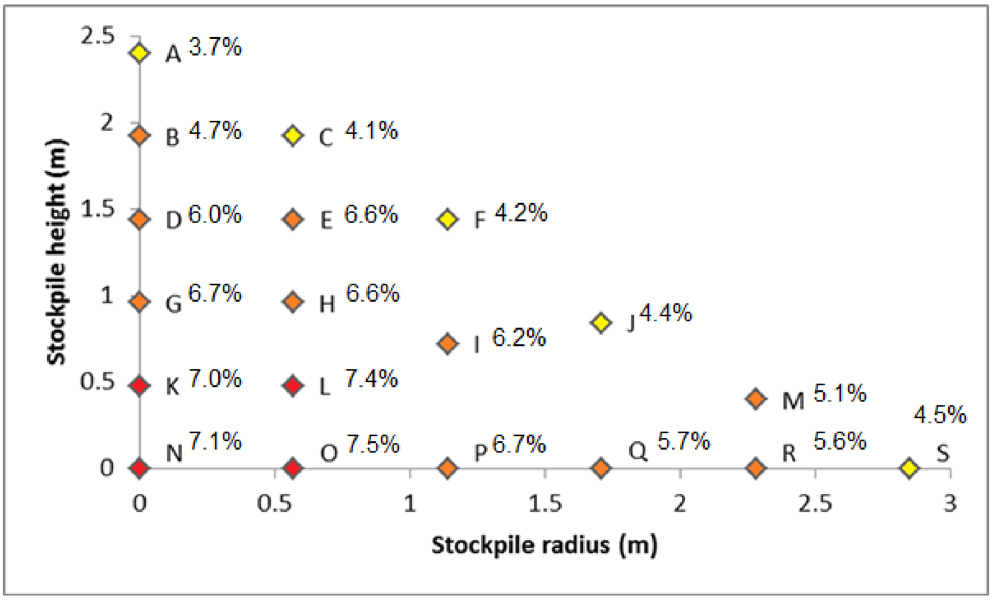

Figure 4.4.4: Total moisture content and position of samples

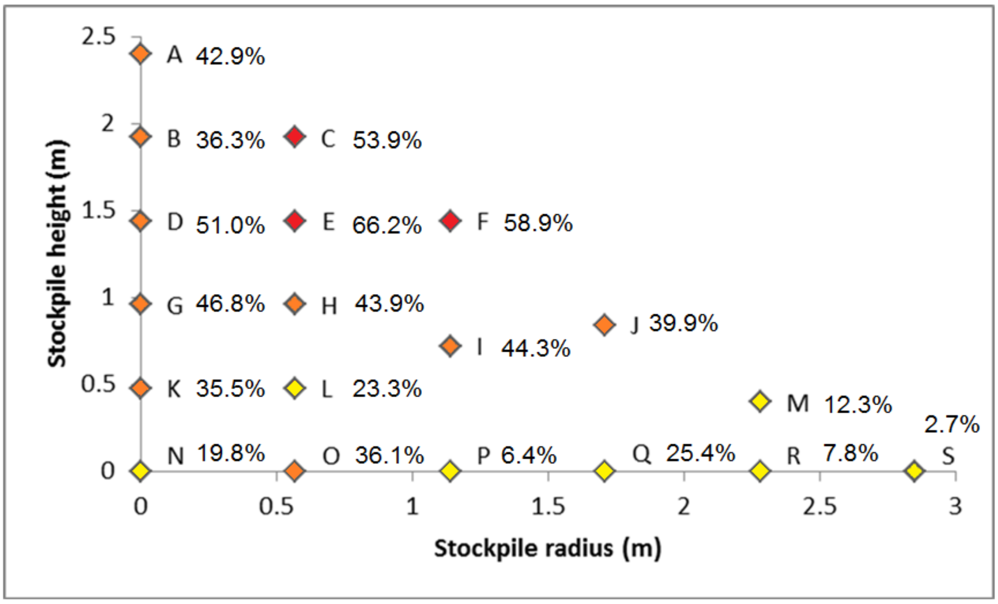

Figure 4.4.5: Fraction of samples less than 1 mm

4.4.3 Comparison to individual experiments

To establish whether the individual experiments correctly represent the mechanisms by which moisture migrates or is retained by a coal stockpile, comparisons were drawn between the experimental setups which represented the individual stockpile characteristics most accurately. These comparisons are discussed in the next sections.

4.4.3.1 Runoff versus infiltration

As the amount of runoff and drained water was not measured individually during the stockpile experiment, quantitative comparisons could not be drawn between the experiments discussed in section 4.1 and the experimental stockpile. The runoff versus infiltration experiment did, however, show that for increased rainfall intensity the proportion of runoff water will be increased. The results illustrated in Figure 4.4.2 showed that the total amount of drained and surface runoff water increased with an increased rainfall intensity. From literature it is known that the coal surface will reach a final infiltration rate once saturation has occurred (Critchley *et al.*,1991). As only one coal stockpile was used in this experiment, it can be assumed that the surface for each rainfall event will be similar. Supposing that the final infiltration rate had been reached in for all experimental runs, the increase in drainage can be attributed to the increase in surface runoff. The runoff versus infiltration experiment is thus representative of the way by which surface runoff is generated in a coal stockpile.

Figure 4.4.6: Illustration of the way by which the drainage column simulates the drainage in a stockpile

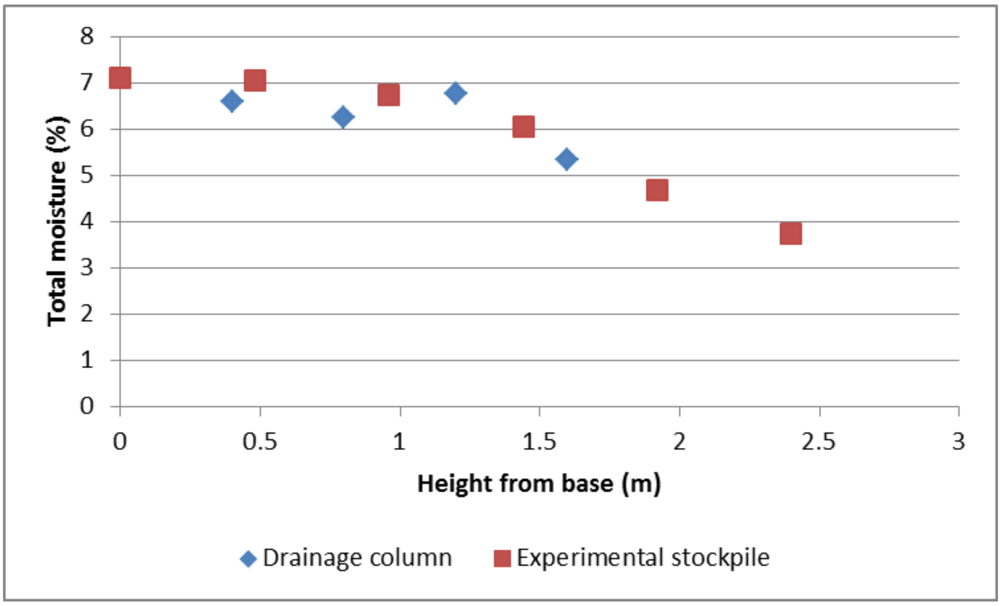

Figure 4.4.7: Comparison between the experimental stockpile and the drainage column

4.4.3.2 Drainage

The drainage column discussed in section 4.2 was intended to be representative of way by which the interior of a coal stockpile drains, as illustrated by Figure 4.4.6. As the centre of the coal stockpile consists primarily of finer particles, a comparison was drawn between the drainage experiment containing -6.7 mm +0 mm as discussed in section 4.2. This comparison is presented in Figure 4.4.7 which shows that the drainage column experiment is a fairly good representation of the drainage process which occurs within a coal stockpile.

4.4.3.3 Evaporation

The evaporation experiments discussed in sections 4.3.1 and 4.3.2 was designed to represent the evaporation process which occurs on the surface of a stockpile. In this section the results from the two experiments are compared to the results obtained by the experimental stockpile.

Rate of evaporation

As summarised in Table 4.4.3, there is a difference in the average rates of evaporation from the coal stockpile surface and that from the coal containers (with a size range of -12.6 +0 mm). The experimental stockpile experienced slower rates of evaporation – even though the average temperatures of the season were much higher. This is attributed to the fact that the experimental stockpile did not experience direct solar radiation as a result of the corrugated iron roof and its location. The platform was located between two buildings, which led to the stockpile remaining in shadows for the majority of the experimental period. This illustrates the large influence which solar radiation has on the rate of evaporation.

Table 4.4.3: Summary of evaporation data

	Average RoE ($kg/m^2/day$)	Average temperature (°C)	Average relative humidity (%)
Experimental stockpile			
Run 1	0.57	24.52	40.90
Run 2	0.46	23.47	45.05
Run 3	0.52	21.73	51.89
Evaporation from containers			
28/04/2015 – 12/05/2015	1.38	16.01	36.11
12/05/2015 – 23/05/2015	1.50	16.53	33.39
02/06/2015 – 16/06/2015	1.13	9.74	48.94
14/07/2015 – 24/07/2015	1.55	12.63	37.77
04/08/2015 – 18/08/2015	1.22	13.16	19.75

Even though the results differ between the two experiments, it is believed that the method by which the small scale evaporation experiments are conducted is a valid way of investigating the various factors which influence the rate of evaporation. Just as the coal beds showed cyclic behaviour as the particles adsorbed and desorbed moisture, the experimental stockpile showed similar behaviour, although to a smaller extent. This is attributed to the large volume of the coal stockpile and the fact that its surface is the only part which is directly exposed to the atmosphere. Coal deeper into the stockpile will not experience the atmospheric conditions as greatly as coal on the stockpile surface, and will thus not experience the adsorption and desorption cyclic process to such a large extent. As shown in Figure 4.4.4, the deeper particles also have larger moisture contents, which mean that the cycle would also not be as pronounced.

Depth of evaporation

As shown in Figure 4.4.8, the results of the evaporation depth experiment does not accurately represent the depth to which evaporation was seen within the coal stockpile. While the surface moisture contents are similar, there is a big discrepancy between the values underneath the surface. There are several reasons why these values differ to such an extent. Firstly, the pipes did not allow for drainage to occur as a result of the sealed pipe-ends. Secondly, the height of the stockpile supported the drainage process as discussed in section 4.2.1. The stockpile had a height of 2.4 m, while the pipes were only 0.7 m long. Thirdly, the porous nature of a coal stockpile aids the process of evaporation. As the evaporation depth experiments were conducted in pipes, air was not able to move through the coal beds as it would have in a coal stockpile.

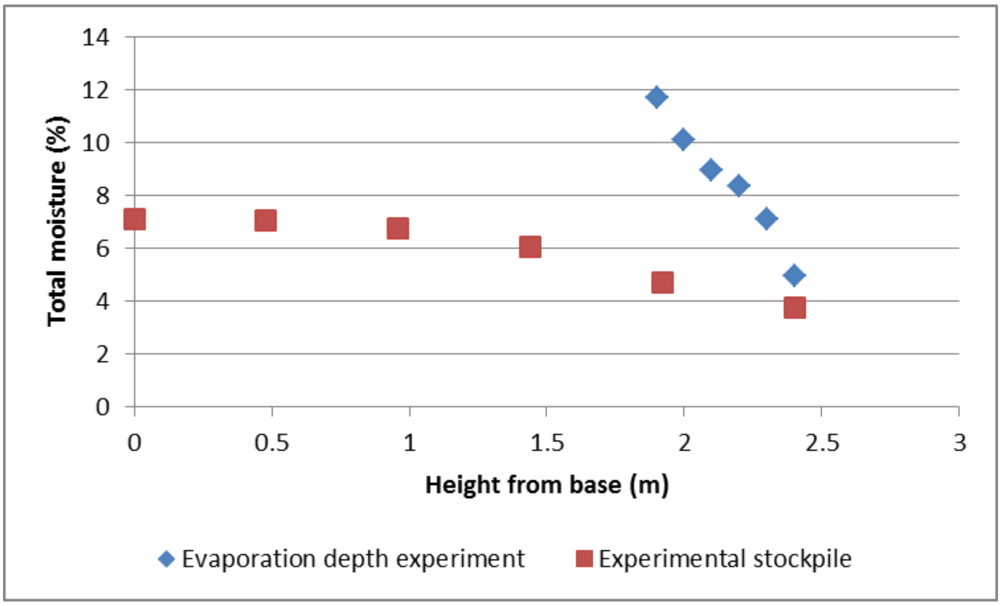

Figure 4.4.8: Comparison between the experimental stockpile and the evaporation depth experiment

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

This chapter contains conclusions which can be drawn from the results of this project in section 5.1. The recommendations which arose as part of this project are given in section 5.2.

5.1 General comments and conclusions

The mechanisms (runoff, infiltration, drainage and evaporation) by which moisture migrates or is retained in a coal stockpile were investigated in this project. The mechanisms were separately simulated in specialised experimental setups. A larger, 9 tonne coal stockpile was constructed to which the small scale experiments was compared. The next sections summarise the conclusions which can be drawn from the results obtained during this investigation. Over the course of this investigation it was found that the inherent moisture content remained constant for both coals investigated. Focus was thus placed on the total moisture content – which changed as a result of the fluctuations in the surface moisture content.

5.1.1 Runoff versus infiltration

From the results discussed in section 4.1 it can be concluded that there is a positive relationship between the proportion of surface runoff and the rainfall intensity, angle of repose, fines content, and the degree of compaction. The strong linear relationship between the rainfall intensity and the amount of surface runoff – together with the constant final rate of infiltration – proved that the amount of surface runoff is largely dependent on the rainfall intensity and the nature of the stockpile surface. Results indicated that the final rate of infiltration is dependent on the characteristics of the stockpile surface – a stockpile consisting out of coarse particles will have a much larger infiltration capacity. A smaller angle of repose will result in a longer contact time between the stockpile surface and water, which will increase the proportion of rainfall which will infiltrate the stockpile. The size of the interparticulate voids plays a large role in determining the proportion of rainfall which will infiltrate a stockpile. A decrease in the size of these voids (either through compaction or high fines content) will lead to increased surface runoff.

The possibility of erosion occurring is increased for stockpiles with high angles of repose and high fines content. To minimise infiltration, stockpile surfaces should be compacted at an angle which will minimise the contact time between the surface and the water and, at the same time, reduce the possibility of erosion occurring.

5.1.2 Drainage

Results confirmed that the PSD plays a large role in determining the extent to which a coal stockpile will be dewatered by means of drainage. The -0.5 mm particles proved to have a large effect on the amount of water retained by a coal sample. It was found that an increased stockpile height will have a positive influence on the degree of dewatering.

During this investigation it was shown that a decrease in the size of the interparticulate voids (either through compaction or high fines content) will result in drainage difficulties. The rate of drainage is a function of the interparticulate void size. A coal stockpile consisting of fine coal particles will thus drain at a slower rate than a coarse coal stockpile. A comparison between the drainage profiles between the two coals studied in this investigation showed that a high ash and clay mineral content will lead to more water being retained by the coal stockpile. It can thus be concluded that certain coals may be more difficult to dewater by means of gravity drainage than other coals. The data obtained by this investigation showed that drainage could be aided by disturbing (thus creating additional pathways) the stockpile.

The moisture profiles determined for the coal beds showed a downwards migration of moisture over time. These profiles were validated by means of mass balances and the sampling method was proven to representative of each section. Results proved that there is a build-up of moisture within the coal sample – a higher initial moisture content will generally result in a higher final moisture content. The results also showed that there the rate at which moisture migrates in a fine coal bed is much slower than in a coarse coal bed.

An empirical model (5.1.1) was fit to the drainage profiles and was found to fit the data extremely well. The constant *a* is believed to be a factor of the PSD, while the constant *b* is thought to be inversely dependent of the clay mineral content of the coal sample

$$R_m = a * t^{-b} \tag{5.1.1}$$

Results indicated that there was some hold-up of moisture within the coal bed at certain heights. The heights at which these hold-ups occurred seemed to be a function of the PSD of the coal sample.

5.1.3 Evaporation

It was proved that the rate of evaporation from coal stockpile surfaces is influenced by many different factors. An increase in temperature will lead to an increase in the rate of evaporation. Relative humidity is a factor of the temperature – as the temperature increases the saturated partial pressure of the air will also increase, which means that the relative humidity will decrease. No definite conclusions can be made regarding the influence of wind speed on the rate of evaporation as the amount of data was insufficient. Literature has, however, shown that wind will aid the process of evaporation by removing saturated air from the surface of the stockpile. Solar radiation was not measured in this investigation. The coal beds showed cyclic events of adsorbing moisture overnight (as the temperature fell and the relative humidity increased) and desorbing this moisture during the day as part of the process of evaporation. This occurrence is attributed to the coal particles attempting to remain in equilibrium with the atmosphere.

The PSD of the coal proved to have a large influence on the extent of evaporation from coal surfaces. While the fine particles have a large surface area, the small interparticulate voids have a negative influence on the rate of evaporation. It can thus be derived that the surface of a fine coal stockpile will evaporate faster than a coarse stockpile, but a coarse stockpile will experience evaporation more effectively as a result of its porous structure. This was proven by the depth of evaporation experiments – the fine coal bed only experienced evaporation on the surface while the coarse coal bed showed signs of evaporation up to 0.4 m below the surface. The rate of evaporation is largely dependent on the moisture content (or the amount of water available for evaporation) of the coal bed. A decrease in moisture content will result in a slower rate of evaporation.

No correlation could be determined for the evaporation from stockpile surfaces and that from a flat body of water. This is due to the fact that certain factors affect the evaporation from coal particles which do not apply to the evaporation from water.

5.1.4 Experimental stockpile

The experimental stockpile confirmed that the amount of infiltrated water (and by definition the final moisture content) is independent of the rainfall intensity. The proportion of infiltrated water is largely dependent on the initial stockpile moisture content. Drainage generally ceased after a period of two days while evaporation took place over the entire duration of the experiment.

The final moisture distribution within the stockpile proved that both evaporation and gravity drainage had an influence on the redistribution of moisture. Evaporation dried the surface of the stockpile, while gravity facilitated the drainage of water towards the base of the stockpile.

Generally the small-scale experiments were a good representation of the way by which moisture is redistributed within the coal stockpile (see section 4.4.3). The exception to this rule is the evaporation depth experiment, to which modifications must be made as suggested in section 5.2.3. The rates of evaporation from the coal containers and that from the coal stockpile also differed. This was attributed to the fact that the coal stockpile did not receive direct solar radiation, unlike the coal containers. It can thus be concluded that solar radiation has a large effect on the rate of evaporation.

5.2 Recommendations

To improve the results obtained by this investigation, there are certain experimental modifications which should be made. Additional factors have also been identified which should be investigated to add to the understanding of moisture retention and migration in coal stockpiles. It is recommended that further investigation of fine particles below 0.5 mm is necessary for all experiments.

5.2.1 Runoff versus infiltration

Several areas of improvement were identified for the experimental setup used to determine the proportion of runoff versus infiltration. First of all, the rainfall simulator should be improved as it was difficult to remain at constant rainfall rates as a result of the build-up of dirt within the containers. Secondly, the depth of the coal container should be decreased. This can be done by installing a grid 0.3 m from the top of the container. This will also ensure even removal of the infiltrated water through the bottom valve. Thirdly, it is recommended to add additional angles to the setup which will enable the investigation of an optimal stockpile angle where both infiltration and erosion will be minimised.

