AN EVALUATION OF THE PERFORMANCE AND EFFECTIVENESS OF IMPROVED SOIL COVER DESIGNS TO LIMIT THROUGH-FLOW OF WATER AND INGRESS OF AIR

JA Wates • SA Lorentz • H Marais •
BJM Baxter • M Theron • L Dollar

WRC Report No. 1350/1/06

Water Research Commission

AN EVALUATION OF THE PERFORMANCE AND EFFECTIVENESS OF IMPROVED SOIL COVER DESIGNS TO LIMIT THROUGH-FLOW OF WATER AND INGRESS OF AIR

Report to the
Water Research Commission

by

JA Wates, SA Lorentz, H Marais, BJM Baxter, M Theron and L Dollar

on behalf of

Golder Associates Africa (Pty) Limited
in association with
The University of the Witwatersrand,
University of Natal and
Council for Scientific and Industrial Research

WRC Report No.1350/1/06
ISBN No. 1-77005-448-0

MAY 2006

Printed by Silowa Printers 012 804 1164

EXECUTIVE SUMMARY

1 Introduction

In 1993, the WRC initiated a research project to develop a better understanding of the performance of soil covers used in the rehabilitation of coal discard dumps and opencast coal mines. The results indicated that infiltration rates could be reduced if a cover is placed on the discard or spoils. The results also indicated that covers comprising of volumetrically stable soils with a depth of greater than 0.7m might be used to significantly reduce infiltration of water and ingress of air. The potential for further reduction of infiltrations rates by combining soils with specific properties was also identified.

Notwithstanding the successes of the research project, questions were raised as to the validity of extrapolating the results of the pilot scale experiments conducted in KwaZulu-Natal, to the Mpumalanga coalfields, where the climatic regime is different and where different soils are used for rehabilitation. Questions were raised whether the soils used for rehabilitation in Mpumalanga could used to construct covers that would limit rainfall infiltration and impede oxygen ingress to the same extent as those of KwaZulu-Natal.

The potential for combining capillary barriers and store-and-release systems used in a combined configuration were also identified as having potential to reduce infiltration even more effectively that the store and release covers tested in KwaZulu-Natal. Cover configurations with a capillary block have been found to impede throughflow at the interface and to cause water to be held in the overlying finer-grained material. This mechanism enhances storage and reduces infiltration.

The assumption to be tested in this research programme is that soils currently used for rehabilitation in the Mpumalanga area and fly ash can be used to construct store-and-release covers. These store-and-release covers, possibly in conjunction with capillary barriers, would provide greater protection against moisture and oxygen ingress and would thereby reduce the production of acid mine drainage. Fly ash could further contribute to acid neutralisation. On slopes the capillary barriers would aid rapid removal of water causing a lowering in infiltration rates.

A systematic evaluation of the status of selected rehabilitation sites was proposed. The boundary conditions of the various sites were not accurately known and it was therefore not possible to assess the effectiveness of the covers with respect to infiltration. The sustainability of the soils covers could however be assessed from the state of the vegetation, the extent of erosion and degree of salinisation of the topsoil. Vegetation and soil specialists undertook in-loco inspections and sampled the vegetation and soils for laboratory testing. The history of each site was documented as accurately as possible from available records.

Soils and fly ash, occurring in the coal-mining region and deemed suitable for use in store and release covers, were identified. These soils represented a spectrum of soils that are typically used for rehabilitation purposes in the region. The soils were identified from available information and aerial photo interpretation. Approximately 15 types of soils and fly ash samples were collected. Indicator tests (Shrinkage limits, Plasticity index) and soil particle size determinations were performed to screen the soils and identify those best suited for store-and-release or capillary barrier covers for further investigation. Further laboratory tests on the short-listed soils included compaction tests, determination of water retention characteristic curves and saturated permeability tests. Breakthrough tests were also carried out to compare the hydraulic and retention characteristics of the candidate soils and ash.

An evaluation of the performances of 10 selected soil and ash arranged in the proposed cover configurations was carried out in order to further refine the selection process. The commercially available programme *SoilCover* was used to determine outflow rates through hypothetical covers and for typical dry, average and wet years occurring in the Witbank region. Based on these results, the thickness and optimum degree of compaction necessary to limit outflow to acceptable limits was selected.

Suitable sites with the potential for construction of the field test plots in the Mpumalanga region were investigated. The most likely sites are those at existing mines with coal discard dumps. Criteria used in the evaluation will be the distance of the site from the identified sources of cover materials, proximity to water and power supply as well as adequate security.

2 Literature review

Coal mining activities in South Africa have produced large quantities of waste that requires rehabilitation and remediation. Acid mine drainage (AMD) is frequently associated with coal waste. Remediation of coal discards that produce AMD is usually directed at limiting AMD production by limiting infiltration and oxygen ingress that in turn, limits the potential for pollution of surface and ground water resources.

AMD is produced when sulphides are exposed to oxygen and moisture. Oxidation takes place to produce sulphuric acid that is carried out by water percolating through the discard. The acidic leachate or AMD has low pH and high concentrations of heavy metals (Morin et al., 1982, Dubrovsky et al., 1994b and Minerals Council of Australia, 1998).

There are two primary methods to reduce the production of AMD. The first is to limit the supply of oxygen to the sulphides in the discard, thereby limiting the rate of the reaction. The second is to limit the rate and total volume of moisture percolating through the discard. If there is little or no percolation, the products of the oxidation reaction can not be mobilised and carried into ground or surface water. Additionally, the rate of the reaction may be reduced since the oxidation products form a barrier to further oxygen penetration if they are not removed by percolating water.

Various soil cover types have been used to restrict infiltration and oxygen ingress. These include:

- Composite covers with geosynthetics
- Wet cover systems
- Reactive barriers
- Store-and-release covers
- Store-and-release covers with capillary barriers

The performance of the last two cover types was evaluated in this research project.

Store-and-release covers store moisture during precipitation events and allow evaporation of stored moisture during dry periods. They usually comprise a single layer of soils and are sometimes referred to as monocovers. The thickness of the layer can be selected so that vegetation can be established and at the same time prevent root penetration into the storage zone. The most effective store and release covers are constructed of soils with low susceptibility to cracking normally associated with desiccation such as silts and low-plasticity clays.

Capillary barriers comprise a fine grained layer overlying a coarse layer. Moisture is retained or temporarily stored in the fine material and moisture movement into the coarser layer is limited by the moisture retention characteristics of the two layers combined. A capillary barrier not only limits moisture ingress into discard, but also limits moisture draw up from the lower lying strata. The performance of the store and release process can be significantly enhanced by the barrier to infiltration created at the interface between the coarse and fine layers.

3 Assessment of existing covers

Existing discard coal dumps in Mpumalanga and KwaZulu-Natal were assessed to establish whether the rehabilitation method had influenced the performance of the dumps after completion. The dumps were assessed in terms of effectiveness of vegetation; dump geometry, limitation of moisture ingress and salinisation of the cover. Two different dump types namely terraced and reprofiled (both whale back and spiral drainage) dumps were assessed.

Although soil loss was observed on all dumps and all dumps, furthermore, showed evidence of localised salinisation, the grass cover was found to perform fairly well on all dumps that were assessed. The loss of soil from especially terraced slopes is a concern as it suggests that the soil cover will continue to erode slowly to a point where cover vegetation will fail. Steeper slopes are susceptible to erosion and in a number of sites breakthrough to the underlying discard was observed. In certain of the dumps the original soil cover thickness had decreased by 50% over a ten to fifteen year period. In general, the depth of soil cover is considerably less on terraced dumps than on either of the reprofiled dump forms. This is the consequence of difficulty in handling of soils on the steep terrace slopes.