It is recommended that experiments are not performed at steady-state. This will assist with creating infiltration rate curves to predict the amount of water which will infiltrate a coal stockpile. This would require measuring the moisture content of the coal bed before, during and after a rainfall event. Experiments should be done with other coal types to enable whether factors such as clay mineral content will influence the infiltration capacity of a stockpile by creating a surface seal. The rainfall intensities should be decreased to amounts characteristic of the areas where coal stockpiling is typically done. The PSD of the fines which either drain out or is washed off the surface of the stockpile should be measured.

5.2.2 Drainage

Further studies with other coal types and PSDs should be done. The drainage column should be used to establish moisture thresholds for various coals and several initial moisture contents. This can lead to the formation of a database which could power a model which would be able to predict the period of time required by a stockpile to reach a certain total moisture content.

5.2.3 Evaporation

It is recommended that a climate-controlled room be built to enable the separate investigation of each of the weather conditions which influences the rate of evaporation. If this is not possible, it is recommended that a weather station capable of recording solar radiation is acquired.

The evaporation depth experiment did not represent the interior of the stockpile. It is recommended that mesh pipes be designed which would mimic the porous nature of a coal stockpile. Samples should be allowed to drain throughout the experiment.

5.2.4 Experimental stockpile

The possibility of relocating the platform should be considered. An ideal location would be one where the stockpile would be able to experience solar radiation and wind action. Further stockpiles should be built with other coal types and PSDs.

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APPENDIX A: CALCULATION OF MOISTURE CONTENT

Three types of moisture contents were investigated during the course of this project. These types of moistures are: surface, inherent and total. This appendix gives a summary of the method by which these moistures were calculated.

A.1 Surface moisture

To determine the surface moisture content of a coal sample, the sample must be air-dried in a climate controlled room at 22 °C and 40% relative humidity over a period of 24 hours. This is a modified method of SANS 10320:2004.

The surface moisture content of the coal samples was calculated by equation A.1.1 (SANS 589:2009):

$$M_S = \frac{m_2 - m_3}{m_2 - m_1} \times 100 \qquad [A.1.1]$$

M_S: Surface moisture content (weight %)

m_1: Weight of the empty container (g)

m_2: Weight of the sample and container before air-drying (g)

m_3: Weight of the sample and container after air-drying (g)

A. 2 Inherent moisture

To determine the inherent moisture content of a coal sample after air-drying as described in secion A.1, the sample is dried in a vacuum oven set to 105 °C to 110 °C at a pressure of 6.7 kPa (SANS 5924:2009).

The inherent moisture content of the coal samples was calculated by equation A.1.2 (SANS 589:2009):

$$M_I = \frac{m_4 - m_5}{m_4 - m_1} \times 100 \qquad [A.1.2]$$

M_I: Inherent moisture content (weight %)

m_1: Weight of the empty container (g)

m_4: Weight of the sample and container before vacuum-oven drying (g)

m_5: Weight of the sample and container vacuum-oven drying (g)

A. 3 Total moisture

The total moisture content of the coal samples was calculated by equation A.1.3 (SANS 589:2009):

$$M_T = M_S + \frac{M_I(100 - M_S)}{100} \qquad [A.1.3]$$

M_Y: Total moisture content (weight %)

M_S: Surface moisture content (weight %)

M_I: Inherent moisture content (weight %)

APPENDIX B: ADDITIONAL RUNOFF VERSUS INFILTRATION DATA

This appendix gives the additional results for the runoff versus infiltration experiments as discussed in section 4.1.

B.1 Experimental error

As shown in Table B.1.1, the experimental errors for the runoff versus infiltration experiment are within acceptable limits considering the highly variable nature of working with the large quantities of coal used in this investigation. In calculating the error margin, a 95% confidence interval was used.

Table B.1.1: Experimental error for the runoff versus infiltration experiment

				Runoff proportion (%)		
RI[a] (mm/h)	**Slope**	**Size range**	**ρ_B[a] (kg/m^3)**	**Average (%)**	**σ (%)**	**Error margin (%)**
220	20°	-53 mm +6.7 mm		0.13	0.000	0.000
220	30°	-53 mm +6.7 mm		0.32	0.066	0.038
220	38°	-53 mm +6.7 mm		0.37	0.007	0.004
290	20°	-6.7 mm +0 mm		14.14	1.462	0.844
290	30°	-6.7 mm +0 mm		31.53	0.966	0.558
290	38°	-6.7 mm +0 mm		42.06	0.452	0.261
174	20°	-53 mm +6.7 mm		0.15	0.011	0.006
174	30°	-53 mm +6.7 mm		0.15	0.010	0.006
174	38°	-53 mm +6.7 mm		0.31	0.001	0.001
290	20°	-53 mm +6.7 mm		0.33	0.188	0.109
290	30°	-53 mm +6.7 mm		0.46	0.008	0.005
290	38°	-53 mm +6.7 mm		0.66	0.249	0.144
174	20°	-6.7 mm +0 mm		0.79	0.279	0.161
174	30°	-6.7 mm +0 mm		16.59	0.943	0.544
174	38°	-6.7 mm +0 mm		32.13	0.495	0.286
220	20°	-6.7 mm +0 mm		11.17	0.997	0.576
220	30°	-6.7 mm +0 mm		29.21	0.091	0.053
220	38°	-6.7 mm +0 mm		40.05	0.271	0.156
174	20°	-53 mm +0 mm	997	1.09	0.002	0.002
174	30°	-53 mm +0 mm	997	4.29	0.652	0.904
174	38°	-53 mm +0 mm	997	17.75	0.493	0.684
220	20°	-53 mm +0 mm	1069	34.27	1.877	2.601

				Runoff proportion (%)		
RI[a] (mm/h)	Slope	Size range	ρ_B[a] (kg/m^3)	Average (%)	σ (%)	Error margin (%)
220	30°	-53 mm +0 mm	1069	45.87	0.220	0.305
220	38°	-53 mm +0 mm	1069	56.19	2.040	2.827
290	20°	-53 mm +0 mm	1157	75.44	0.814	1.128
290	30°	-53 mm +0 mm	1157	78.73	0.434	0.601
290	38°	-53 mm +0 mm	1157	78.84	0.616	0.853
174	20°	-53 mm +0 mm	1069	19.09	1.339	1.855
174	30°	-53 mm +0 mm	1069	35.92	0.621	0.861
174	38°	-53 mm +0 mm	1069	45.30	0.244	0.338
220	20°	-53 mm +0 mm	997	5.31	1.015	1.407
220	30°	-53 mm +0 mm	997	27.50	1.634	2.265
220	38°	-53 mm +0 mm	997	43.17	0.098	0.136
290	20°	-53 mm +0 mm	997	29.57	3.984	5.521
290	30°	-53 mm +0 mm	997	46.85	0.652	0.903
290	38°	-53 mm +0 mm	997	58.97	0.428	0.593
174	20°	-53 mm +0 mm	1157	65.32	1.397	1.937
174	30°	-53 mm +0 mm	1157	73.60	0.881	1.222
174	38°	-53 mm +0 mm	1157	0.674	0.933	0.933
220	20°	-53 mm +0 mm	1157	67.67	0.109	0.151
220	30°	-53 mm +0 mm	1157	74.18	0.110	0.153
220	38°	-53 mm +0 mm	1157	78.60	0.207	0.287
290	20°	-53 mm +0 mm	1069	47.96	1.663	2.305
290	30°	-53 mm +0 mm	1069	59.85	1.295	1.794
290	38°	-53 mm +0 mm	1069	60.95	0.708	0.981

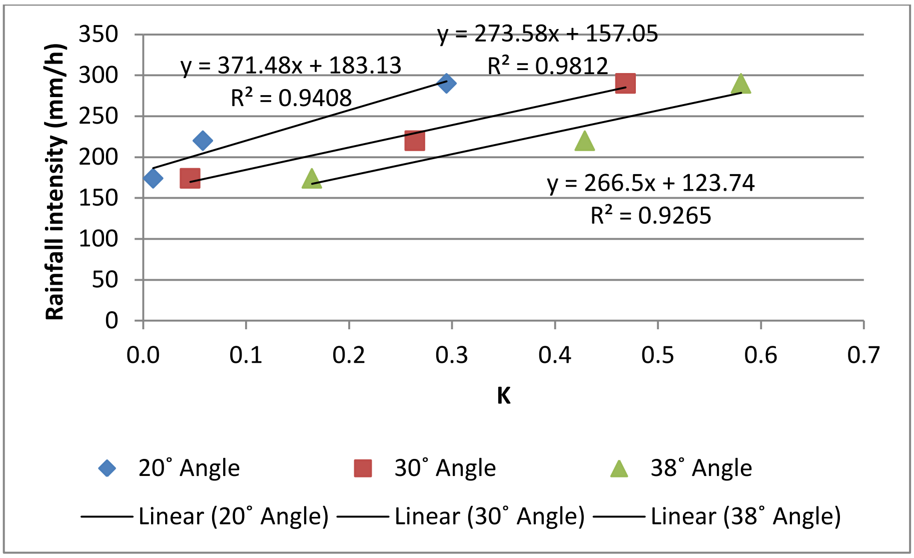

Figure B.2.1: Relationship between the rainfall intensity and K (-53 mm +0 mm, ρ_B = 997 kg/m^3)

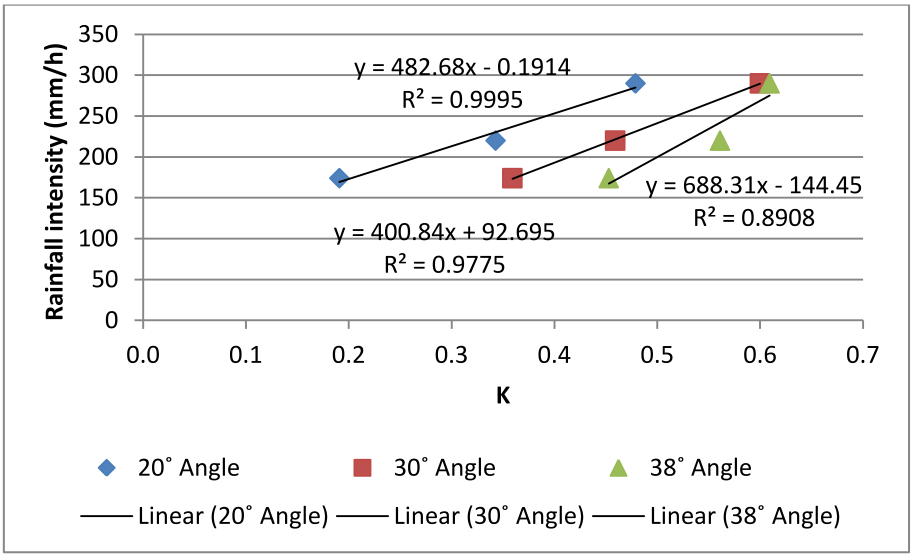

Figure B.2.2: Relationship between the rainfall intensity and K (-53 mm +0 mm, ρ_B = 1069 kg/m^3)

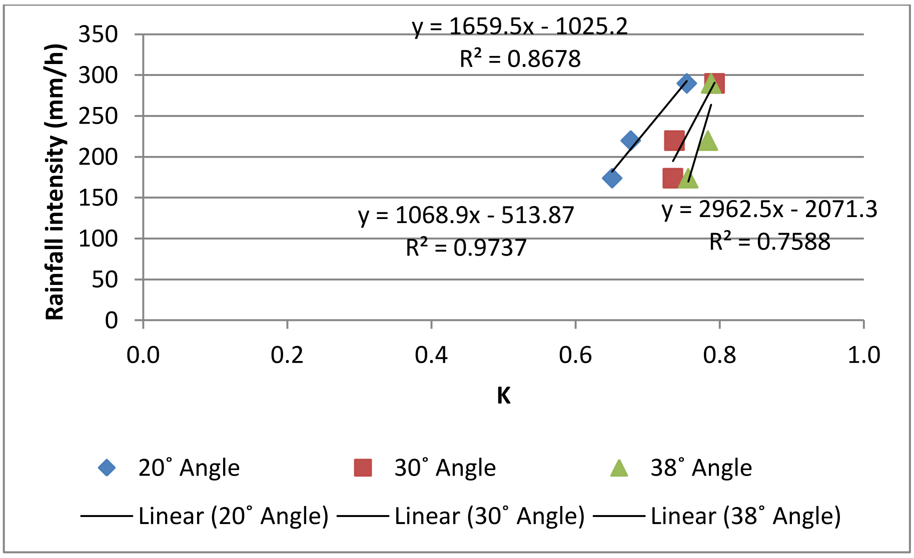

Figure B.2.3: Relationship between the rainfall intensity and K (-53 mm +0 mm, ρ_B = 1157 kg/m^3)

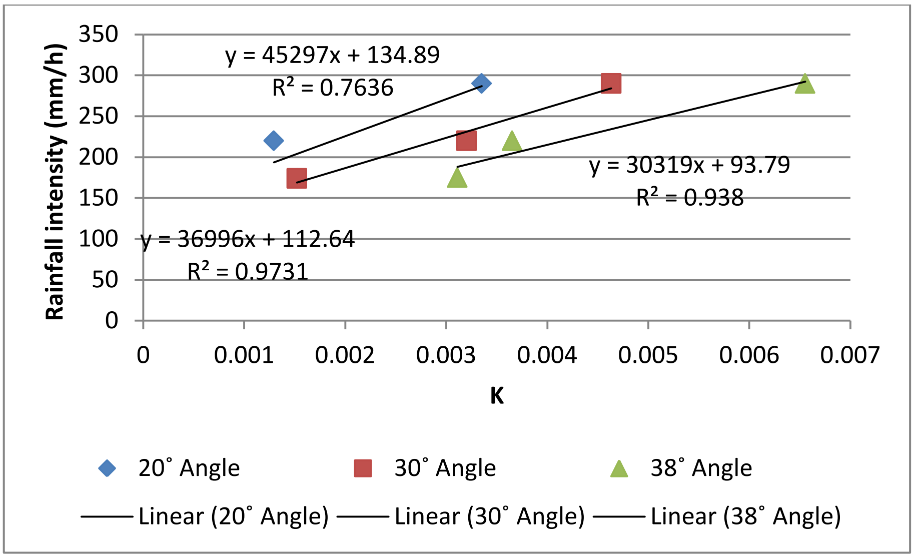

Figure B.2.4: Relationship between the rainfall intensity and K (-53 mm +6.7 mm)

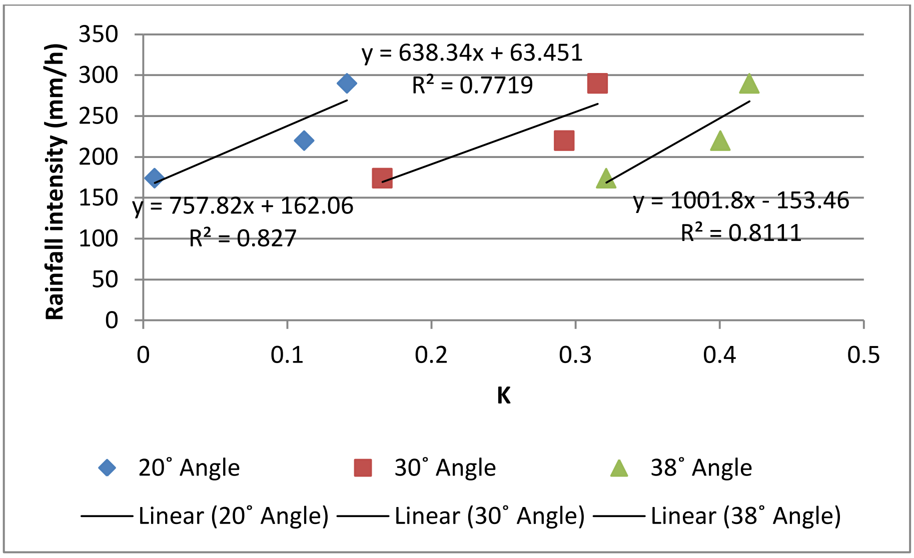

Figure B.2.5: Relationship between the rainfall intensity and K (-6.7 mm +0 mm)

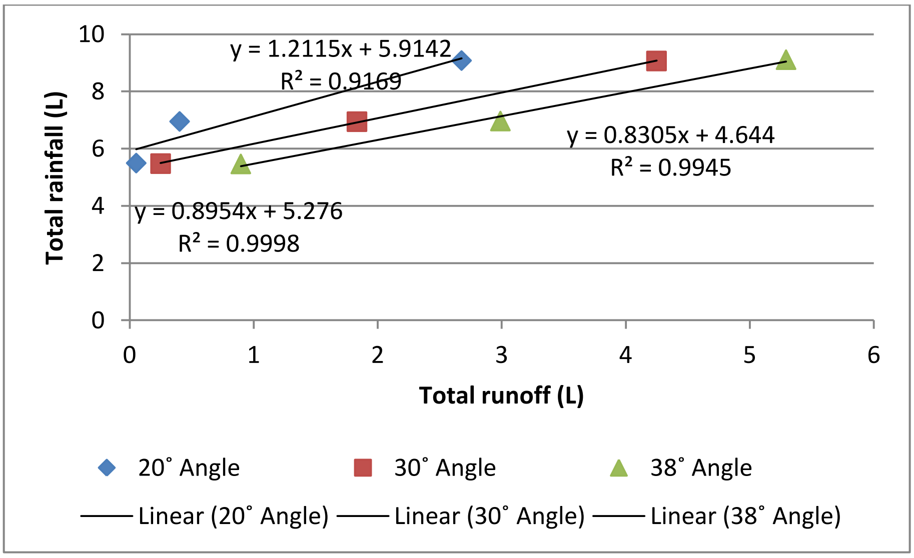

Figure B.2.6: Relationship between the total rainfall and total runoff (-53 mm +0 mm, ρ_B = 997 kg/m^3)

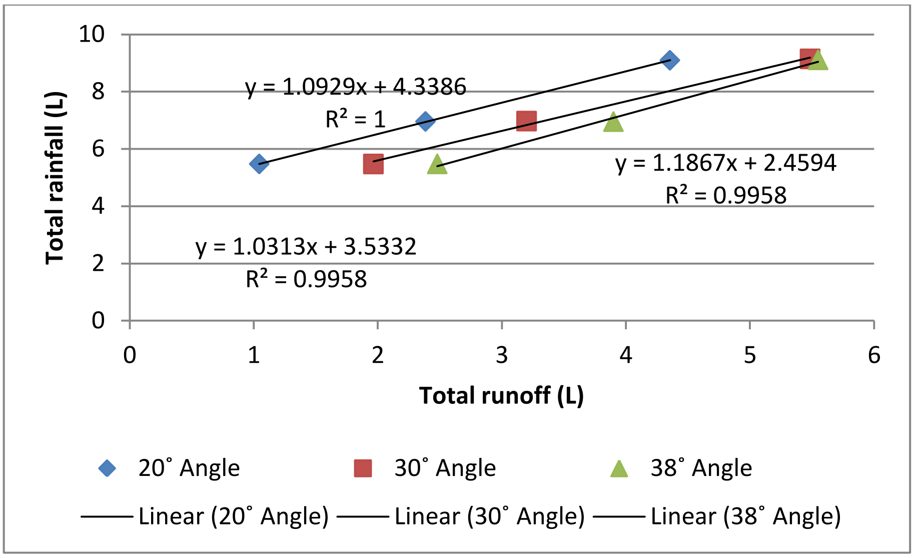

Figure B.2.7: Relationship between the total rainfall and total runoff (-53 mm +0 mm, ρ_B = 1069 kg/m^3)

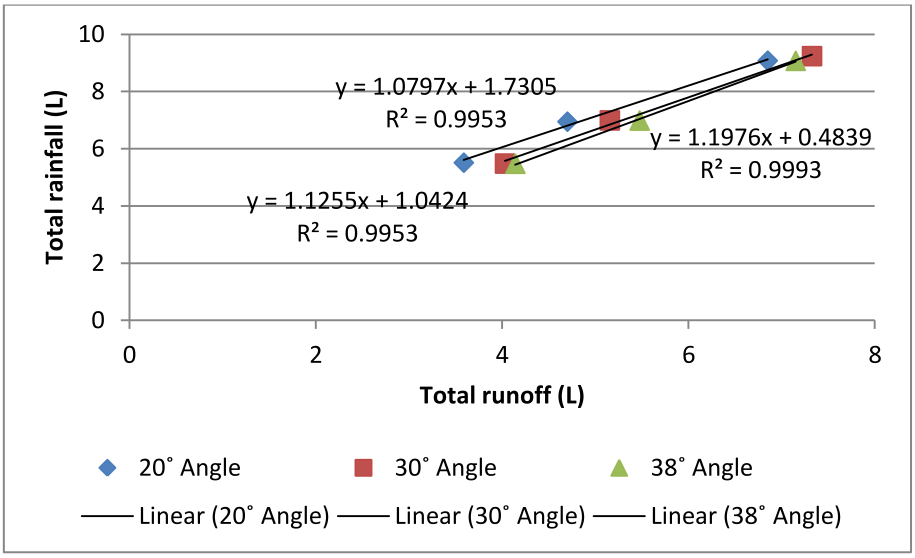

Figure B.2.8: Relationship between the total rainfall and total runoff (-53 mm +0 mm, ρ_B = 1157 kg/m^3)

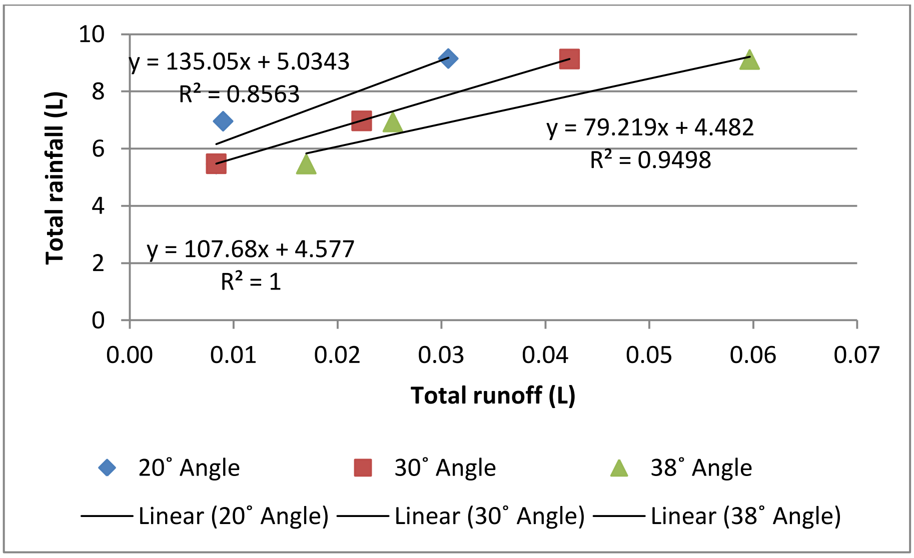

Figure B.2.9: Relationship between the total rainfall and total runoff (-53 mm +6.7 mm)

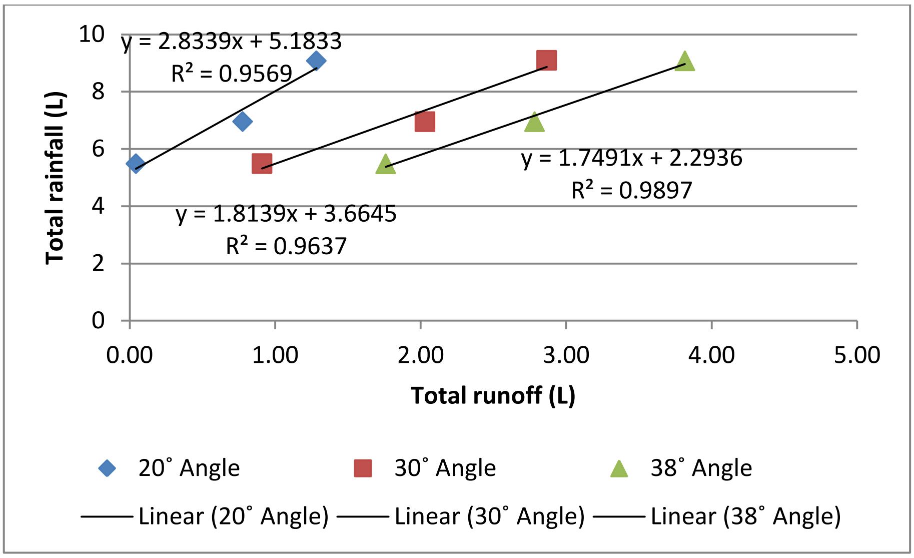

Figure B.2.10: Relationship between the total rainfall and total runoff (-6.7 mm +0 mm)

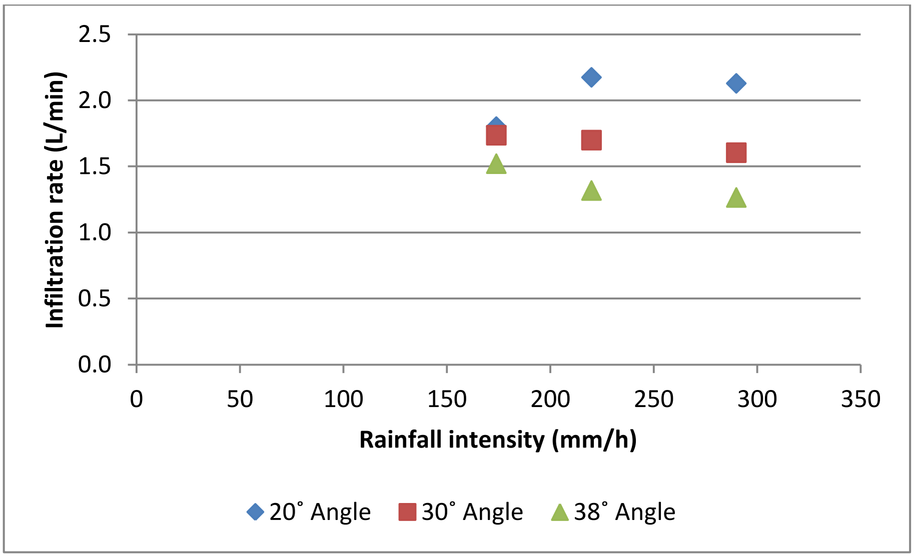

Figure B.2.11: Relationship between the total rainfall and total runoff (-53 mm +0 mm, 997 kg/m^3)

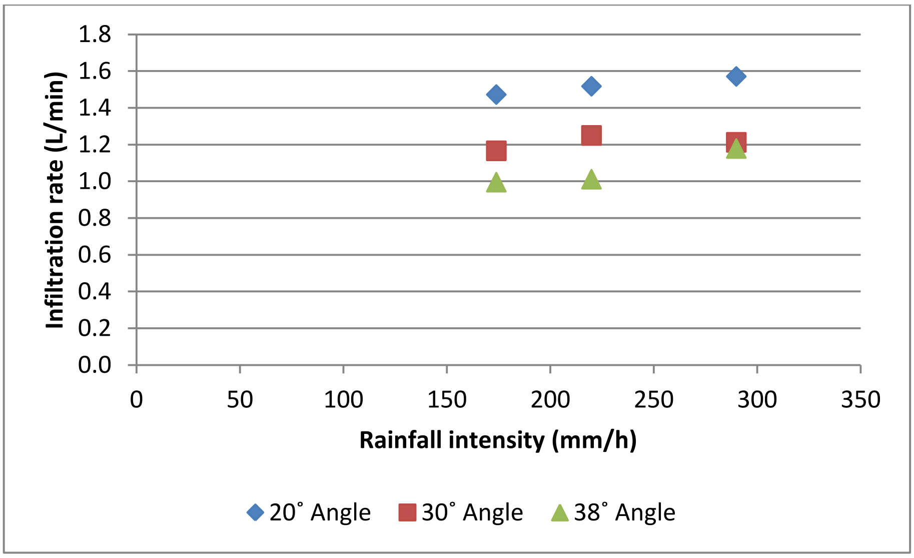

Figure B.2.12: Relationship between the total rainfall and total runoff (-53 mm +0 mm, 1069 kg/m^3)

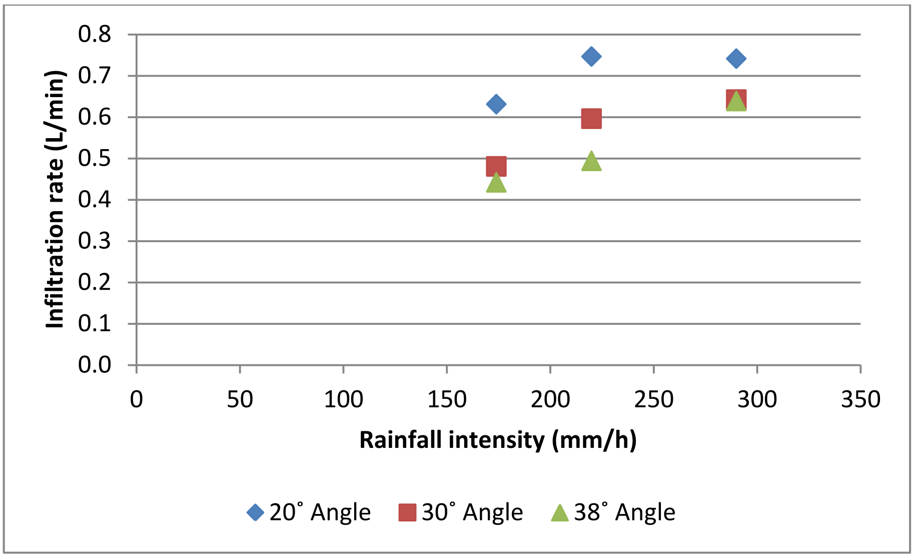

Figure B.2.13: Relationship between the total rainfall and total runoff (-53 mm +0 mm, 1157 kg/m^3)

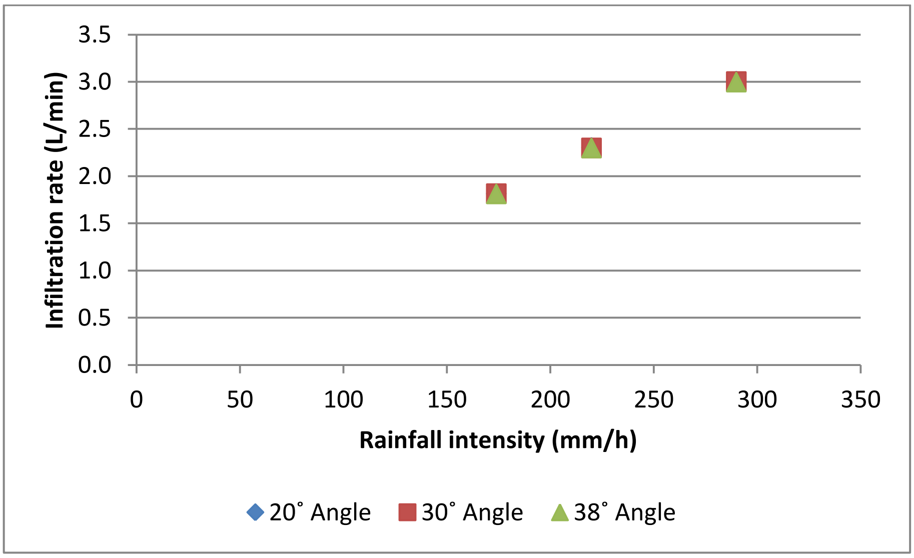

Figure B.2.14: Relationship between the total rainfall and total runoff (-53 mm +6.7 mm)

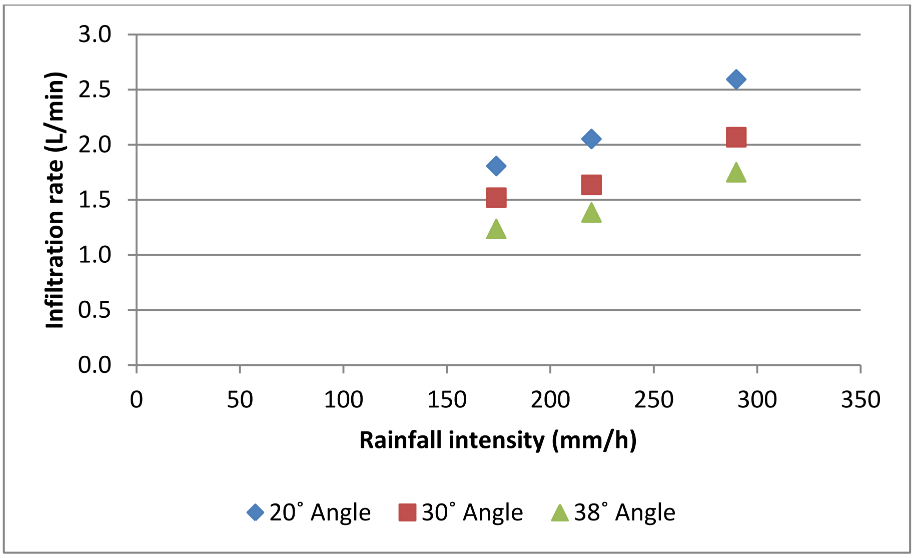

Figure B.2.15: Relationship between the total rainfall and total runoff (-6.7mm +0 mm)

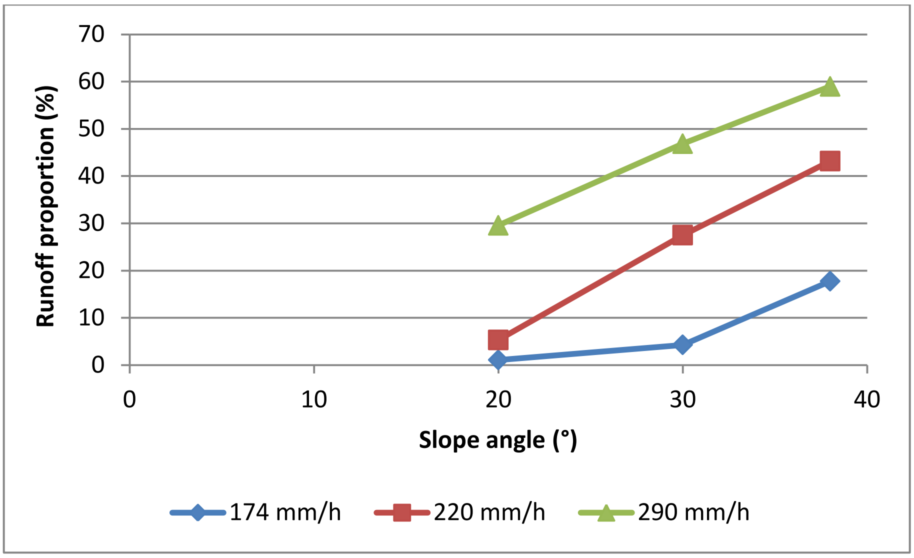

Figure B.2.16: Runoff proportion versus slope angle (-53 mm +0 mm, 997 kg/m^3)

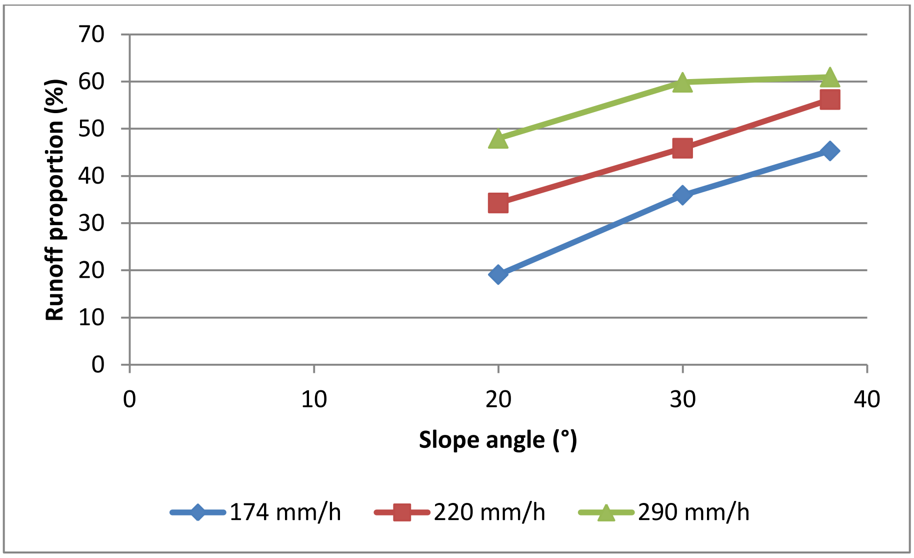

Figure B.2.17: Runoff proportion versus slope angle (-53 mm +0 mm, 1069 kg/m^3)

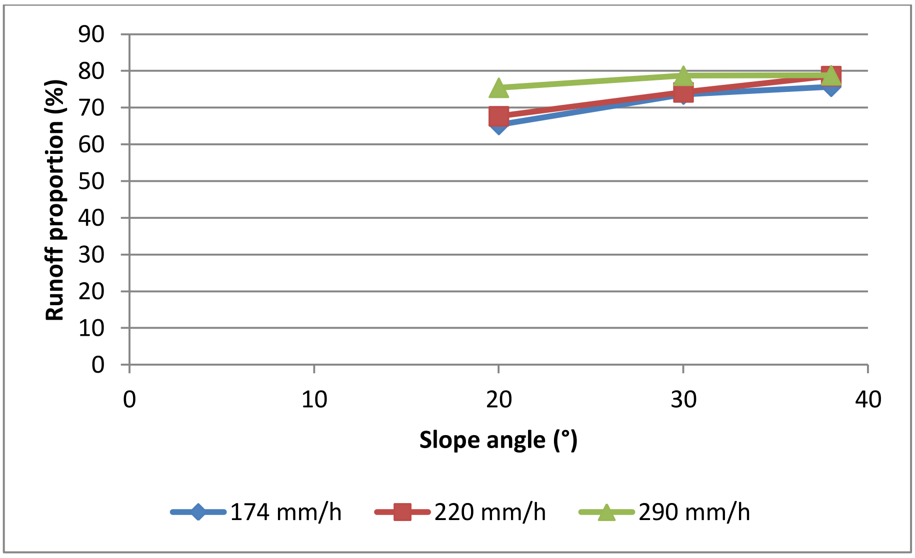

Figure B.2.18: Runoff proportion versus slope angle (-53 mm +0 mm, 1157 kg/m^3)