Settling of soils on terrace slopes after placement frequently leads to cracking through the soil cap to the underlying discards. These cracks short circuit the passage of runoff water through the soil cap and may also provide a ready conduit for air to the underlying discards.

4 Soil identification

A desktop study was carried out to establish which soils in the Mpumalanga region would be suitable for use in alternative covers such as store-and-release and store-and-release with capillary barriers. No soils were found that met the criteria for coarse soil while 11 were found that might be sufficient for the fine grained layers of the covers. Foundation indicator tests were carried out on these soils which were then evaluated using a set of predetermined criteria to narrow the selection for numerical analysis.

5 Soil analysis

It was found that only five of the original eleven soils met the criteria for store-and-release and store-and-release covers with capillary barriers. These five samples were then subjected to an advanced laboratory testing program to finally confirm their suitability. Coal ash was also included in the soil analysis, but it was found that the properties were not acceptable for use as the-store-and release layer.

6 Kilbarchen monitoring

The Kilbarchan experiment provided a basis for comparison of various rehabilitation techniques and established a degree of consensus on appropriate design philosophy for soil covers. The work was one of the first detailed research experiments in South Africa where soil covers have been researched for use for the mitigation of coal discard and for the development of a clear understanding of the flow mechanisms in the upper unsaturated layers of a natural soil cover.

The outflow rates of 8 experimental cells were monitored for a period of nine and a half years. The outflow through the cells was found to be a function of cover thickness and composition. The outflow results of sloped cells were inconclusive. Uncovered and single cover cells displayed high oxygen concentrations while the concentration below the composite covers was found to be low. Acid breakthrough was recorded in all of the uncovered cells due to high oxygen ingress. Decrease in sulphate concentrations in the cells with composite covers indicated sustained low oxygen ingress.

7 Numerical modelling and cover design

SoilCover, a finite element numerical programme, was used to assess the performance of the alternative cover configurations of the soil types selected for the experimental work. The computed unsaturated flow was calibrated against the Kilbarchan field results. After calibration the models were used to simulate performance of the typical Mpumalanga soils in the preferred cover configurations.

Two types of numerical analysis were carried out namely an event (single year) and representative climatic (15 consecutive years) analysis. In the former analysis, the influence of cover density, thickness, vegetation, coal discard depth as well as capillary barriers was investigated for Soils 1 and 8. Based on the results of this analysis, the performance of the best performing soil (Soil 1) was evaluated at two different densities with and without a capillary barrier.

8 Laboratory experiment

The suitability of the various cover designs was also evaluated by means of laboratory experiments. The influence of slope on runoff and infiltration into the soil cover were evaluated. A 1.5m long, 1.2m wide and 1.2m deep flume was constructed. The flume was equipped with sensors to measure pore pressure, volumetric water content, soil temperature, air temperature and humidity. A cover configuration of 0.54m Soil 8 compacted to 90% of standard Proctor on top of 0.22m of coal discard was adopted. Two rainfall events were simulated for slope angles of 1:50 and 1:5. The results of the second rainfall event were simulated using *HYDRUS2D* model.

9 Discussion

Past rehabilitation practises favoured soil covers on coal discard dumps primarily to provide a substrate to support vegetation. In recent years the soil cover thickness used has increased to limit the oxygen ingress and water infiltration into the coal discard. Cover performance deteriorates with time due to loss of soil through erosion.

The performance of the two soil covers (Soil 1 and 8) was assessed by means of numerical simulations using *Soilcover*. The single year simulations indicated that the performance of Soil 1 was better than that of Soil 8. The minimum infiltration was obtained for 85% Standard Proctor compaction with a capillary break. Vegetation slightly improved the performance of the soil cover and the lightly compacted cover (85%) outperformed the better compacted cover (90%) (both with and without the capillary break). Numerical analysis over a representative climatic period was carried out on Soil 1 and confirmed the above results.

The laboratory experiment illustrated the importance of in-situ measurement of hydraulic characteristics to take micro structure such as surface cracking into account. The results of these experiments indicated that runoff and infiltration were affected by the surface cracking. Numerical modelling of the flume experiments using *HYDRUS2D* did not incorporate surface cracking.

10 Conclusions

Most of the rehabilitated coal discard dumps assessed during the study were found to exhibit erosion, indicating that the covers are becoming progressively thinner with time. Salinisation of the soil covers was also found although confined to localised zones on most dumps. Future covers will thus need to be designed to prevent erosion by means other than vegetation. Surface armouring is considered to provide an effective means of improving erosion resistance and enhancing the sustainability of slopes. Slope length is also an important determinant of erosion and should be considered in future designs.

The importance of selecting soils with the appropriate characteristics in terms of moisture retention and volumetric stability has been illustrated by the research. Compaction has been shown to play an important role. Lightly compacted soil was found to provide better storage capacity and less through-flow than better compacted soil of the same type. The presence of the capillary barriers was not found to significantly influence the performance of the covers. It should however be noted that this conclusion was drawn on the basis of theoretical considerations and runs contrary to observations made by other researchers.

The simulation of a range of cover configurations based on laboratory derived parameters shows that a cover thickness of between 0.5m and 1.0m will be optimum for the Mpumalanga coal fields region with soils typically available in the region. (cf. the conclusion of the Kilbarchan experimental work that the minimum thickness should be 0.7m).

The laboratory tests indicated that cracking of the soil reduces runoff and increases the amount of water that infiltrates into the soil cover. This conclusion is supported by intuition and by the experience of other researchers in the field of geotechnical engineering. It confirms the importance of selecting soils that are volumetrically stable and the role that compaction plays. The valuable experience derived from geotechnical engineering should therefore be used to identify soils with the requisite properties and to specify the compaction requirements to minimise the occurrence of cracking and the formation of microstructure.

The research supports the proposition that soils that are available in the Mpumalanga region may be used for store and release covers and that the results of the experimental work conducted at Kilbarchan in KwaZulu-Natal can be used to calibrate designs conducted for other soils types and climatic regions.

11 Recommendations

The following general recommendations follow from the conclusions of this research project:

- Volumetrically stable soils with permeability of less than $1x10^{-8}$ m/s should be used for covers, The following criteria should be adopted for selection of soils for covers:
- Clay fraction <10%
- Non plastic
- Linear shrinkage <1%
- Coefficient of uniformity <10
- The selection of soils for covers should be done in advance of rehabilitation planning and should be based on baseline studies that provide the geotechnical parameters required for design of the covers. Laboratory testing to confirm that the candidate soils are volumetrically stable and will have the required permeability should be undertaken.
- Cover designs should be substantiated by throughflow modeling based on laboratory determined parameters and should be verified by field trials before full scale implementation
- Field trials should not be done without first demonstrating that the trial configurations are potentially viable on the basis of the throughflow modeling.
- Effects of erosion, surface cracking and vegetation on the runoff and infiltration should be taken into account in the design of future covers. Soils for covers should be selected on the basis of a thorough investigation and on criteria selected to serve the objective of minimisation of infiltration, erosion prevention and support of vegetation. A multidisciplinary team having the necessary range of skills and experience should therefore be involved in the design.
- The effect of salinisation should be considered in the design and where vegetation is to play an important role on the water balance and stabilization should be resolved in the design of the cover.
- The use of rock armouring (approximately 40% rock and 60% topsoil) should be investigated as a means of further stabilising covers. (The practice of using rock armouring is receiving considerable research attention in other sectors of the South African mining industry for stabilisation of mine residue slopes).