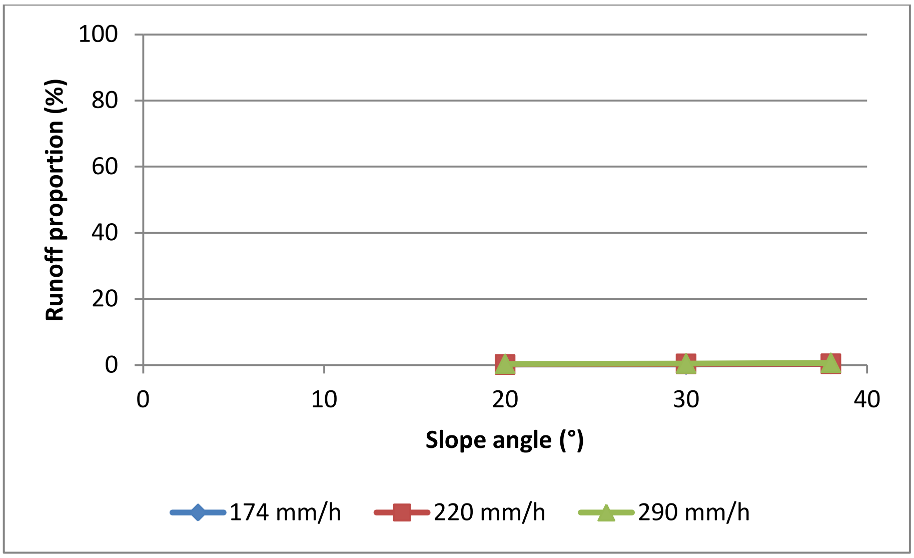

Figure B.2.19: Runoff proportion versus slope angle (-53 mm +6.7 mm)

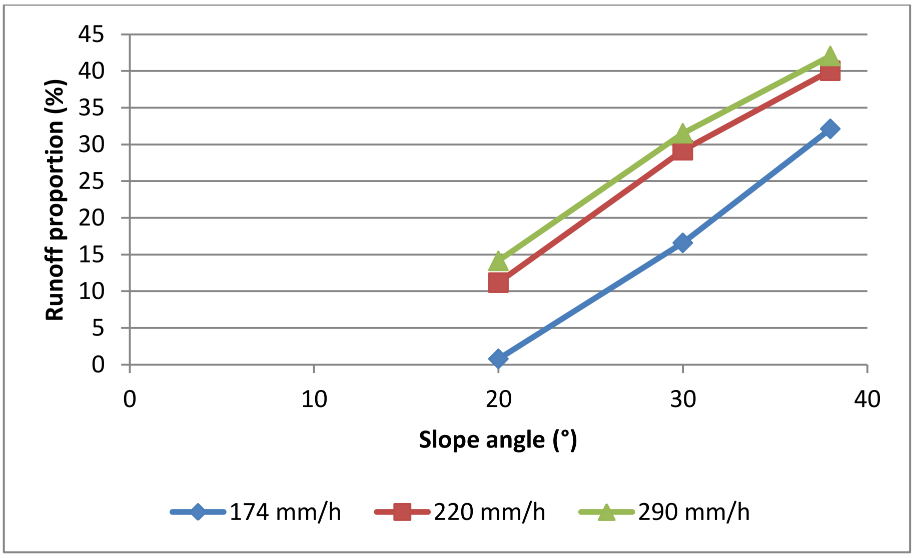

Figure B.2.20: Runoff proportion versus slope angle (-6.7 mm +0 mm)

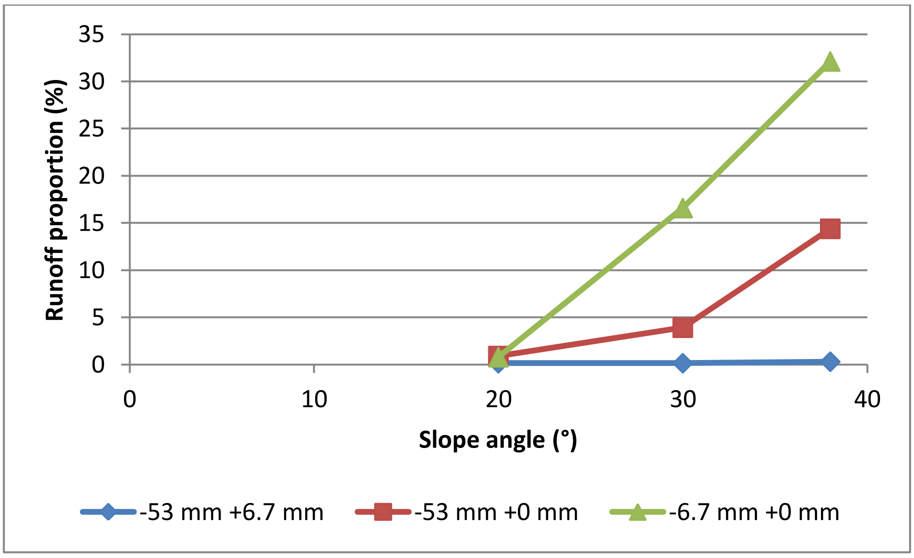

Figure B.2.21: Proportion of runoff versus slope angle as a function of PSR at 174 mm/h

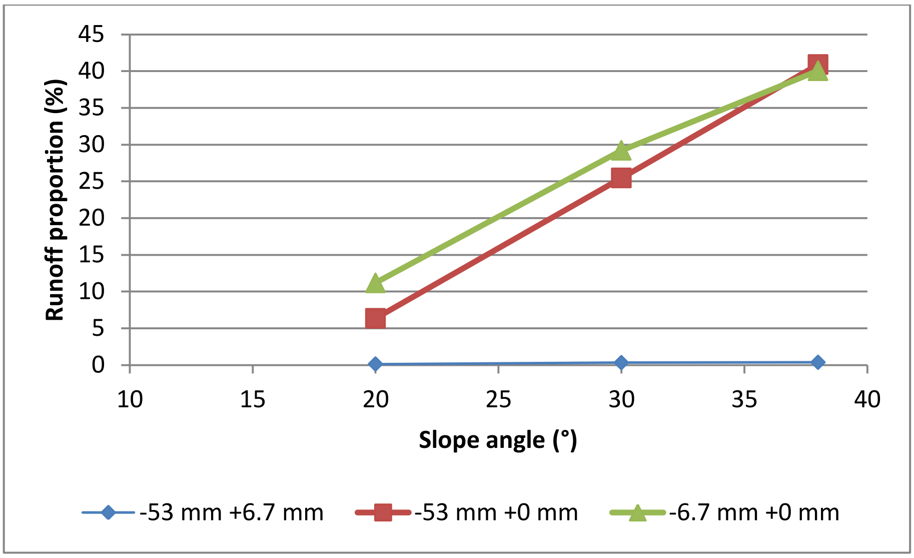

Figure B.2.22: Proportion of runoff versus slope angle as a function of PSR at 220 mm/h

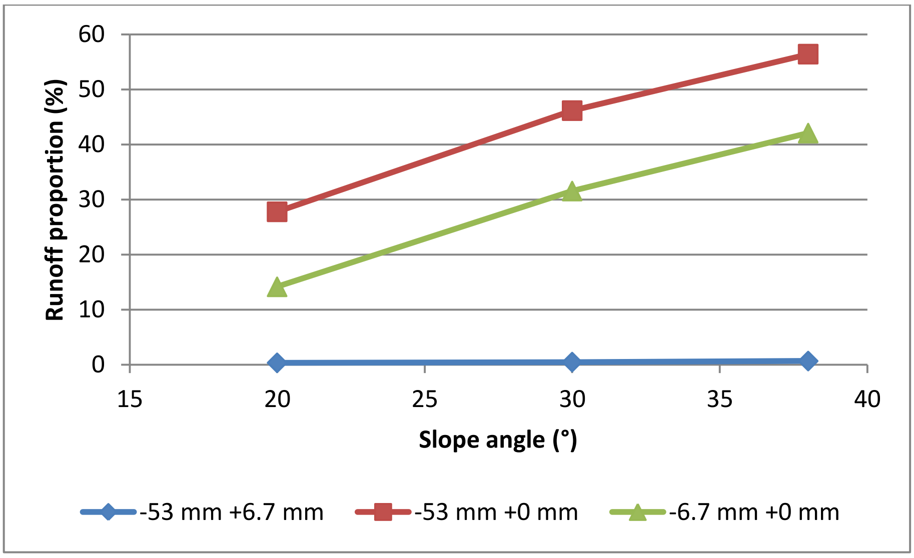

Figure B.2.23: Proportion of runoff versus slope angle as a function of PSR at 290 mm/h

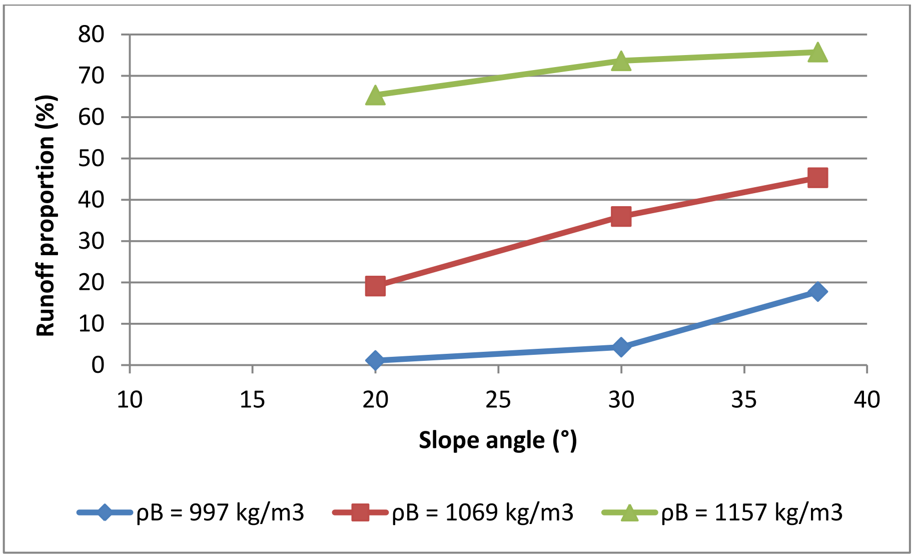

Figure B.2.24: Proportion of runoff versus slope angle as a function of compaction at 174 mm/h

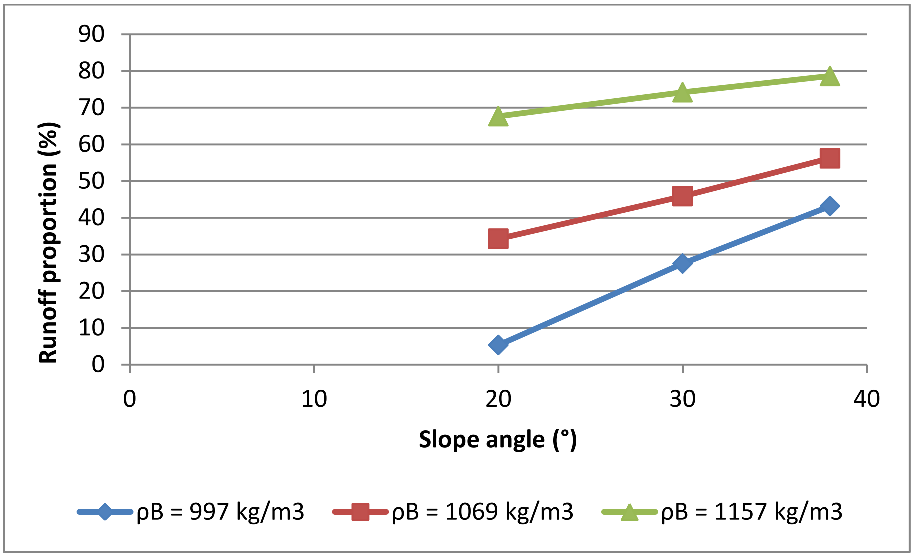

Figure B.2.25: Proportion of runoff versus slope angle as a function of compaction at 220 mm/h

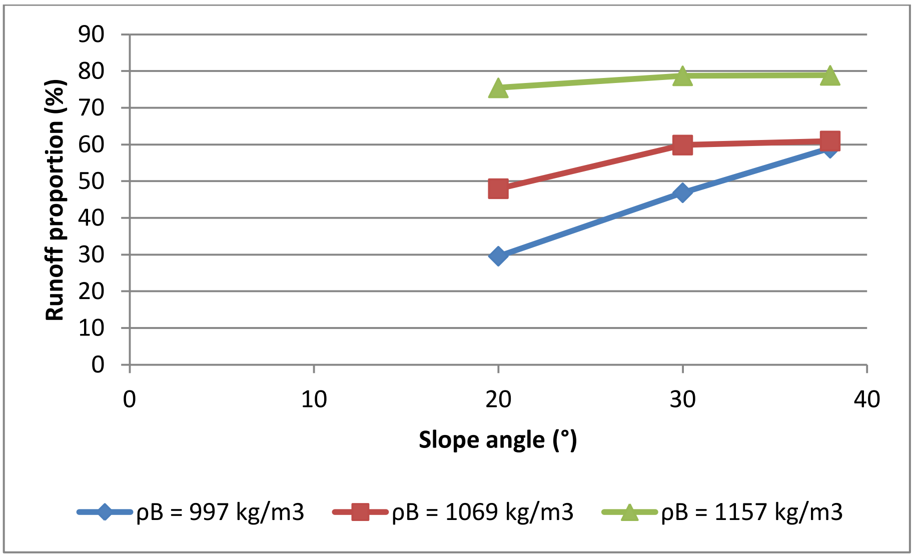

Figure B.2.26: Proportion of runoff versus slope angle as a function of compaction at 290 mm/h

APPENDIX C: ADDITIONAL DATA FOR THE DRAINAGE EXPERIMENTS

This appendix gives additional results for the drainage experiments as discussed in section 4.2.

C.1 Mass balances

Table C.1.1: Mass balance for the -53 mm +0 mm coal B sample repeat 2 in the 2 m high drainage column

Time period		In (kg)	Initial mass (kg)	Final mass (kg)	Accumulated (kg)	Out (kg)	Actual out (kg)	Difference (kg)
Day 0	**A**	20.00	3.06	3.23	0.17	19.83		
to	**B**	19.83	3.88	5.21	1.33	18.50		
day 2	**C**	18.50	4.16	5.76	1.60	16.90		
(2 days)	**D**	16.90	4.42	5.18	0.75	16.15	15.57	0.58
Day 2	**A**	0.00	3.23	2.74	-0.49	0.49		
to	**B**	0.49	5.21	4.17	-1.04	1.53		
day 4	**C**	1.53	5.76	4.63	-1.13	2.66		
(2 days)	**D**	2.66	5.18	4.72	-0.45	3.11	0.00	3.11
Day 4	**A**	0.00	2.74	2.82	0.08	-0.08		
to	**B**	-0.08	4.17	3.77	-0.40	0.33		
Day 7	**C**	0.33	4.63	3.77	-0.87	1.19		
(3 days)	**D**	1.19	4.72	4.10	-0.62	1.82	0.00	1.82

Table C.1.2: Mass balance for the -6.7 mm +0 mm coal B sample repeat 1 in the 2 m high drainage column

Time period		In (kg)	Initial mass (kg)	Final mass (kg)	Accumulated (kg)	Out (kg)	Actual out (kg)	Difference (kg)
Day 0	**A**	20.00	2.74	3.53	0.79	19.21		
to	**B**	19.21	2.69	4.17	1.48	17.73		
day 2	**C**	17.73	3.33	3.65	0.32	17.41		
(2 days)	**D**	17.41	2.61	4.14	1.53	15.88	11.86	4.02
Day 2	**A**	0.00	3.53	2.87	-0.66	0.66		
to	**B**	0.66	4.17	3.28	-0.89	1.55		
day 4	**C**	1.55	3.65	3.22	-0.43	1.97		
(2 days)	**D**	1.97	4.14	3.57	-0.57	2.54	0.00	2.54

Day 4	**A**	0.00	2.87	2.09	-0.78	0.78		
to	**B**	0.78	3.28	2.66	-0.62	1.40		
Day 7	**C**	1.40	3.22	2.61	-0.61	2.01		
(3 days)	**D**	2.01	3.57	2.77	-0.80	2.82	0.00	2.82

Table C.1.3: Mass balance for the -6.7 mm +0 mm coal B sample repeat 2 in the 2 m high drainage column

Time period		**In (kg)**	**Initial mass (kg)**	**Final mass (kg)**	**Accumulated (kg)**	**Out (kg)**	**Actual out (kg)**	**Difference (kg)**
Day 0	**A**	20.00	2.64	2.64	0.00	20.00		
to	**B**	20.00	2.71	4.01	1.30	18.70		
day 2	**C**	18.70	2.35	3.25	0.91	17.79		
(2 days)	**D**	17.79	2.87	3.65	0.78	17.01		
Day 2	**A**	0.00	2.64	2.10	-0.55	0.55		
to	**B**	0.55	4.01	3.13	-0.88	1.43		
day 4	**C**	1.43	3.25	2.88	-0.37	1.80		
(2 days)	**D**	1.80	3.65	3.06	-0.59	2.39	0.00	2.39
Day 4	**A**	0.00	2.10	2.63	0.53	-0.53		
to	**B**	-0.53	3.13	3.25	0.12	-0.66		
Day 7	**C**	-0.66	2.88	3.02	0.14	-0.80		
(3 days)	**D**	-0.80	3.06	3.34	0.28	-1.08	0.00	1.08

Table C.1.4: Mass balance for the -6.7 mm +0 mm coal B sample repeat 3 in the 2 m high drainage column

Time period	**In (kg)**	**Initial mass (kg)**	**Final mass (kg)**	**Accumulated (kg)**	**Out (kg)**	**Actual out (kg)**	**Difference (kg)**
Day 0	20.00	1.58	3.68	2.10	17.90		
to	17.90	2.49	3.57	1.08	16.82		
day 2	16.82	2.48	3.47	0.99	15.83		
(2 days)	15.83	2.12	4.10	1.98	13.85		
Day 2	0.00	3.68	2.14	-1.54	1.54		
to	1.54	3.57	3.06	-0.51	2.05		
day 4	2.05	3.47	2.62	-0.85	2.90		
(2 days)	2.90	4.10	2.54	-1.55	4.45	0.00	4.45

Day 4		0.00	2.14	2.28	0.13	-0.13		
to		-0.13	3.06	2.70	-0.36	0.23		
Day 7		0.23	2.62	2.51	-0.12	0.35		
(3 days)		0.35	2.54	3.35	0.80	-0.46	0.00	0.46

Table C.1.5: Mass balance for the -53 mm +6.7 mm coal B sample repeat 1 in the 2 m high drainage column

Time period		In (kg)	Initial mass (kg)	Final mass (kg)	Accumulated (kg)	Out (kg)	Actual out (kg)	Difference (kg)
Day 0	**A**	20.00	2.40	2.81	0.41	19.59		
to	**B**	19.59	2.67	1.92	-0.75	20.34		
day 2	**C**	20.34	2.81	2.23	-0.58	20.92		
(2 days)	**D**	20.92	2.44	2.72	0.28	20.64	18.5239	2.12
Day 2	**A**	0.00	2.81	2.24	-0.57	0.57		
to	**B**	0.57	1.92	2.32	0.40	0.17		
day 4	**C**	0.17	2.23	2.30	0.08	0.09		
(2 days)	**D**	0.09	2.72	2.71	-0.02	0.02	0.00	0.02
Day 4	**A**	0.00	2.24	1.96	-0.28	0.28		
to	**B**	0.28	2.32	2.24	-0.08	0.08		
Day 7	**C**	0.08	2.30	2.27	-0.03	0.03		
(3 days)	**D**	0.03	2.71	2.48	-0.23	0.23	0.00	0.23

Table C.1.6: Mass balance for the -53 mm +6.7 mm coal B sample repeat 2 in the 2 m high drainage column

Time period		In (kg)	Initial mass (kg)	Final mass (kg)	Accumulated (kg)	Out (kg)	Actual out (kg)	Difference (kg)
Day 0	**A**	20.00	1.96	1.89	-0.06	20.06		
to	**B**	20.06	2.24	2.11	-0.13	20.19		
day 2	**C**	20.19	2.27	2.41	0.14	20.05		
(2 days)	**D**	20.05	2.48	2.36	-0.12	20.17	17.71	2.46
Day 2	**A**	0.00	1.89	2.08	0.19	-0.19		
to	**B**	-0.19	2.11	2.29	0.17	-0.36		
day 4	**C**	-0.36	2.41	2.26	-0.16	-0.21		
(2 days)	**D**	-0.21	2.36	2.38	0.02	-0.22	0.00	0.22

Day 4	**A**	0.00	2.08	2.04	-0.04	0.04		
to	**B**	0.04	2.29	2.06	-0.22	0.26		
Day 7	**C**	0.26	2.26	2.31	0.05	0.21		
(3 days)	**D**	0.21	2.38	2.10	-0.28	0.50	0.00	0.50

Table C.1.7: Mass balance for the -53 mm +6.7 mm coal B sample repeat 3 in the 2 m high drainage column

Time period		In (kg)	Initial mass (kg)	Final mass (kg)	Accumulated (kg)	Out (kg)	Actual out (kg)	Difference (kg)
Day 0	**A**	20.00	2.04	1.93	-0.11	20.11		
to	**B**	20.11	2.06	2.19	0.12	19.98		
day 2	**C**	19.98	2.31	2.31	0.00	19.98		
(2 days)	**D**	19.98	2.10	2.34	0.24	19.74	17.54	2.20
Day 2	**A**	0.00	1.93	2.01	0.07	-0.07		
to	**B**	-0.07	2.19	2.13	-0.06	-0.02		
day 4	**C**	-0.02	2.31	2.30	-0.01	-0.01		
(2 days)	**D**	-0.01	2.34	2.19	-0.15	0.14	0.00	0.14
Day 4	**A**	0.00	2.01	1.83	-0.17	0.17		
to	**B**	0.17	2.13	2.11	-0.02	0.20		
Day 7	**C**	0.20	2.30	2.25	-0.06	0.25		
(3 days)	**D**	0.25	2.19	2.15	-0.04	0.29	0.00	0.29