The following recommendations are made to guide future research work:

- Field trials of promising alternative cover configurations using the soil types satisfying the criteria set out in the general recommendations above should be carried out in the Mpumalanga region
- Field trials should investigate the following:
- influence of compaction

- salinisation of the soil cover
- influence of capillary breaks
- armouring of slopes to control erosion
- natural (possibly compacted) or geosynthetic barriers below store and release covers
- The performance of existing soil covers on existing dumps should be investigated in more detail to assess the progress of erosion, the extent of salinisation and throughflow and to correlate this with the soil types used, the slope angle, the slope geometry and time. In this regard existing soil covers should be instrumented and monitored over time in order to assess the progression and rate of erosion and salinisation and to correlate this with soil type, slope and geometry.
- Laboratory scale experiments and simulations should be conducted to investigate different soil types, layering configurations and slopes, interface mechanisms between materials of different hydraulic characteristics and layer configurations with different boundary conditions and the effects of preferential flow in the water balance by induced cracking or preferential pathways into the medium. This should be done in order to identify further promising opportunities to further reduce infiltration and oxygen ingress into rehabilitated coal discard.
- Further scenarios should be investigated by simulation to illustrate the effects of soil water retention and hydraulic conductivity combinations. The optimum compaction effort for a cover configuration and the associated voids ratio pore space arrangement should thus be established. This should be done by incorporating a capillary break as this proved to be the best cover design for limiting moisture ingress into the coal discard.

ACKNOWLEDGEMENTS

The research in this report emanated from a project funded by the Water Research Commission and entitled:

"An evaluation of the performance and effectiveness of improved soil cover designs to limit through-flow of water and ingress of air"

The Steering committee responsible for this project, consisted of the following:

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The Water Research Commission financed this project and the contribution of the members of the Steering Committee is gratefully acknowledged.

The contribution of Coaltech in financing the monitoring program during the research period is gratefully acknowledged.

The project was only possible with the co-operation of many individuals and institutions. The authors therefore wish to record their sincere thanks to the people and institutions:

- Department of Water Affairs and Forestry for its contribution in conducting weekly monitoring.
- The Institute for Water Quality Studies (Department of Water Affairs and Forestry), which conducted bi-weekly analysis of leachate samples.
- Mr Y Nero of Department of Water Affairs and Forestry (Dundee) who took the physical experimental measurements on a weekly basis at the experimental site.
- Mr P van Deventer for his inputs in the assessment of existing soil covers.

The many individuals and institutions that were involved in the project from its outset in 1993.

TABLE OF CONTENTS

SECTION	PAGE
Executive summary	(i)
Acknowledgements	(ix)
List of figures	(xiii)
List of tables	(xvi)
1. INTRODUCTION	1
2. LITERATURE	4
2.1 Introduction	4
2.1.1 Problems with existing covers	5
2.2 Background theory	13
2.2.1 Acid mine drainage formation	13
2.2.2 Oxygen transfer	14
2.2.3 Soil water characteristic curves and unsaturated hydraulic conductivity	15
2.3 Store-and-release covers	21
2.3.1 Moisture storage potential and material selection	22
2.3.2 Case studies	23
2.4 Capillary barriers	26
2.4.1 Moisture storage mechanism and estimating moisture storage potential of capillary barrier cover systems	27
2.4.2 Material selection	31
2.4.3 Case studies	34
2.4.4 Summary of working principles of cover designs considered in research	37
3 Assessment of Existing Covers	39
3.1 Background	39
3.2 Rehabilitation approaches assessed	39
3.2.1 Terraced dumps	39
3.2.2 Reprofiled "whaleback" dumps	40
3.2.3 Reprofiled dumps with "spiral drainage"	40
3.2.4 Combination of approaches	40
3.3 Methodology	41
3.4 Findings	42
3.4.1 Performance of Terraced Dumps	42
3.4.2 Reprofiled dumps – whaleback	44
3.4.3 Reprofiled dumps – spiral drainage	47
4 Soil Identification	48
4.1 Introduction	48
4.2 Background on alternative covers under investigation	48
4.3 Sample collection	49
4.4 Initial criteria for soil selection and initial sample selection	50

4.5 Detailed Selection tests....52
5 Soil Analysis....54
5.1 Introduction....54
5.2 Soil data collected....54
5.3 Results....56
6 Kilbarchan monitoring....61
6.1 Introduction....61
6.2 Monitoring Program....61
6.2.1 Problems encountered during the monitoring period....63
6.3 Outflow analysis....64
6.3.1 Uncovered cells (Cells 1, 2 and 3)....64
6.3.2 Single layered covers (Cells 4 and 5)....65
6.3.3 Double layered covers (Cells 6 and 8)....66
6.3.4 Store-and-release cover (Cell 7)....67
6.3.5 Sloped covers (Cells 9 and 10)....68
6.3.6 Explanation of outflow rates....69
6.4 Analysis of concentration vs time of selected chemical species....71
7 Numeric Modelling & Cover Design....72
7.1 Introduction....72
7.2 SoilCover....72
7.3 Recharge Modelling....74
7.4 Model Set-up....75
7.4.1 Single year simulations....75
7.4.2 Analysis of representative climatic period....80
8 Laboratory experiment....83
8.1 Introduction....83
8.1.1 Flume structure....83
8.1.2 Rainfall simulator....83
8.1.3 Instrumentation....84
8.1.4 Cover material....86
8.2 Results of events and evaporation....88
8.2.1 Soil water response: Event 1 (1:50 slope)....89
8.2.2 Soil water response: Event 2 (1:5 slope)....89
8.3 Flume simulation....94
8.4 General slope runoff analysis....97
9 Discussion....102
10 Conclusions....108
11 RECOMMENDATIONS....111
11.1 General recommendations....111
11.2 Recommendations for future work....112
12 References....113

APPENDICES

Appendix 1	Sample collection points
Appendix 2	Initial soil testing results
Appendix 3	Detailed soil analysis
Appendix 4	Soil water characteristic curves
Appendix 5	*Soilcover* analysis results
Appendix 6	Experimental flume data
Appendix 7	Capacity Building

The Appendices are available on the CD attached to the back cover of this report.

LIST OF FIGURES

Figure 1:Configuration of a capping systems using compacted clay.. 6

Figure 2: Components of a multi-layer composite cap (after Kim and Benson, 2004)..................... 9

Figure 3: Schematic diagram of a moisture retaining barrier (Yanful et al., 1993a and b)............... 10

Figure 4: Typical SWCC for a silty soil (after Fredlund and Xing, 1994).................................. 16

Figure 5: Schematic diagram of a store-and-release cover.. 22

Figure 6: Schematic diagram of capillary barrier layers.. 26

Figure 7: Graphs of measure and predicted soil water characteristic curves for three soils and corresponding unsaturated hydraulic conductivities derived using the Mualem-van Genuchten model (after Stormont and Anderson, 1999).. 27

Figure 8: Particle size distribution envelopes derived from flume tests (after von der Hude et al., 1999b).. 33

Figure 9: Capillary barrier system (after Dwyer, 1998 and 2001).. 36

Figure 10: Anisotropic barrier (after Dwyer, 1998).. 36

Figure 11: Diagram indicating risk to terrace dump benches due to accumulation of eroded soil (yellow vs. brown line) which results in runoff flow movement away from the base of the terrace slope (blue solid line vs. stippled line).. 43

Figure 12: Slumping of the soil cover and erosion frequently result in exposure of underlying coal discard at the top of terrace slopes. Solid brown line indicated soil cover at placement. The fill represents the actual soil cover ten years after rehabilitation.. 44

Figure 13: Soil-water characteristic curves from laboratory data for Samples 1 and 8.................. 57