C.1 Moisture profiles

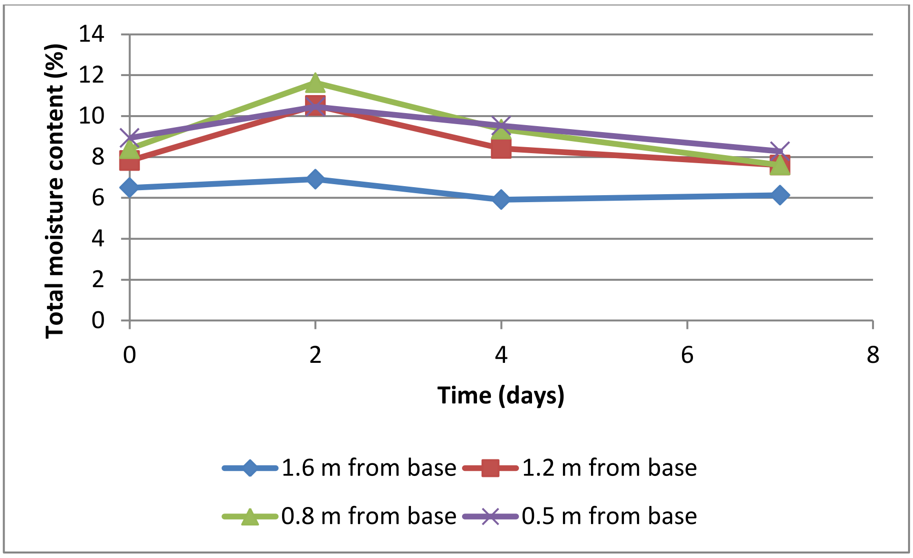

Figure C.2.1: Average moisture profile of coal B -53 mm +0 mm

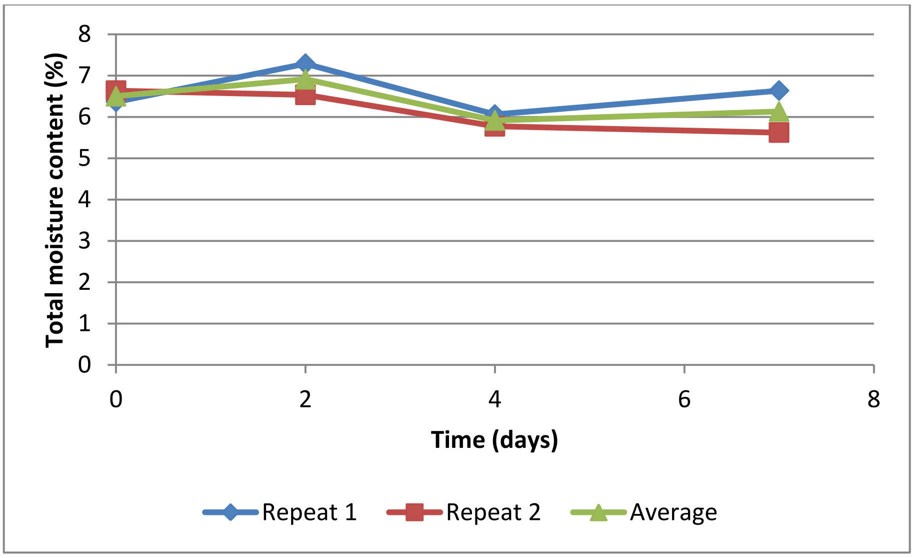

Figure C.2.2: Moisture profile of coal B -53 mm +0 mm at 1.6 m above base

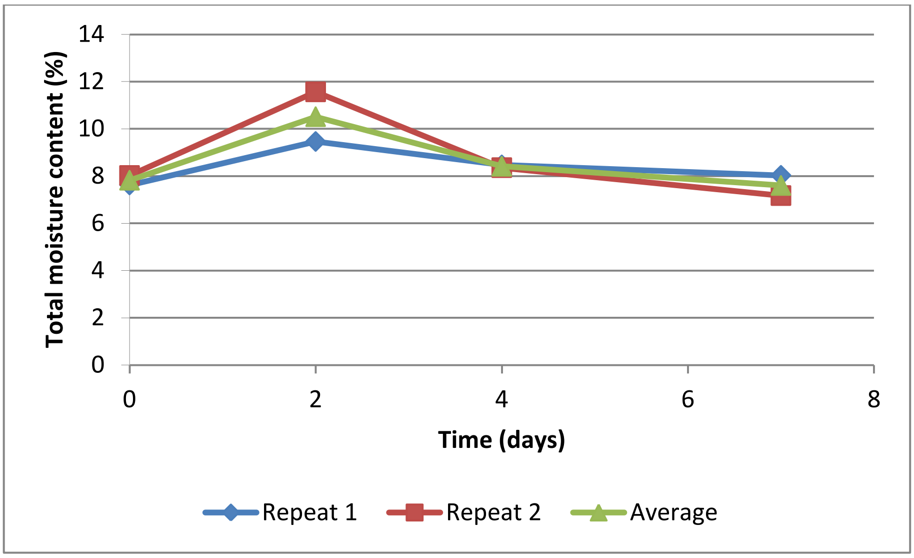

Figure C.2.3: Moisture profile of coal B -53 mm +0 mm at 1.2 m above base

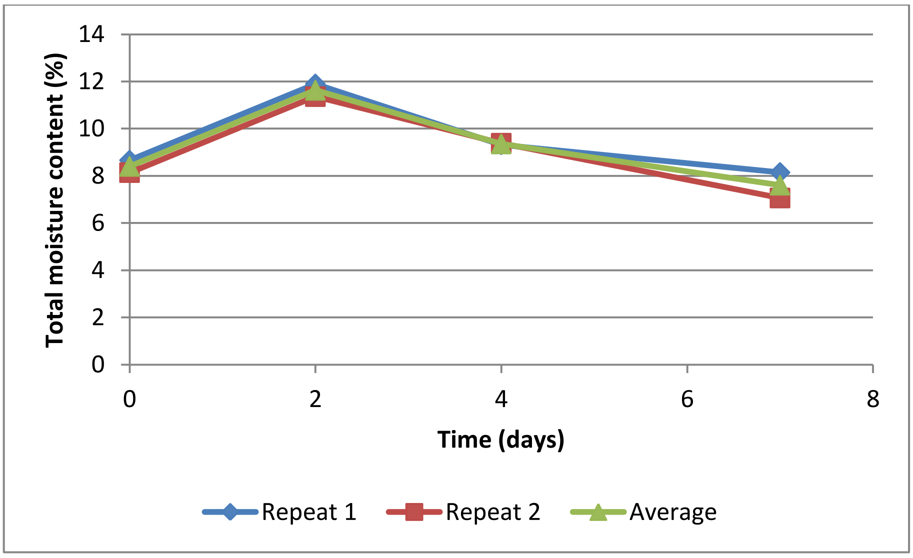

Figure C.2.4: Moisture profile of coal B -53 mm +0 mm at 0.8 m above base

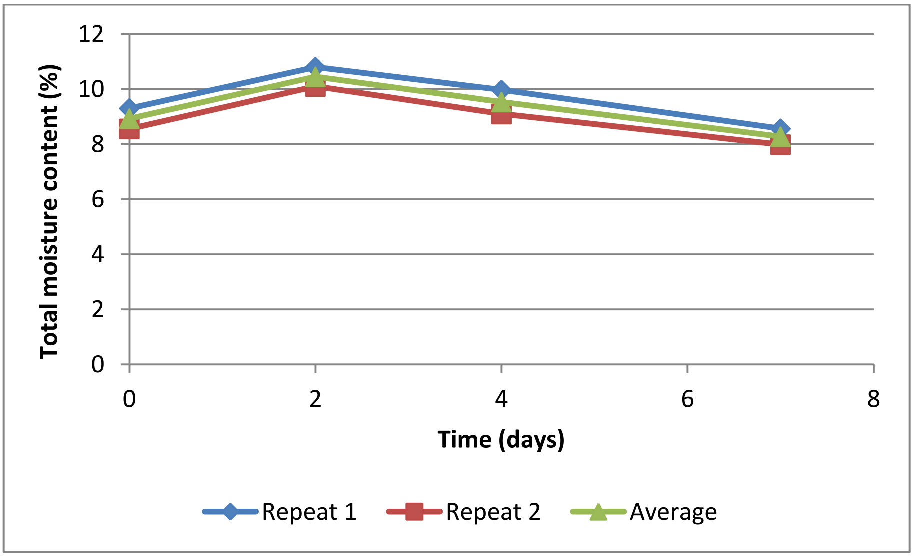

Figure C.2.5: Moisture profile of coal B -53 mm +0 mm at 0.5 m above base

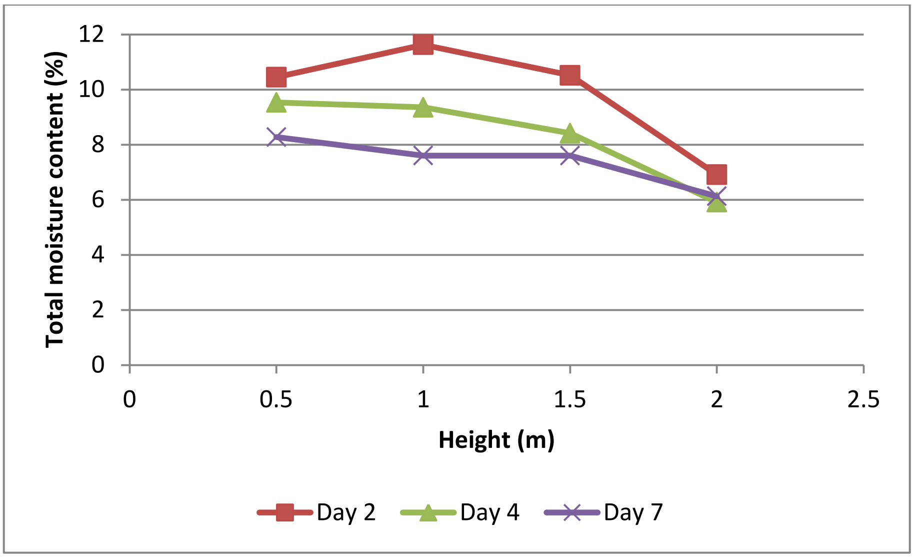

Figure C.2.6: Moisture profile of coal B -53 mm +0 mm over time

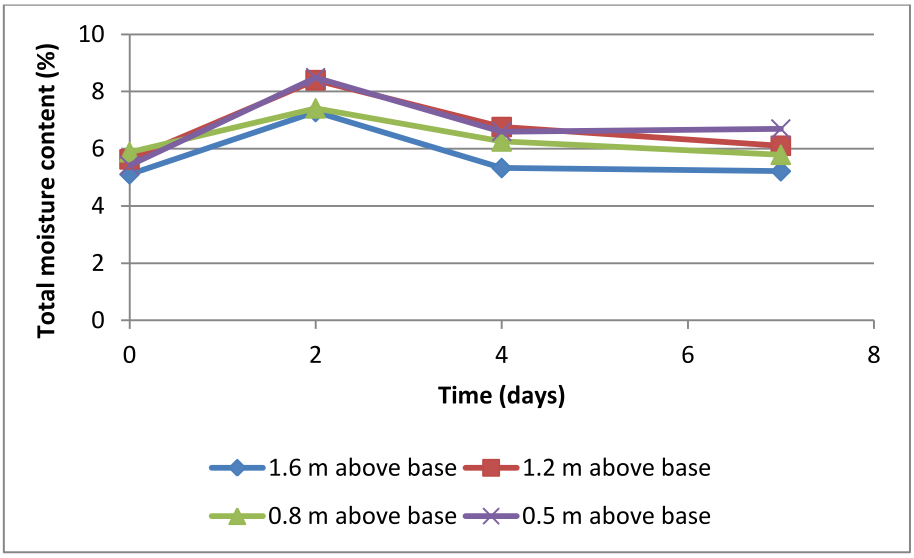

Figure C.2.7: Average moisture profile of coal B -6.7 mm +0 mm

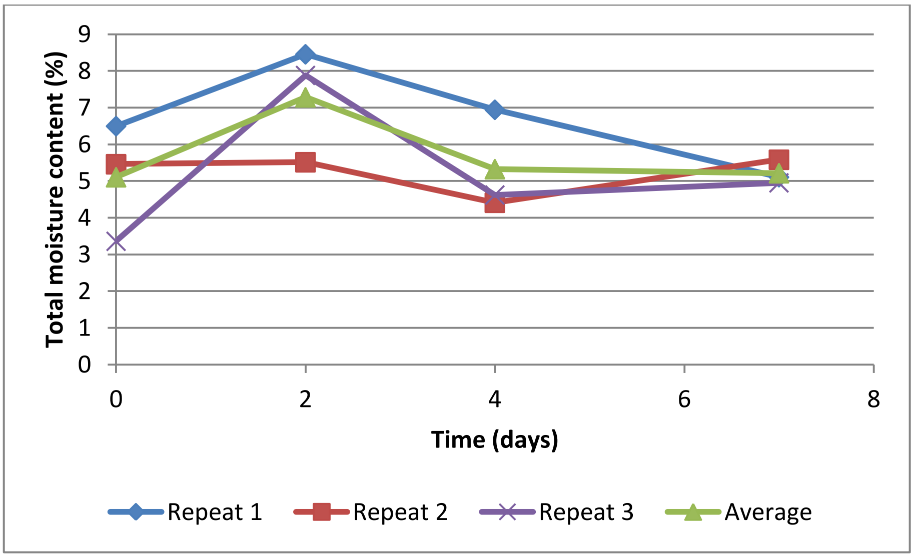

Figure C.2.8: Moisture profile of coal B -6.7 mm +0 mm 1.6 m above base

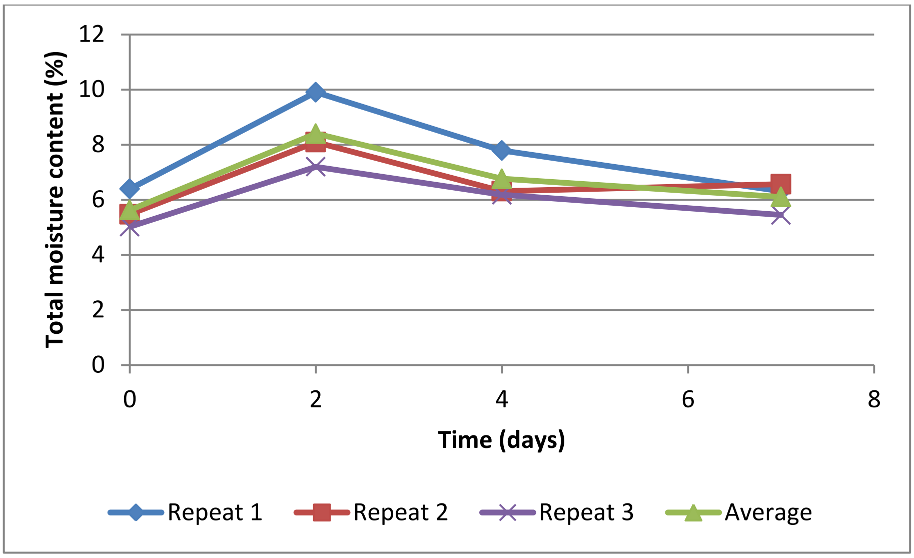

Figure C.2.9: Moisture profile of coal B -6.7 mm +0 mm 1.4 m above base

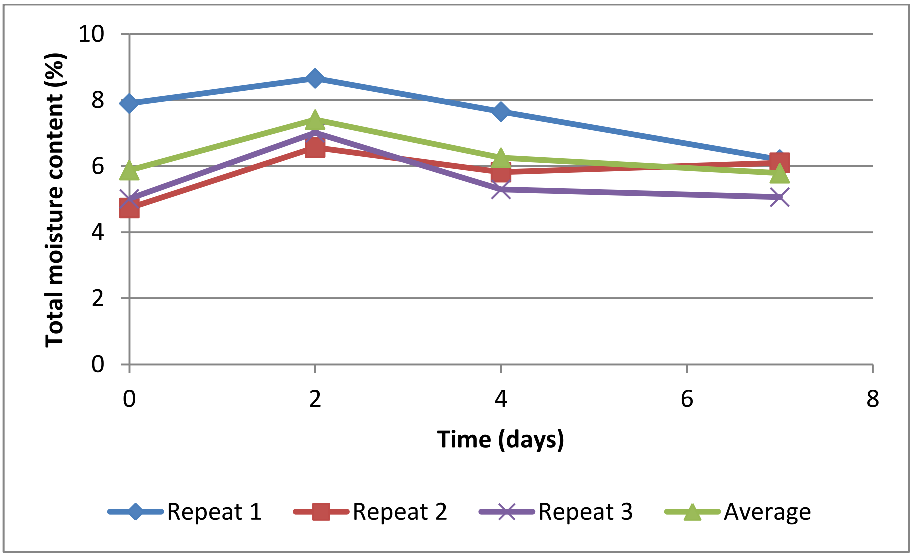

Figure C.2.10: Moisture profile of coal B -6.7 mm +0 mm 0.8 m above base

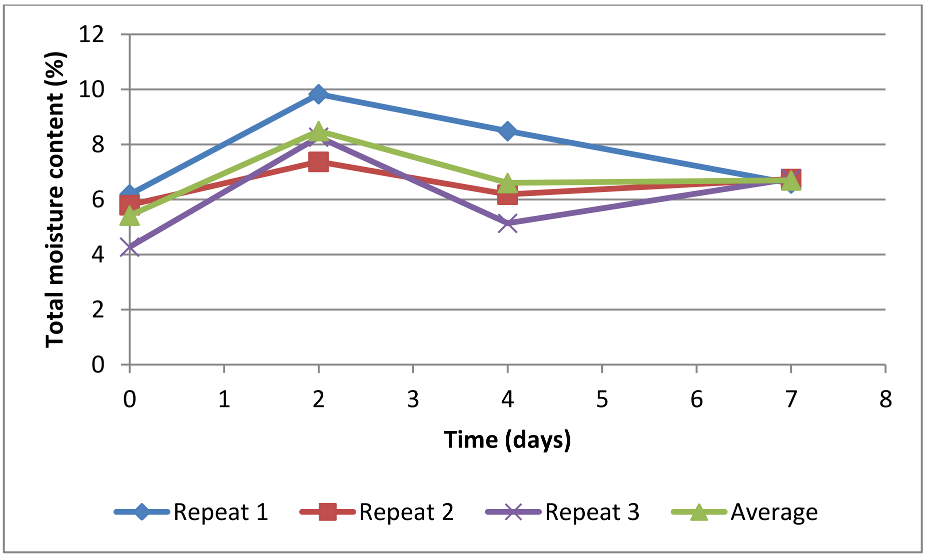

Figure C.2.11: Moisture profile of coal B -6.7 mm +0 mm 0.5 m above base

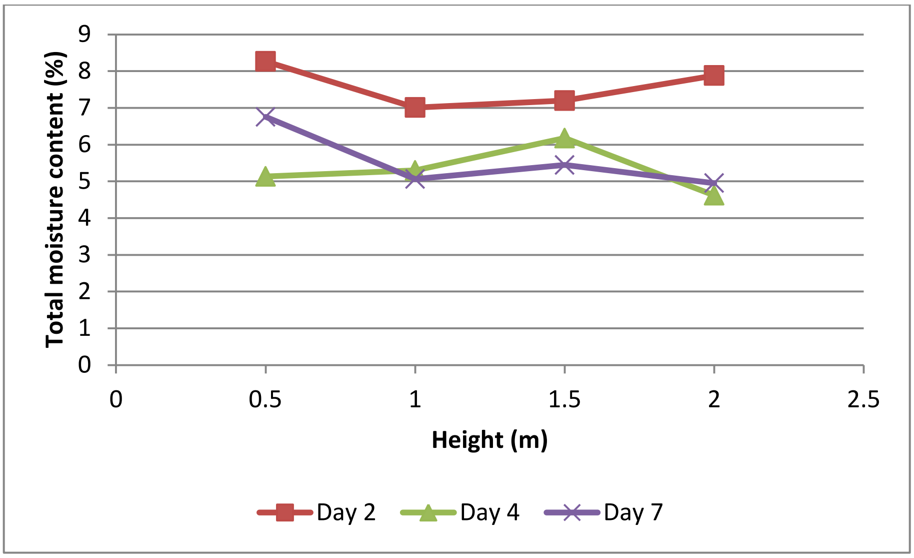

Figure C.2.12: Moisture profile of coal B -6.7 mm +0 mm over time

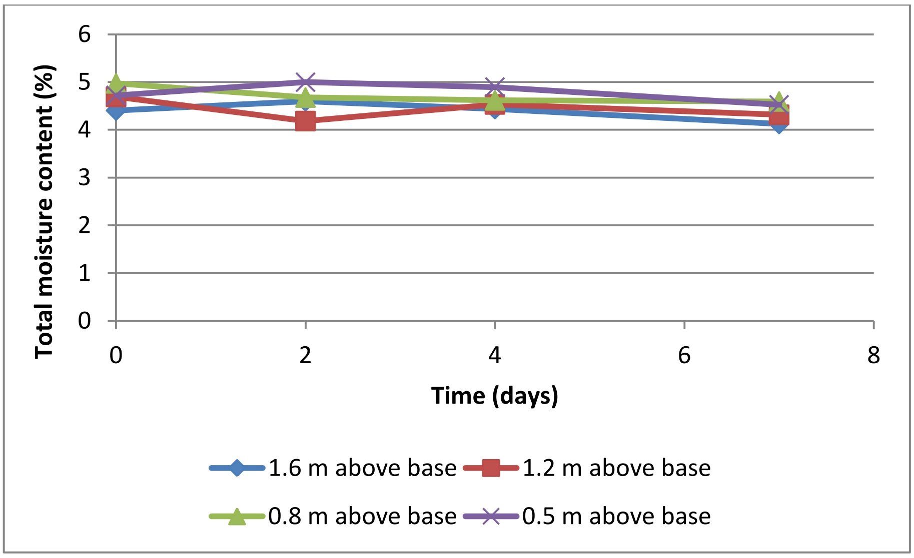

Figure C.2.13: Average moisture profile of coal B -53 mm +6.7 mm

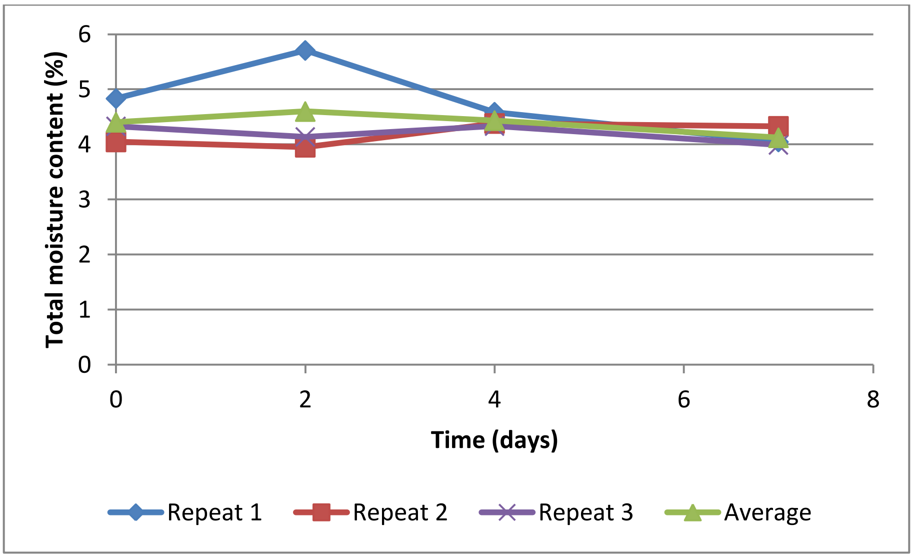

Figure C.2.14: Moisture profile of coal B -53 mm +6.7 mm 1.6 m from base

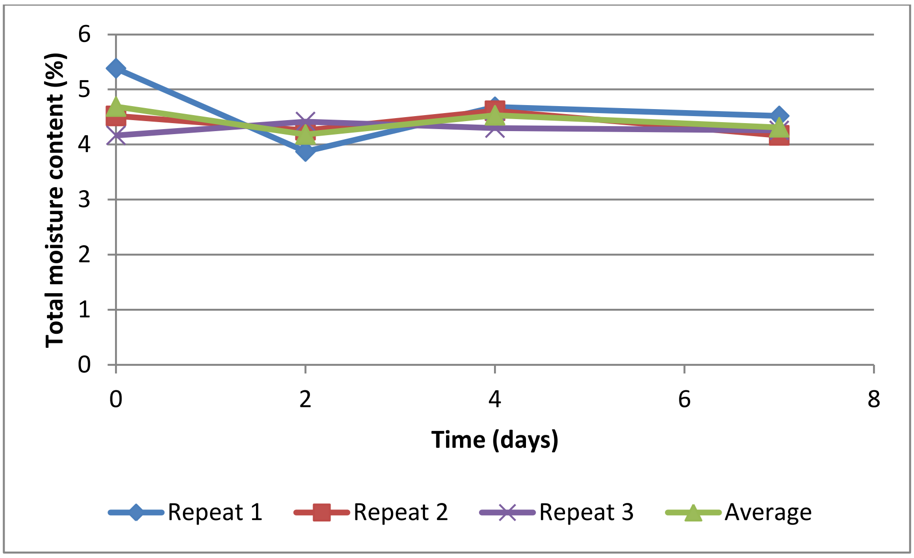

Figure C.2.15: Moisture profile of coal B -53 mm +6.7 mm 1.2 m from base

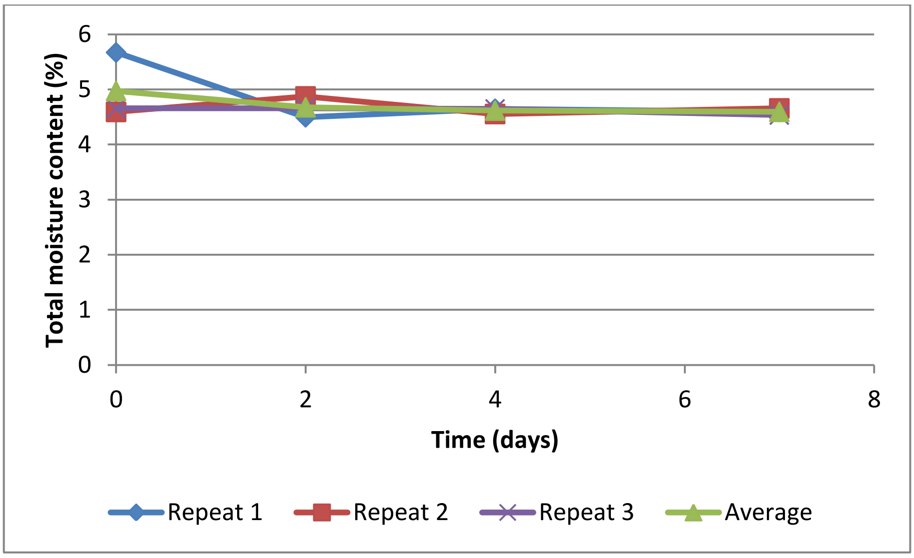

Figure C.2.16: Moisture profile of coal B -53 mm +6.7 mm 0.8 m from base

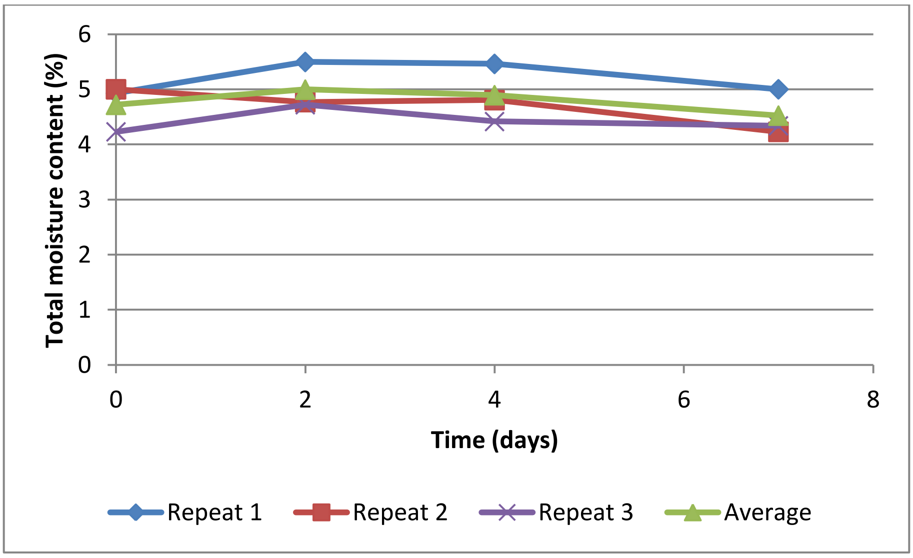

Figure C.2.17: Moisture profile of coal B -53 mm +6.7 mm 0.5 m from base