Figure 14: Soil-water characteristic curves from laboratory data of Sample 1 at different degrees of compaction.. 58

Figure 15: Soil-water characteristic curves from laboratory data of Sample 8 at different degrees of compaction.. 58

Figure 16: Soil water characteristic curves of soil samples and ash at 90% maximum Standard Proctor dry density.. 59

Figure 17: Layout of experimental site (after Vermaak and Bezuidenhout, 2003)........................ 62

Figure 18: Plant Transpiration Reduction Versus Log Suction at the Root Centroid Node............. 73

Figure 19: Soil water characteristic curve for Soil 1 with Fredlund and Xing curve as fitted by SoilCover.. 76

Figure 20: Results of the Soil 1 covers long term simulations, showing annual precipitation and the discharge through the cover into the discard.. 81

Figure 21: The experimental flume and rainfall simulator at the Ukulinga farm, University of KwaZulu-Natal.. 84

Figure 22: Layout of the cover profile and instrumentation (numbered markers refer to TDR and tensiometer probe positions in the compacted Soil 8) for the laboratory flume experiments............ 85

Figure 23: Textural analysis of the soil used in the flume experiment.................................... 86

Figure 24: Cracks evident on the surface of the soil material after wetting events...................... 87

Figure 25:Measured rainfall and runoff of Event 1 in the laboratory flume.............................. 88

Figure 26: Measured rainfall and runoff of Event 2 in the laboratory flume............................. 89

Figure 27: Soil water content response during Event 1 of probe sets at a) 0.05m b) 0.15m c) 0.3m and d) 0.45m.. 91

Figure 28: Soil matric pressure response during Event 1 of probe sets at a) 0.05m b) 0.15m c) 0.3m and d) 0.45m.. 92

Figure 29: Soil water content response during Event 2 of probe sets at a) 0.05m b) 0.15m c) 0.3m and d) 0.45m.. 93

Figure 30: Soil matric pressure response during Event 2 of probe sets at a) 0.05m b) 0.15m c) 0.3m and d) 0. 45m... 94

Figure 31: Initial conditions in the HYDRUS2D simulation, with soil matric pressure head varying from 2.9m at the base of the discard to 3.8m at the surface of the soil cover.................... 95

Figure 32: Simulated and observed water content response for Event 2 at a) 0.05m b) 0.15m c) 0.3m and d) 0.54m depths.. 96

Figure 33: Simulated and observed matric pressure head response for Event 2 a) 0.05m b) 0.15m c) 0.3m and d) 0.54m depths.. 98

Figure 34: Schematic view of the kinematic, finite difference surface runoff algorithm showing the mass balance of a surface runoff element.. 100

Figure 35: Best fit SWCCs for Sample 1 using van Genuchten (1980) and Fredlund and Xing (1994)........103

Figure 36: Best fit SWCCs for Sample 8 using van Genuchten (1980) and Fredlund and Xing (1994)........103

LIST OF TABLES

Table 1: Initial sample selection criteria....49

Table 2: Sample types collected....50

Table 3: Summary of values used in decision-making.... 51

Table 4: Values and soil parameters.... 60

Table 5: Summary of cell configuration....64

Table 6: Summary of key trends in leachate quality data.... 71

Table 7: Summary of *SoilCover* model runs....77

Table 8: Summary of model run results.... 79

Table 9: Summary of the laboratory flume simulated rainfall events....88

Table 10: Summary of runoff response to rainfall on slopes of 0.5% and 5%....101

1 INTRODUCTION

In 1993, the WRC initiated a research project to measure and monitor the performance of soil covers used in the rehabilitation of coal discard dumps and opencast coal mines. The results indicated that infiltration rates could be significantly reduced if an appropriate cover is placed on the discard or spoils, which in turn, reduced the waste load discharge to the water environment. The results also indicated that covers comprising of volumetrically stable soils with a depth of greater than 700mm might be used to reduce infiltration significantly. The potential for further reduction of infiltration rates by combining soils with specific properties was also identified.

Notwithstanding the successes of the research project, questions were raised on the validity of extrapolating the results of this research, situated in KwaZulu-Natal, to the situation of the Mpumalanga coalfields, where the climatic regime is different and where different soils are used for rehabilitation. Questions were raised whether the soils used for rehabilitation in Mpumalanga can be used to construct covers that will limit rainfall infiltration and impede oxygen ingress to the same extent as those of KwaZulu-Natal.

New capping technologies came into being since the initiation of the first WRC research project. The most promising being store-and-release covers which were incidentally also tested at Kilbarchan although the term "store-and-release" had not yet been defined at the time. The effectiveness of store-and-release covers has been demonstrated internationally as well as by the first WRC research project. It is important to know how these store-and-release covers can be refined to provide an optimum cover design (Chapter 2).

Another fairly recent development in cover designs for coal discards has been the concept of capillary barriers. Capillary barriers rely on the unsaturated properties of the cover to drain infiltrating water along inclined unsaturated drainage layers from where it can be intercepted and removed. A typical capillary barrier system comprises of a relatively fine-grained material (the unsaturated drainage layer (UDL)) and a coarser base layer (capillary block). Infiltrating water flows along the interface between the UDL and capillary block, but does not infiltrate the capillary block because of differences in soil suction in the layers. The water flows along the interface of the two layers and is then collected in drains.

It has been hypothesised that capillary barriers and store-and-release systems can be used in a combined form. By choosing cover materials such that the capillary block causes water to be held in the overlying finer-grained material, storage during wet periods will be enhanced and infiltration reduced.

This project aims assess the effectiveness of various cover configurations in limiting rainfall infiltration and oxygen ingress into coal discards and spoils, specifically:

- Assessing the performance and sustainability of existing in-field coal discard covers in Mpumalanga.
- Analysing promising new cover configurations by using mathematical and physical models to predict the performance of soils and fly ash of Mpumalanga.
- Designing and motivating a cover experiment as a separate project if the analysis conducted suggests that there are viable options likely to perform well under Mpumalanga conditions.

The basic assumptions to be tested in this research programme are that soils currently used for rehabilitation in the Mpumalanga area and fly ash can be used to construct store-and-release covers. Store-and-release covers, possibly in conjunction with capillary barriers, would provide greater protection against moisture and oxygen ingress and thereby reduce the production of acid mine drainage compared to existing cover configurations. Fly ash would further contribute to the acid neutralising potential of leachate. On slopes the capillary barriers would aid rapid removal of water causing a lowering in infiltration rates.

A systematic evaluation of the status of selected rehabilitation sites was proposed. The boundary conditions of the various sites were not accurately known and it was therefore not possible to assess the effectiveness of the covers with respect to infiltration control. The sustainability of the soil covers can however be assessed from the state of the vegetation, the extent of erosion and degree of salinisation of the topsoil. Vegetation and soil specialists undertook in-loco inspections and sampled the vegetation and soils for laboratory testing. The history of each site was documented as accurately as possible from available records (Chapter 3).

The coal mining industry has expressed their willingness to assist in the construction of a new experimental site in the Witbank region. Information gathered from numerical modelling, laboratory testing and site investigations of existing covers will therefore be used to motivate for construction of selected cover configurations in experimental cells. The choice of covers would be limited to those that had the potential to limit moisture and oxygen ingress into coal discards.

Soils and fly ash, occurring in the coal-mining region and deemed suitable for test work, were identified. A representative spectrum of soils typically used for rehabilitation purposes in the region were selected. The soils were identified from available information and aerial photo interpretation, followed by auger holes and test pits to prove the suitability of the source. Approximately 15 types of soils and fly ash samples were collected (Chapter 4). Indicator tests (Shrinkage limits, Plasticity index) and soil grading were performed to select the soils best suited for store-and-release or capillary barrier covers for further investigation.

Further laboratory tests included compaction tests, water retention characteristics and saturated permeability tests (Chapter 5).

A cover design programme was initiated to compare the likely cover performances of 10 selected soils and ash that can be used in the proposed cover configurations. Commercially available programmes such as *HYDRUS2D* and *SoilCover* were used to determine likely outflow rates through hypothetical covers and for typical dry, average and wet years occurring in the Witbank region (Chapters 7 and 8). Based on these results, the thickness and compaction state of the covers necessary to limit outflow to acceptable limits was selected.

Suitable sites with the potential for construction of the field test plots in the Mpumalanga region were investigated. The most likely sites are those at existing mines with coal discard dumps. Criteria used in the evaluation will be the distance of the site from the identified sources of cover materials, proximity to water and power supply as well as adequate security. Coal discard was sourced from local coalmines. The discard should have a high acid potential and have physical characteristics representative of most coal discard in the region. Acid Base Accounting was conducted to screen coal discard material and this was followed by more detailed geochemical tests including shake flask and mineralogical analyses. Humidity cell tests were also conducted. The screening criteria for ash included neutralisation potential, water-soluble elements and pozzolanic activity. This was followed by tests to determine the potential for secondary precipitation and geotechnical and hydraulic tests.

2 LITERATURE REVIEW

2.1 Introduction

The many mining activities in South Africa have produced large quantities of mining waste and discard that require rehabilitation and remediation. Associated with some of the waste types is acid mine drainage (AMD). When remediating waste discards that may produce AMD, it is important to limit its production, which in turn, will limit the potential pollution of surface and ground water resources in proximity to the mining discard. Mine wastes that produce AMD include gold tailings and coal discard.

Acid mine drainage is produced when sulphate-bearing waste or ore is exposed to oxygen. Oxidation takes place, and the sulphuric acid produced is leached out by water percolating through the discard or tailings (Section 2.2.1). The acidic leachate or AMD has low pH resulting in a high concentration of heavy metals to be leached (Morin et al., 1982, Dubrovsky et al., 1994b and Minerals Council of Australia, 1998). There are two primary methods to reduce the production of AMD. The first is to limit the amount of oxygen available in the discard, thereby limiting the rate of the reaction. The second, and the primary focus of this investigation, is to limit the amount of moisture percolating through the discard. If there is little or no percolation, the products of the oxidation reaction are not mobilised and transferred to ground or surface water. Additionally, the rate of the reaction may be reduced since the oxidation products form a barrier to further oxygen penetration.

This investigation focuses on the remediation of coal discard, in the Mpumalanga region of South Africa where it is estimated that 82% of the total coal production takes place (Department of Minerals and Energy Affairs, 1998). The aim of the research project has been to assess the performance of existing dumps and to determine whether available soils in the area provide a suitable cover to limit AMD generation.

The distribution of coal mining activities in South Africa has been reported in detail in Vermaak et al. (2002) and will not be repeated here. The re-commissioning of thermal power stations in the Mpumalanga area to meet the current energy demands will result in additional mining of coal, including poor grade resources with concomitant increases in discard dumps. The need for a suitable cover that limits the cumulative impact of the current and future dumps is therefore apparent.

Mpumalanga Province can be divided into two areas for the purposes of discussions on climate. There is the higher lying grassland savannah Highveld area and the area below the escarpment, the subtropical Lowveld area. Most of the coal discards are associated with the Karoo sediments that underlie the Highveld region of Mpumalanga. The climatic data of importance for this study is therefore that relating to the higher-lying regions around Witbank and Middelburg. The area is in the summer rainfall area and is concentrated in the early summer (Schulze et al., 1997). The mean annual precipitation is in the range of 600-800mm (Schulze et al., 1997). The mean potential evaporation estimated from A-pan evaporation data is 1 946mm (Schulze et al., 1997), which makes this a water-deficit area, since potential evaporation exceeds precipitation. The mean daily temperature for December is 20.5°C (mean daily maximum of 24.6°C and mean daily minimum of 14.7°C) and for June is 11.5°C (mean daily maximum of 19.1°C and mean daily minimum of 3.8°C) (Schulze et al., 1997). The growing season is from late September or early October to late March or early April (Schulze et al., 1997).

2.1.1 Problems with existing covers

The performance of existing covers on coal discards in Mpumalanga and the northern part of KwaZulu-Natal are discussed in Chapter 3.

Internationally, compacted clay has been the cover type often specified for mine rehabilitation and landfill covers. Many studies have therefore been undertaken to determine the efficacy of such systems. As with most cover types discussed in this chapter, there are additional layers to protect the layers that provide the waterproofing element of the cover and also to provide a supporting substrate for vegetation. Figure 1 is a schematic diagram of one possible configuration comprising of a layer to support vegetation over the waterproofing layer.

Compacted clay is used as a barrier layer in covers because of its low saturated hydraulic conductivity. When placed with adequate care and construction quality assurance, permeabilities of 10^{-9} m/s or lower, can be attained. The proportion of fine-grained particles (clay and silt size) and clay content are important in selecting the source of material. In addition, it is recommended that the clay be compacted wet of the optimum water content, as determined from laboratory compaction tests (Standard or Modified AASHO or Standard or Modified Proctor tests, Rowe et al., 1997). Daniel and Benson (1990) showed that the hydraulic conductivity of compacted clay was reduced by two to three orders of magnitude when the clay was compacted 2% wet of optimum, compared to values obtained at optimum water content. When placed at these high water contents, however, care must be taken to ensure that the shear strength and associated stability of the soil are not compromised as this could lead to slope failures within the cover (Daniel and Benson, 1990). According to Blotz et al. (1998) "compaction control is often the most significant factor affecting the behaviour of compacted fine-grained soil".

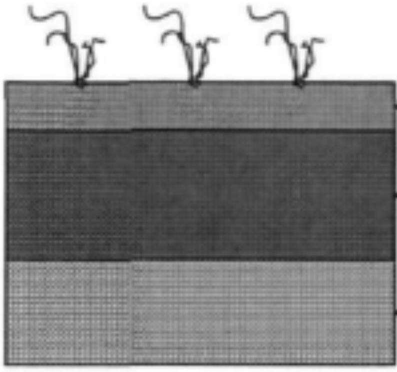

Figure 1:Configuration of a capping systems using compacted clay

The compacted clay limits acid mine drainage since it does not allow large volumes of percolation, and if it retains sufficient moisture in the layer, the movement of oxygen is also limited. Precipitation runs off and only a small proportion is expected to pass through into the discard.

Disadvantages of compacted clay layers are that they are prone to desiccation and cracking (Daniel and Wu, 1993 and Brauns et al., 2000) even when covered by protective layers of soil (Melchior, 1997). The water content in compacted clay layers has been shown to vary seasonally due to changes in precipitation and evaporation (Khire et al., 1997).

Shrinkage due to drying is increased as the clay content and plasticity of soils is increased (Albrecht and Benson, 2001). In addition, shrinkage is increased if the soil is compacted either wet or dry of optimum (Albrecht and Benson, 2001). The increase in hydraulic conductivity as a result of desiccation cracks can be up to three orders of magnitude (Albrecht and Benson, 2001). Compacted clay, due to its plasticity, swells when rehydrated and this enables some of the cracks to be partially closed. However, according to experimental work of Albrecht and Benson (2001), clays do not return to their pre-drying hydraulic conductivity even after extensive permeation.