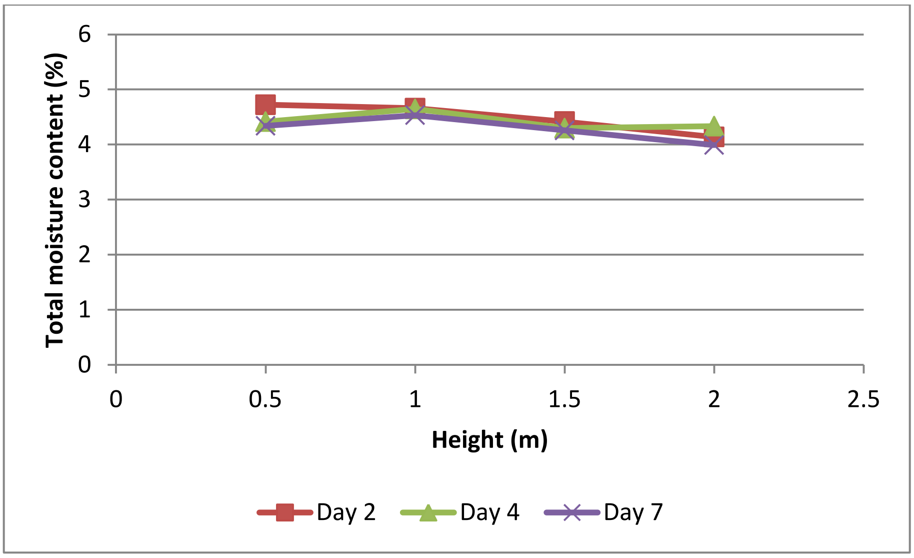

Figure C.2.18: Moisture profile of coal B -53 mm +6.7 mm over time

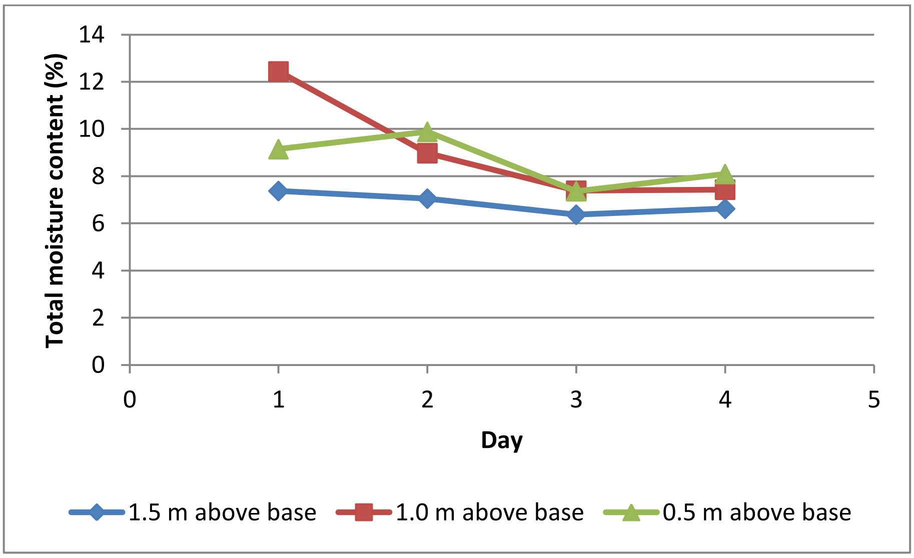

Figure C.2.19: Average moisture profile of coal A -53 mm +0 mm

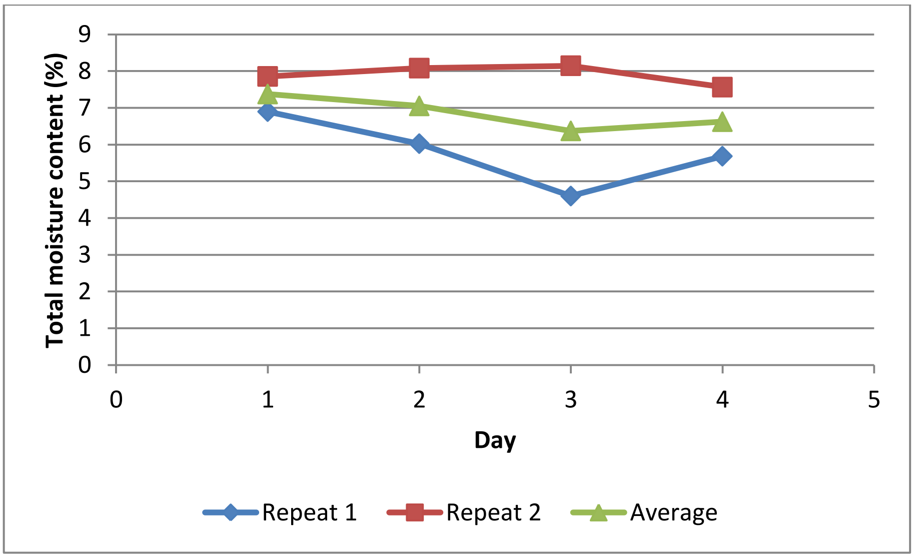

Figure C.2.20: Moisture profile of coal A -53 mm +0 mm 1.5 m above base

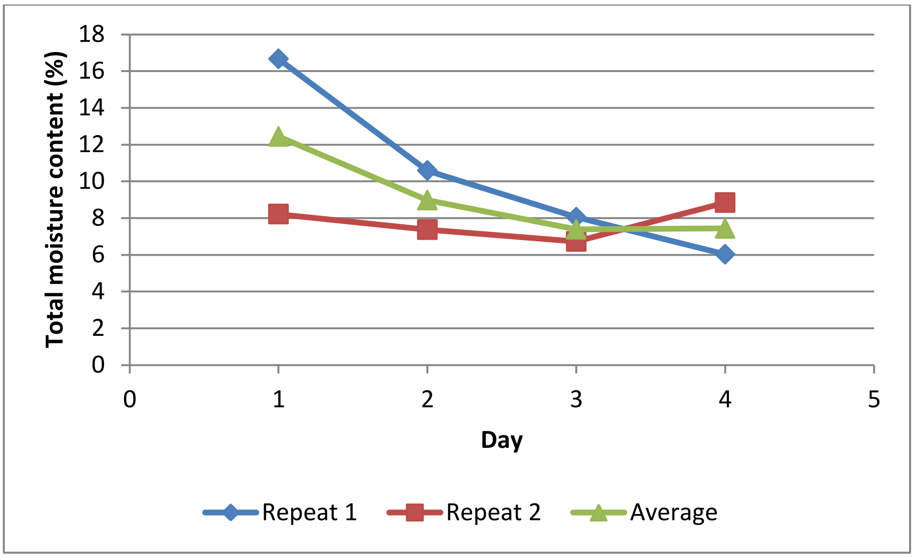

Figure C.2.21: Moisture profile of coal A -53 mm +0 mm 1.0 m above base

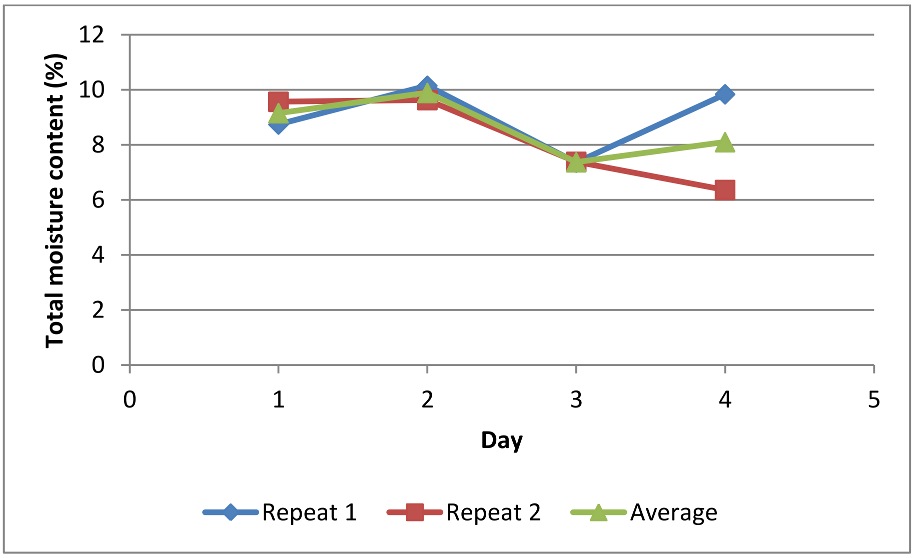

Figure C.2.22: Moisture profile of coal A -53 mm +0 mm 0.5 m above base

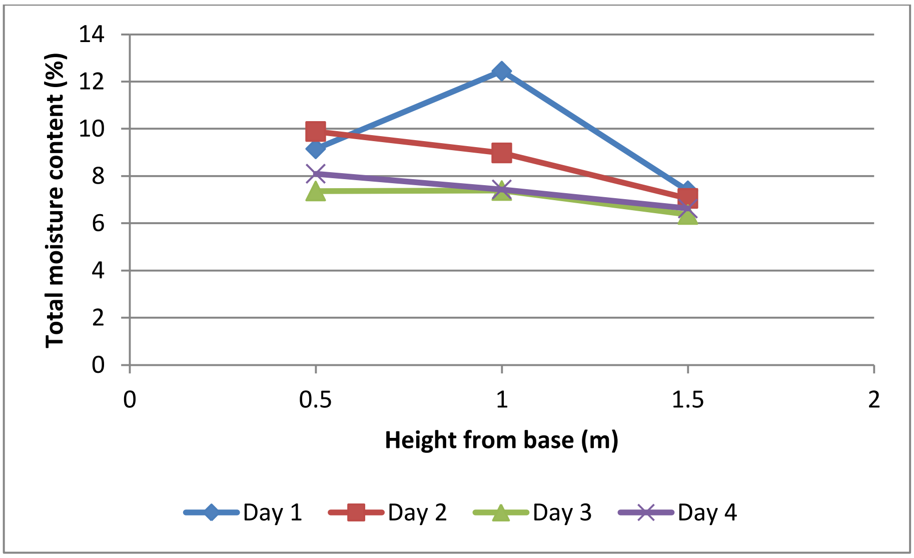

Figure C.2.23: Moisture profile of coal A -53 mm +0 mm over time

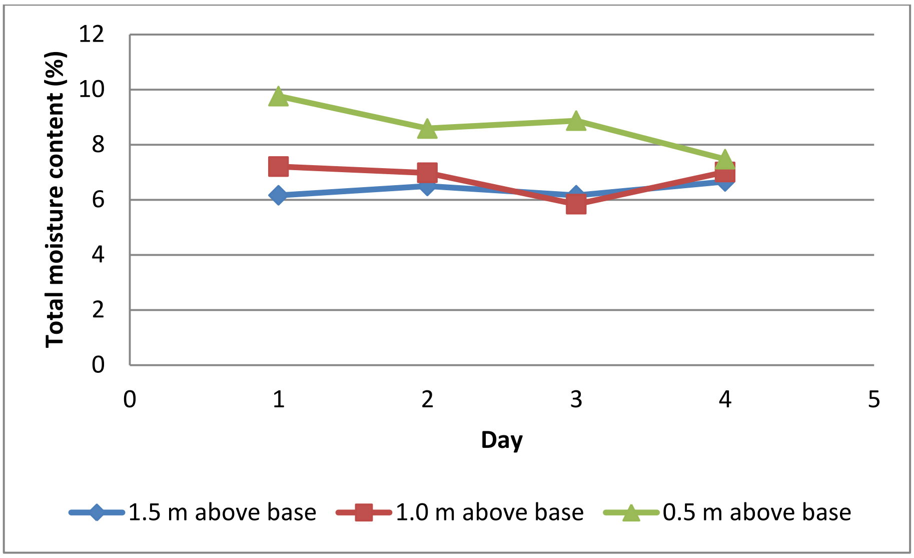

Figure C.2.24: Average moisture profile of coal A -53 mm +0.5 mm over time

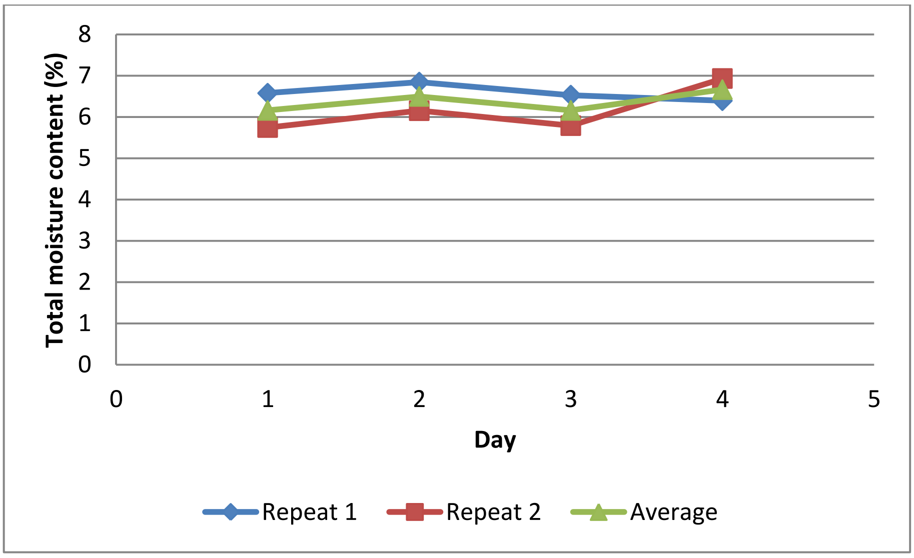

Figure C.2.25: Moisture profile of coal A -53 mm +0.5 mm 1.5 m from base

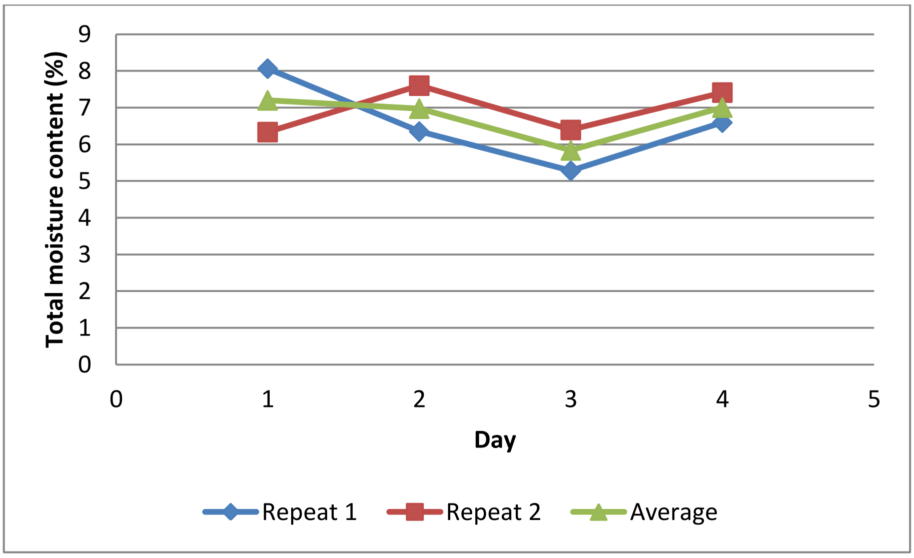

Figure C.2.26: Moisture profile of coal A -53 mm +0.5 mm 1.0 m from base

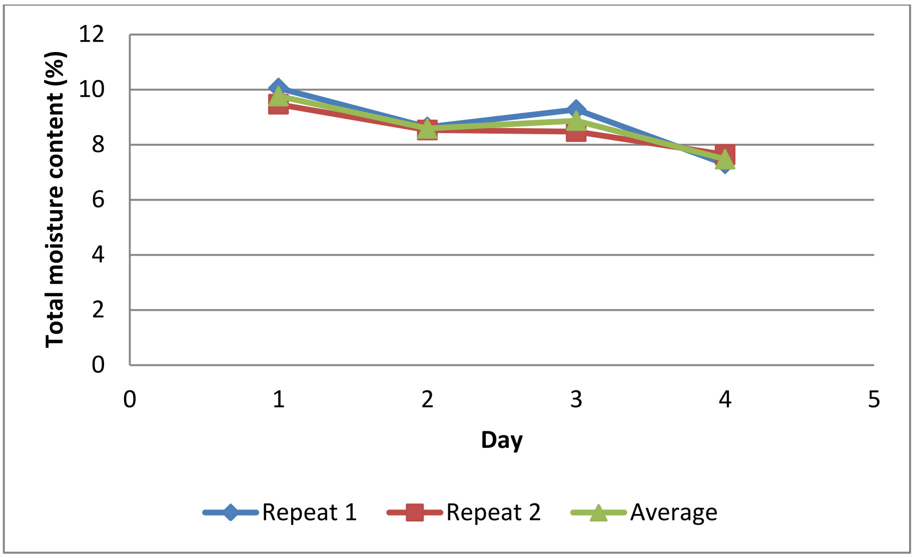

Figure C.2.27: Moisture profile of coal A -53 mm +0.5 mm 0.5 m from base

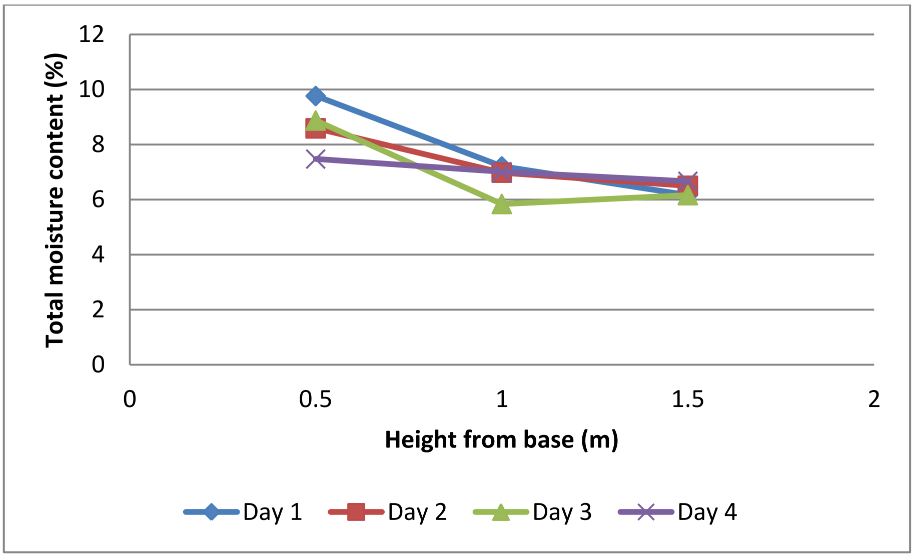

Figure C.2.28: Moisture profile of coal A -53 mm +0.5 mm over time

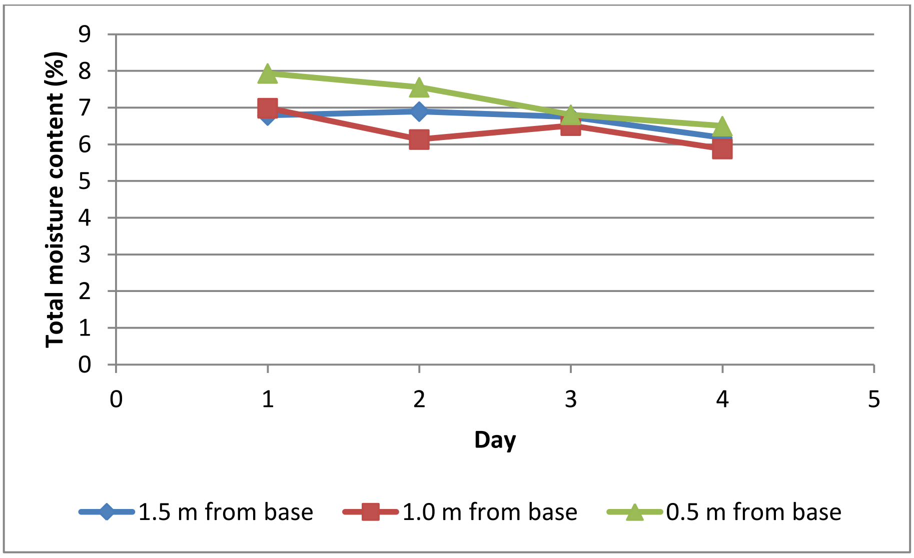

Figure C.2.29: Average moisture profile of coal A -53 mm +1 mm over time

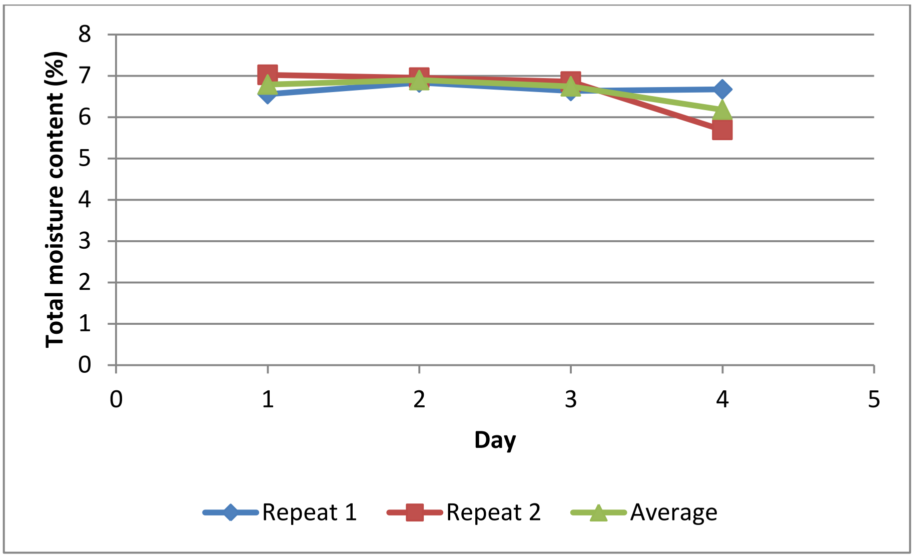

Figure C.2.30: Moisture profile of coal A -53 mm +1 mm 1.5 m above base

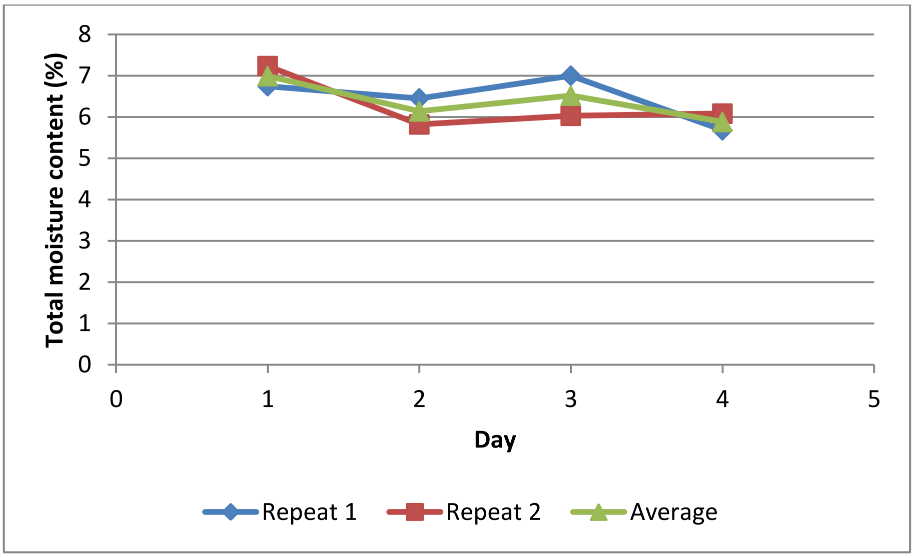

Figure C.2.31: Moisture profile of coal A -53 mm +1 mm 1.0 m above base

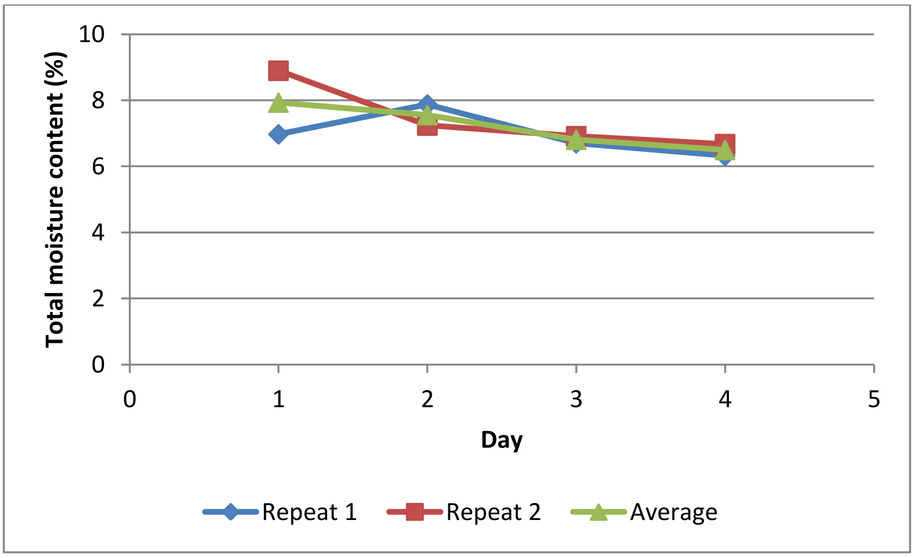

Figure C.2.32: Moisture profile of coal A -53 mm +1 mm 0.5 m above base

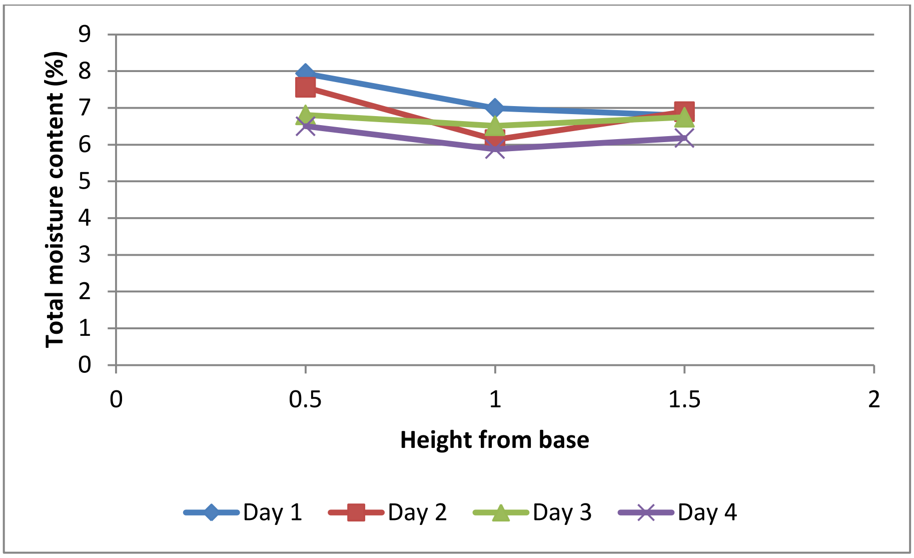

Figure C.2.33: Moisture profile of coal A -53 mm +1 mm over time

APPENDIX D: EXTRA DATA FOR THE EVAPORATION EXPERIMENTS

This appendix gives additional results for the drainage experiments as discussed in section 4.3.