Various studies have shown that the performance of compacted clay covers deteriorates over time, primarily as a result of desiccation, even in temperate climates, but primarily in arid and semi-arid climates (Melchoir, 1997, Dwyer, 1998 and Wagner and Schnatmeyer, 2002). Covers are not subjected to high compressive stresses and this leads to increases in the hydraulic conductivity of coves as they are subjected to drying (Albrecht and Benson, 2001). Additional disadvantages with compacted clay covers are that they are not resistant to subsidence or differential settlement, cracking, freeze/thaw cycles and root and animal intrusion (Suter et al., 1993). Compacted clay is cohesive and therefore during movements caused by differential settlement, cracks develop. Cohesionless materials (e.g. sand) are able to move without the formation of tension cracks. Freeze thaw cycles are not considered here, as this is not a common occurrence in South Africa, particularly in Mpumalanga. Roots were discovered to have grown into a compacted clay cover test section to a depth of more than 1.6m below the layer of soil designed to support vegetation (Melchior, 1997). These roots open cracks and also leave preferential flow paths if they die back.

Given the many concerns with regard to compacted clay capping systems, particularly in dry climates, alternative cover systems should be considered. The primary function of the compacted clay layer (sometimes referred to as a resistive layer) is to limit moisture percolation. For AMD prevention, compacted clay is also used to reduce oxygen fluxes by maintaining high water content. Various cover configurations are described in Section 2.1.2. Some of these covers include compacted clay layers that are protected from desiccation by geomembranes or sand layers above and below them. The remaining covers use other soils types.

2.1.2 Alternative covers

Internationally, various soil cover types were investigated and commissioned for use in mining and municipal or hazardous waste landfill applications. The choice of final cover depends largely on the nature of the waste to be covered and the prevailing climatic conditions. According to the Australian Department of the Environment (1998), the annual rainfall and distribution arguably has the greatest influence on the design of stable landforms. The advantages and disadvantages of a few cover types are described here.

Composite covers with geosynthetics

Multi-layer composite caps (MLCs) are composed of up to seven layers. The primary feature, however, is the geomembrane layer placed directly onto a moist compacted clay layer or geosynthetic clay liner (GCL)[1] (Kim and Benson, 2004). This combination forms a barrier to both liquid and gas-phase transport.

Geomembranes are considered almost impermeable to water. However, hydrophobic substances such as toluene are able to pass through geomembranes of low hydraulic permeability (Park et al., 1996 and Rowe, 1999). Further, even the most carefully placed geomembranes are found to have small holes (Giroud and Bonaparte, 1989). Moisture flow through holes in the geomembrane is limited by the presence of the low permeability clay layer or GCL below. Similarly, the low permeability of the geomembrane limits upward movement of moisture from the clay or GCL, thereby giving protection against desiccation due to evapotranspiration.

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[1] GCL's are thin layers of sodium bentonite (less than 10mm) held between two layers of geotextile (La Gatta et al., 1997 and Daniel et al., 1998). When hydrated, the sodium bentonite swells as it retains a thick layer of water around the clay particles (Mesri and Olson, 1991), but the fibres holding the two layers of geotextiles (stitching or needle punched fibres) resist the swelling. This results in the GCL having very low hydraulic conductivity.

Although research has indicated that geomembranes can last for hundreds of years (150 to 350 years at 25°C and 12°C, respectively, Rowe, 1999), geomembrane integrity with age (i.e. durability) is as yet, unknown. Antioxidants in geomembranes may be depleted in as little as 11 years at 60°C or 40 years at 30°C (Hsuan and Koerner, 1998). As temperature increases, the loss of antioxidants from the geomembranes increases and they become brittle.

Multi-layer composite caps (MLC) are composed of up to seven layers as shown in Figure 2. These are (from top to bottom) a) vegetated layer b) protection layer c) drainage layer d) geomembrane e) compacted clay layer or GCL f) base layer and g) grading layer.

The primary path for oxygen diffusion through a MLC is through the holes in the geomembrane (Kim and Benson, 2004). Moisture in the clay layer or GCL limit further movement of oxygen through the cover as the diffusion coefficient of oxygen is 10 000 times lower through water than through air (Weast, 1985, see also Section 2.2.2). A limited amount of oxygen may also be consumed in the root zone as a result of biological activity or chemical oxidation (if minerals capable of being oxidised are present).

As discussed in Section 2.1.1, compacted clay is prone to desiccation. This is also true of GCL's. Melchoir (1997) reported desiccation of two types of GCL's within the first year after placement. The site received 865mm/a precipitation, spread almost evenly throughout the year. Wetting of the GCL did not significantly reduce the percolation rates.

An additional problem arising with multi-layer systems in covers is the issue of stability. Layers of materials in the cover systems are not subjected to high compressive stresses, and therefore only low shear strengths can be mobilised. The interface shear strengths between the various layers must be considered to avoid failure (Koerner and Soong, 1998). Much information on interface design has been collated for designs of liner systems and this can be used when designing cover systems (Stark et al., 1996, Koerner and Soong, 1998, Giroud, 2000, Esterhuizen, 2002 and others).

Although MLCs limit both oxygen and moisture movement through the capping system, they have some associated disadvantages. These include the indeterminate durability of the geomembrane, desiccation of the GCL or clay (including by heat within the waste impoundment), high cost of geomembranes and GCL's, possible transportation of clay to site and slope stability issues. According to Daniel (1994), the ability of these covers to meet long-term design objectives is doubtful. The US EPA lists this cover type as a subtitle C cover used for hazardous waste landfills (Resource Recovery Act). The design guidelines for the subtitle C cover state that this type of cover "is not very effective" in arid regions (Dwyer, 1998).

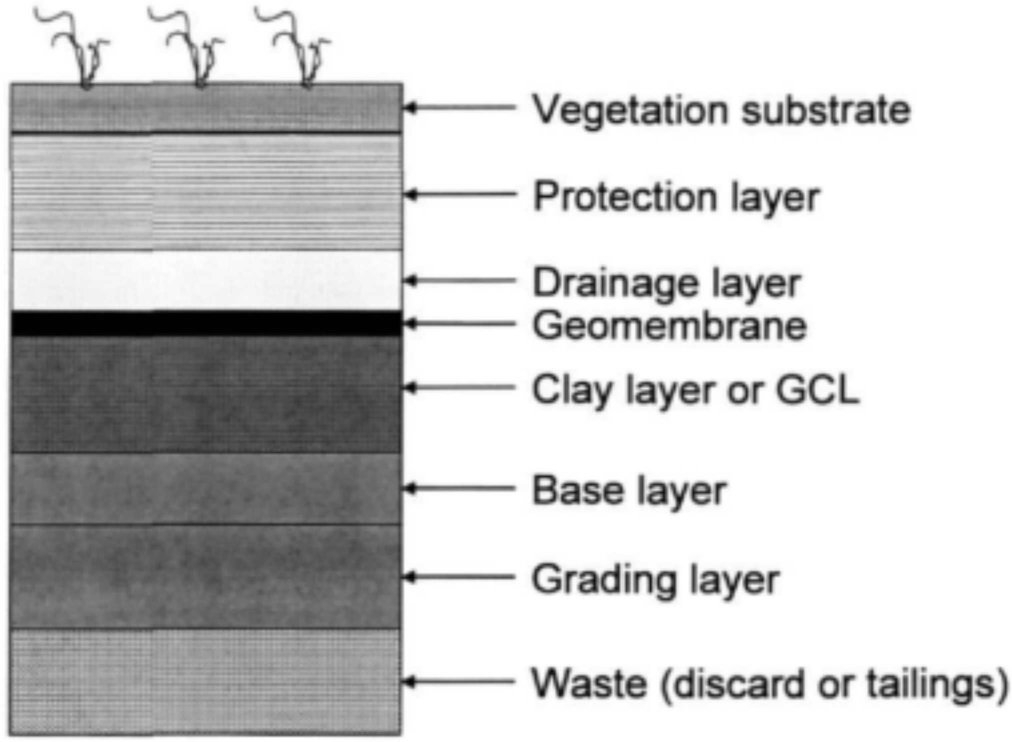

Figure 2: Components of a multi-layer composite cap (after Kim and Benson, 2004)

Wet cover systems

In Canada, a cover type known as "wet covers" has emerged. The primary function of this cover type is to reduce AMD production by limiting oxygen ingress through the inclusion of a moisture retaining layer. At the same time, moisture percolation is also limited. Various covers of this type have been proposed and evaluated (e.g. Nicholson et al., 1989, Yanful et al., 1993a and b, Woyshner and Yanful, 1995, Yanful et al., 2003 and Swanson et al., 2003).

The cover design investigated by Nicholson et al. (1989) used a fine-grained soil over a coarser material. Moisture is stored in the fine grained material overlying the coarse material and is prevented from downward migration by the break or discontinuity in capillary pressure at the interface between the coarse and the fine layer. This phenomenon is the same as that discussed later in Section 2.4 and is termed a capillary barrier effect. In addition to the moisture storage in the fine layer, which reduces the oxygen flux into the lower layers, moisture movement into the waste dump is limited. AMD production is therefore reduced through limiting both oxygen and moisture availability. An expected decline in oxygen flux of four orders of magnitude for a 1m thick cover has been suggested (Nicholson et al., 1989). It was suggested that the fine-grained soils used should be in the medium to fine silt range because clay has the disadvantages of desiccation and placement problems. Alternative sources of fine-grained material included processed tailings with low sulphide content or even thickened tailings (Robinsky, 1979), which would not suffer from segregation problems (Nicholson et al., 1989).

Yanful et al. (1993a and b), Woyshner and Yanful (1995) and Yanful et al. (2003) investigated a different design for moisture retaining covers. The cover comprised of a gravel erosion protection layer, a granular layer (0.3m), compacted clay or moisture retention layer (0.6m) and a sand base layer (0.3m) (Figure 3). The cover also relied, in part, on the capillary barrier effect introduced by the sand under the compacted clay. The top granular layer reduced evaporative loss from the clay by an estimated 40% (Yanful et al., 2003) and protected the compacted clay layer from freeze/thaw effects (Yanful et al., 2003b).

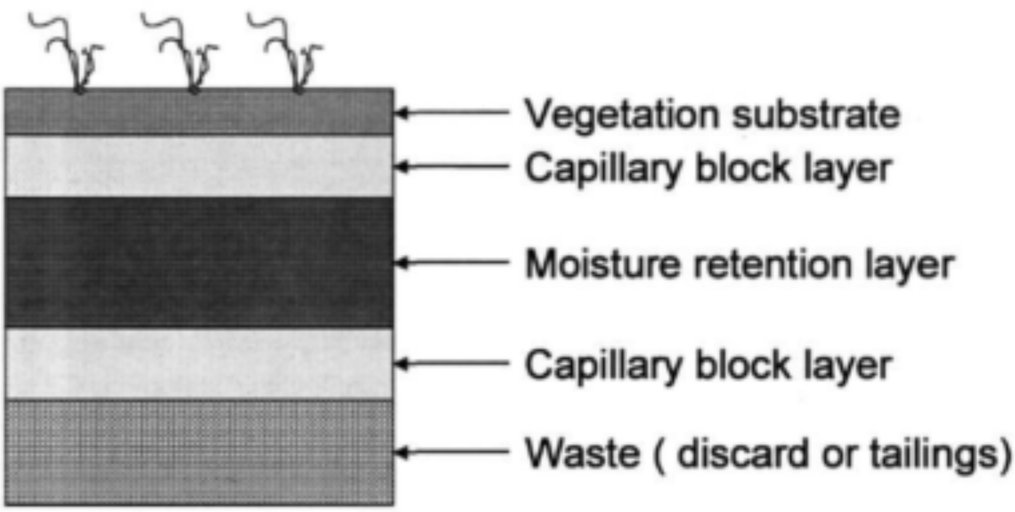

Figure 3: Schematic diagram of a moisture retaining barrier (Yanful et al., 1993a and b)

The compacted clay layer consisted of glacial till, compacted to 95% of the maximum Modified Proctor dry density and was placed at 2-3% wet of optimum water content. It was placed at the maximum degree of saturation which could withstand the design shear force. The undrained shear strength was estimated from Leroueil et al. (1992).

The cover reduced oxygen concentrations from 20% (atmospheric oxygen concentration) to 3% and reduced temperatures in the waste pile due to limitation of the exothermic oxidation of sulphide (Yanful et al., 1993b). Percolation of 2 to 2.5% of precipitation was recorded during a 55 day period of heavy rainfall, although the water content of the compacted till remained almost unchanged after the first year of monitoring (Yanful et al., 1993b). No significant improvement in the seepage quality could be observed during the year of monitoring (Yanful et al., 1993b).

Saturation can be maintained in a fine-grained layer between two coarser layers, even if the water table is far below the depth of the cover. According to Akindunni et al. (1991), no infiltration is necessary to maintain this condition if evaporation is neglected and an appropriate cover thickness are chosen. The two characteristics that must be assessed to determine the cover thickness are the air entry value of the cover layer (Section 2.2.3) and the pressure head at which the residual water content[3] in the lower layer is approached (Akindunni et al, 1991).

Reactive barriers

One approach to limiting oxygen movement through the cover system is to introduce materials that consume oxygen and thereby reduce the potential for oxidation of reactive wastes. Various oxygen-consuming layers have been suggested in conjunction with other cover types discussed in this chapter. Oxygen consuming layers may be part of the protection or vegetation substrate or a separate layer in a multi-layer system.

Cabral et al. (2000) suggested the use of an organic layer, in particular, a paper pulp. Suggestions of the inclusion of small amounts of iron sulphide, in the form of pyrite or purrhotite, have also been made (Mbonimpa et al., 2000). However, moisture movement through a sulphide-bearing layer would also result in AMD, since the same mass of oxidation products would be produced (whether within the cover or the main body of waste).

An alternative to oxygen consumption in the cover is to add chemical layers that are able to buffer acids formed by oxidation. Any water percolating through the cover dissolves these chemicals and carries them into the waste body where they react with acids, thereby neutralising the acids. As a result of the increased pH, fewer metals are solubilised and the resulting leachate quality is improved. However, this layer will ultimately be depleted, and therefore its buffering capacity and initial thickness must be designed to exceed the acid production potential of the waste body.

Doye and Duchesne (2003) reported on a series of experiments where reactive tailings were amended with alkaline industrial residues in order to produce a fine material suitable for a moisture retention layer in a wet cover system or capillary barrier. The alkaline industrial residues used were cement kiln dust and red mud bauxite. They listed the objectives as chemical precipitation to limit chemical transport to and from the sulphide minerals, oxide or hydroxide sorption or co-precipitation of trace metals, and reduction in bacterial growth. At concentrations of 10%, the kiln cement was effective in maintaining neutral pH throughout the 365 day study and reduced metal concentrations in the leachate compared to reactive

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[3] Defined as the water content at which a large increase in suction is required to draw further moisture from the soil.

tailings. The results using red mud bauxite showed less improvement than those with cement kiln dust.