D.1 Daily rates of evaporation

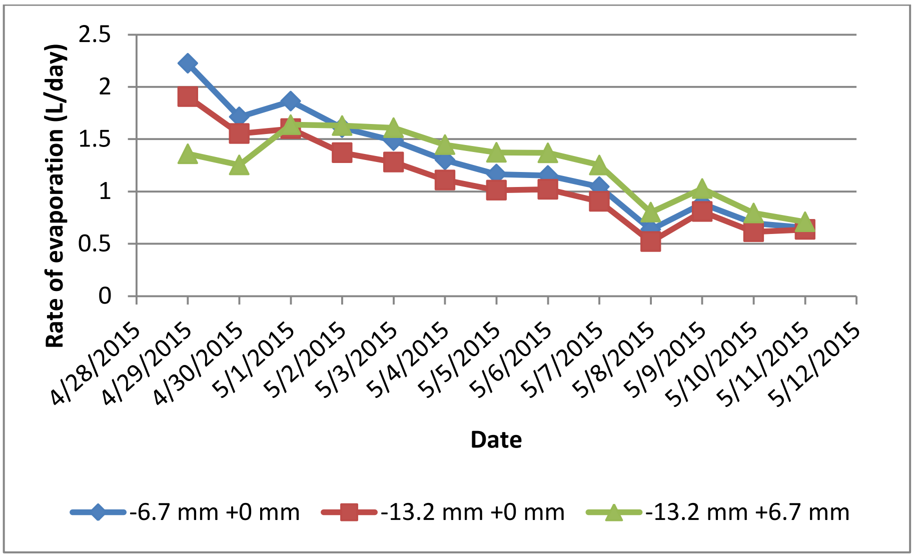

Figure D.1.1: Daily rate of evaporation for coal type B run 1

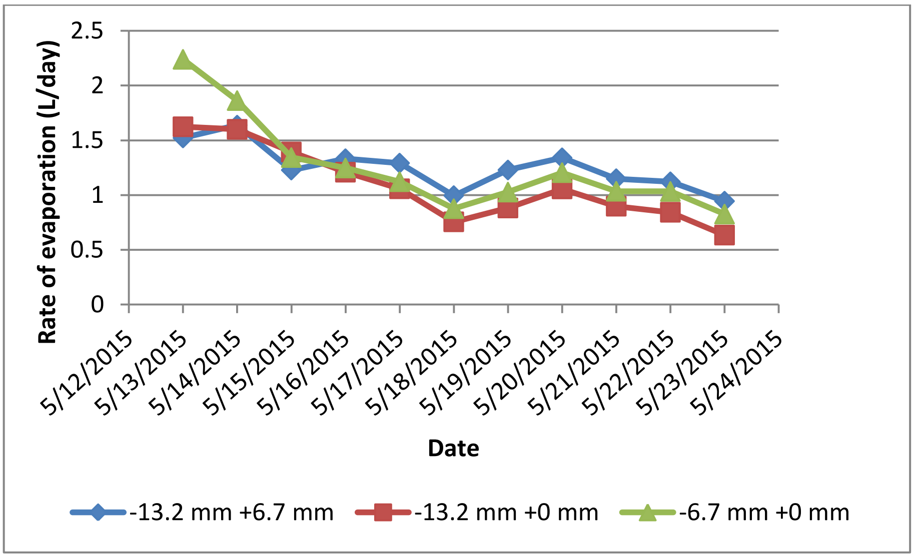

Figure D.1.2: Daily rate of evaporation for coal type B run 2

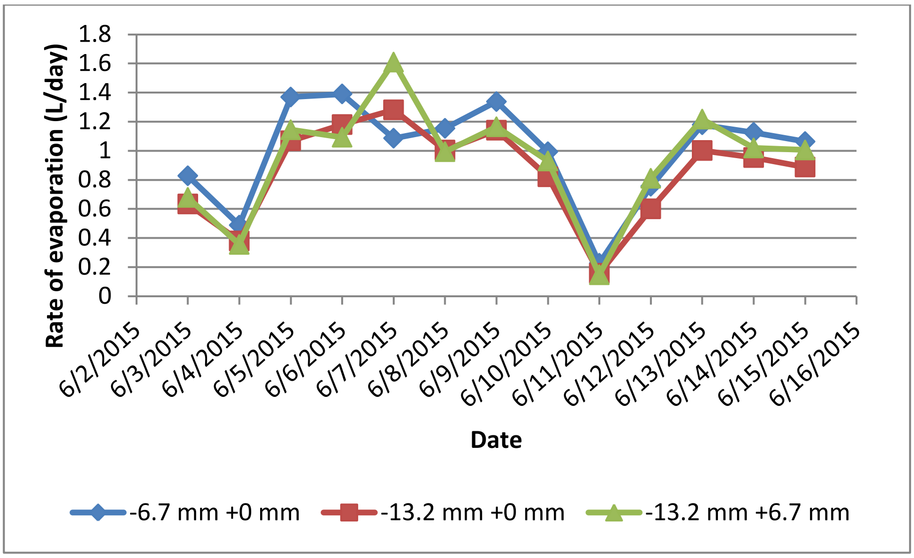

Figure D.1.3: Daily rate of evaporation for coal type B run 3

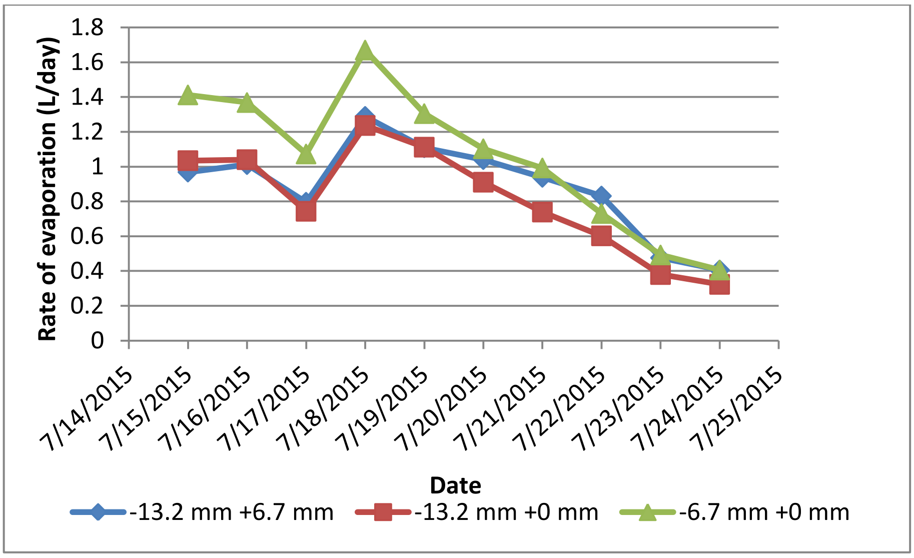

Figure D.1.4: Daily rate of evaporation for coal type B run 4

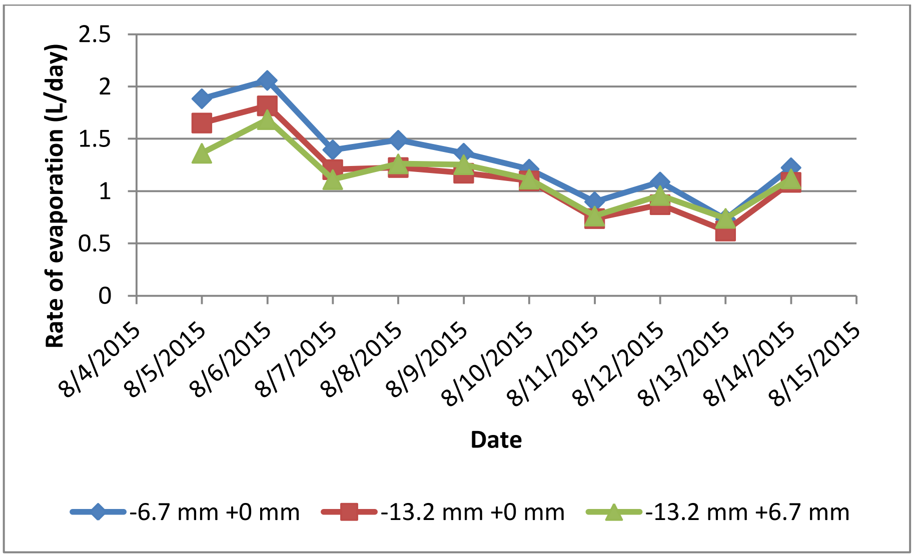

Figure D.1.5: Daily rate of evaporation for coal type B run 5

D.2 Depth of evaporation

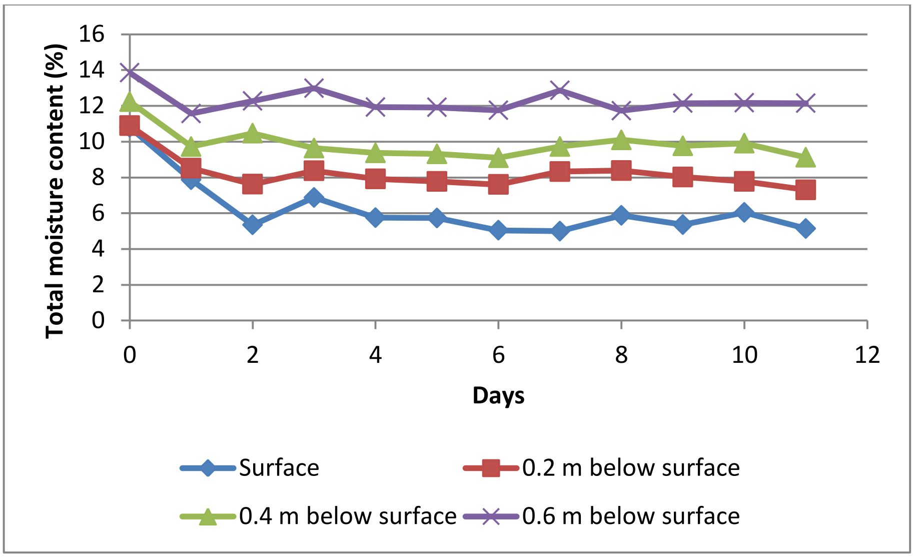

Figure D.2.1: Depth of evaporation for coal B -6.7 mm +0 mm run 2

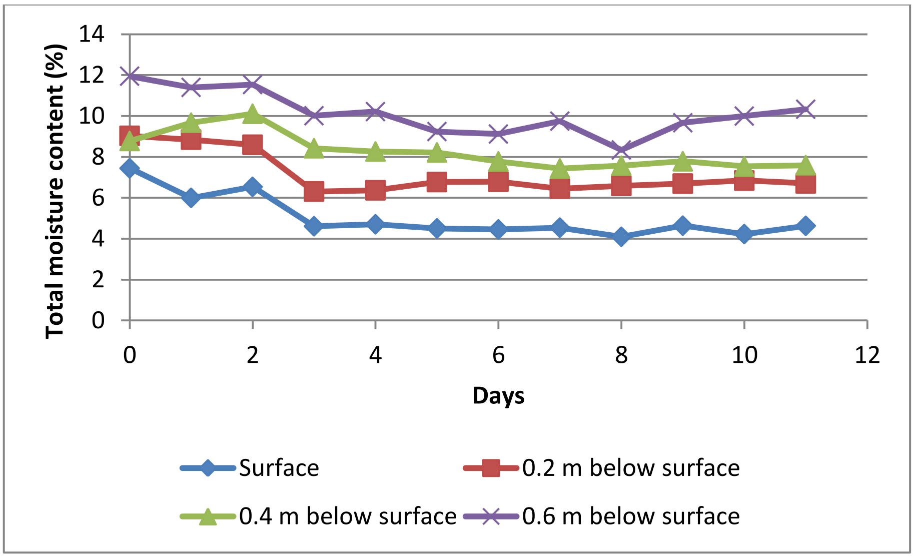

Figure D.2.2: Depth of evaporation for coal B -10 mm +0 mm run 2

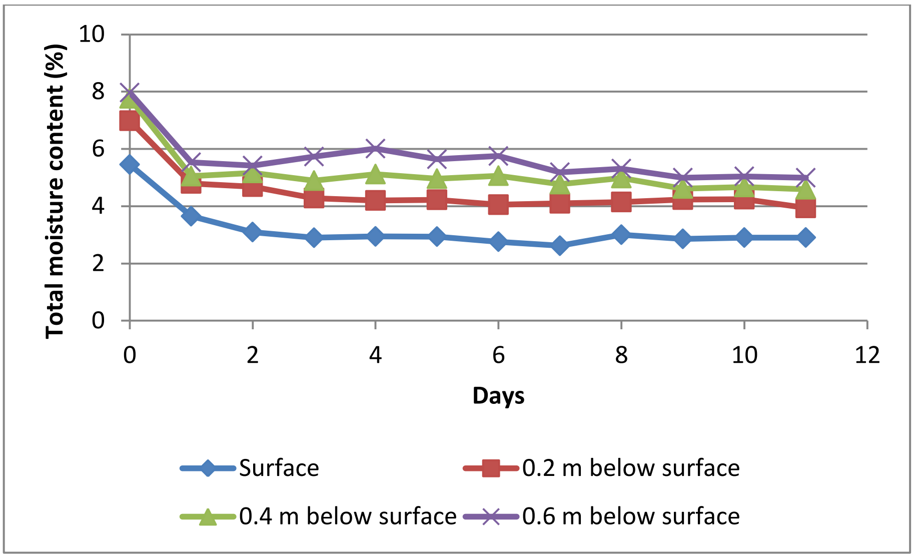

Figure D.2.3: Depth of evaporation for coal B -10 mm +6.7 mm run 2

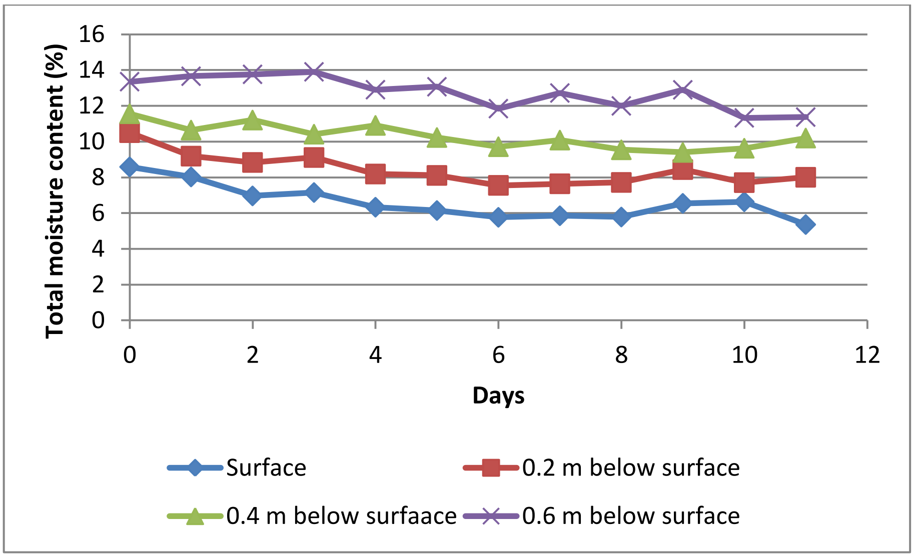

Figure D.2.4: Depth of evaporation for coal B -6.7 mm +0 mm run 3

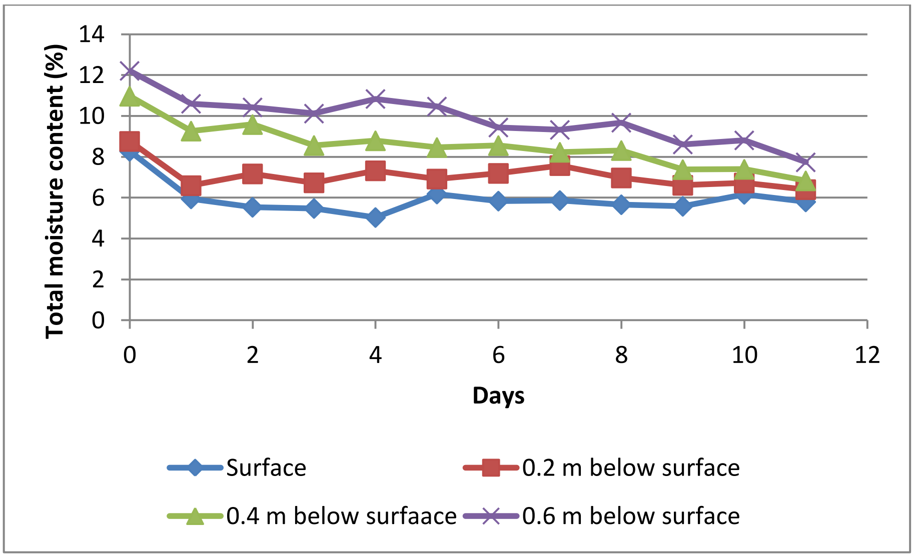

Figure D.2.5: Depth of evaporation for coal B -10 mm +0 mm run 3

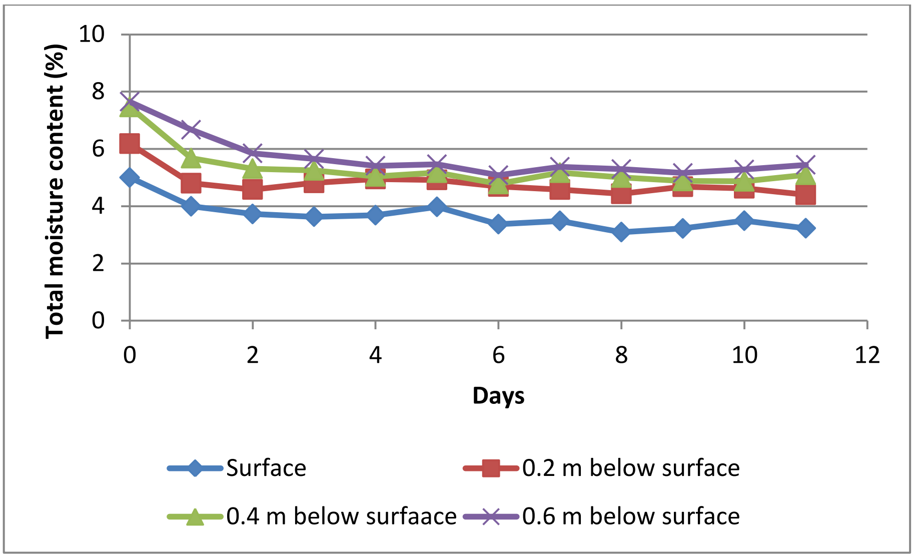

Figure D.2.5: Depth of evaporation for coal B -10 mm +6.7 mm run 3