Another potential method of buffering is the addition of lime. It is reported that this method is most effective when in contact with fine-grained acid-generating material (Hodgson and Krantz, 1998). For coal discard, the open structure may allow percolation without effective reaction with acids produced. The use of lime has been found to be effective, despite encrustation with aluminium, iron and hydroxides (Cravotta and Trahan, 1999). Lime kiln dust was used at Kaufmann Mine in Pennsylvania to reduce AMD at a coal mine with pyritic overburden (Rose et al., 1995). Kiln dust was placed on the surface prior to blasting mixed in during material handling while additional lime was placed on the pit floor prior to the placement of topsoil.

An alternative would be to replace the lime with coal power station ash. Large amounts of ash are produced by coal burning power stations in the Mpumalanga region. However, the acid neutralisation capacity of ash is only 5-16% of that of lime (Hodgson and Krantz, 1998). Further, the ash contains high concentrations of heavy metals that could be leached by acid in the coal discard if the acid is not sufficiently neutralised. The potential use of ash in store-and release covers is considered in Chapter 5.

Store-and-release covers, evapotranspirative or monocovers

Store-and-release covers, evaporative covers and monocovers are all names given to the same cover system. The cover comprises a layer of silty to sandy material or even clays with low plasticity, which is able to store moisture during high precipitation events and then releases it through evaporation or transpiration. By varying the thickness of these covers, the storage potential can be manipulated.

Unlike compacted clay layers, the store-and-release layer does not function as a barrier to water flow, but absorbs the water rather like a sponge would before releasing it again (Zornberg et al., 2003). Advantages of these covers are that they require low maintenance and can be constructed with a broad range of soils. If constructed with silts and clay with low plasticity, they have low susceptibility to both desiccation cracking and to cracking due to differential settlement.

Not much information is available for covers of this nature, although they appear to have potential for application in South African conditions. They are therefore one of the cover types considered in detail in this investigation. The study by Vermaak et al. (2002) on cells constructed at Kilbarchan described the intended cover configurations as store-and-release covers. The soils used in the construction, however, do not meet the criteria for soils suitable for store-and-release covers generally presented in the current literature. A more detailed discussion of material selection and the mechanisms of storage is given in Section 2.3. Further discussion of the soil parameters of the Kilbarchan cells is presented in Section 2.3.2.

Covers with capillary barriers

Covers with a fine-grained layer overlying a coarse-grained layer have the potential to behave as capillary barriers. If the particle size contrast between the two layers is appropriate, the coarse layer causes storage of moisture in the fine-grained material (Smesrud and Selker, 2001). The fine-grained layer can in itself be a store-and-release cover such as that described above or a moisture retaining layer within a cover. Capillary barriers may therefore be used in dry or wet climates.

The thickness of the fine-grained layer determines the amount of moisture that can be stored for evapotranspiration. In addition to increasing the moisture storage in the fine-grained layer, water in this layer can drain laterally along the interface with the coarse layer if the cover is sloped. By draining moisture, the need for moisture storage can be managed.

Many examples of capillary barrier performance and design have been reported in the literature (Ross, 1990, Melchior, 1997, Khire et al., 2000 etc). Since this cover type is considered to have potential for rehabilitation of coal discards, Section 2.4 contains a detailed discussion on the mechanism for moisture retention in the double layer systems and various design considerations.

2.2 Background theory

2.2.1 Acid mine drainage formation

Acid mine drainage typically has a pH of 2-3 and has high concentrations of sulphate, iron, and sometimes heavy metals such as zinc, copper, lead and cadmium (Choo and Yanful, 2000). If AMD is then flushed from the mine discard it can pose significant threat to surface or groundwater resources.

Acid mine drainage is the result of oxidation of sulphide-rich minerals. When minerals containing sulphide, particularly pyrite (FeS_2) comes into contact with oxygen and water, the oxidation can result in highly acidic pore water in the absence of sufficient quantities of solid buffer material (Nicholson et al., 1989). The oxidation produces H_2SO_4 which lowers the pH in solution (Yanful et al., 2003 and Doye and Duchesne, 2003). At low pH, certain metals are solubilised and removed in solution (e.g. Cu and Zn).

The oxidation of sulphide is rapid when mediated by the bacteria, *Thiobacillus ferroxidans*, at shallow depths where oxygen is present (Nicholson et al., 1989). The optimal pH range for the bacterial activity is 1.5-3.5 (Nicholson et al., 1989). These bacteria oxidise aqueous Fe^{2+}

to Fe^{3+} which is then the principal oxidising agent of sulphide in both aerobic and anaerobic conditions (Doye and Duchesne, 2003). The ferric iron (Fe^{3+}) is able to oxidise other sulphide-bearing minerals, other than pyrite, and may cause metals to be released from galena, sphalerite and chalcopyrite (Yanful et al., 1993a).

Field studies on uranium ores have shown that typical oxidation zones extend 0.5–3m below the tailings surface (Feenstra et al., 1981, Smyth, 1981 and Dubrovsky et al., 1985a). The oxygen concentrations in the voids drop rapidly with depth. The depth of detectable oxygen is greater in coarse-grained than fine-grained soils (Nicholson et al., 1989).

2.2.2 Oxygen transfer

Movement of oxygen through fine-grained soil is mainly by molecular diffusion (Yanful, 1993 and Mbonimpa et al., 2003). This diffusion essentially occurs in the air phase at a degree of saturation below approximately 85-90% (Aubertin and Mbonimpa, 2001 and Aachib et al., in prep). Corey (1957) found that at greater degrees of saturation the air phase becomes discontinuous and oxygen flux also occurs through water-filled voids. When the oxygen movement is through water, it is limited by the maximum concentration of oxygen in water (Nicholson et al., 1989 and Mbonimpa et al., 2003), which is about 30 times less than the equilibrium constant in air (Mihelcic, 1998).

Diffusion is commonly evaluated using Fick's laws for both aqueous and gaseous phases. Spatial and temporal variations in concentration of oxygen are related to the effective diffusion coefficient which depends on void volumes in the material, tortuosity, volumetric water content and the diffusion coefficient of oxygen in an unobstructed medium, in this case, the cover soil (Rowe et al., 1997, Lim et al., 1998 and Mbonimpa, 2003). Diffusion through water-filled voids is much slower than through air-filled voids because the free diffusion coefficient (i.e. in an unobstructed medium) for oxygen is about 10 000 times lower in water than in air (Weast, 1985).

Rowe et al. (1997) noted that the tortuosity for clay materials is related to the geometric tortuosity (L/Le)[3], which decreased fluidity due to the double layer of water molecules adsorbed to clay particles and electrostatic interaction. Further, geometric tortuosity is considered a reasonable approximation for the tortuosity of granular materials.

[3] Defined as the ratio of the macroscopic distance across a soil to the actual length of the diffusion pathway across the soil.

In order to determine the effective diffusion across unsaturated soils of varying texture, a comprehensive testing programme is often required at different stress levels (Lim et al., 1998). However, Lim et al. (1998) proposed a model based on testing of three soil types at varying degrees of saturation, but noted that further verification of the model was required.

2.2.3 Soil water characteristic curves and unsaturated hydraulic conductivity

In developing an understanding of the mechanisms of moisture movement through cover materials, an important concept is that of unsaturated hydraulic conductivity. Covers are subjected to precipitation, drainage and evapo-transpiration and therefore the level of moisture in the cover varies, but is often below saturation. Detailed descriptions of the theory of water flow under unsaturated conditions and related topics are provided in the literature (e.g. Fredlund and Rahardjo, 1993), but only a brief discussion is included here to aid in the understanding of the discussions presented in subsequent sections of the report.

Equations to describe the soil water characteristic curve

The soil water characteristic curve (SWCC) or water retention characteristic curve describes the relationship between the water content (gravimetric or volumetric water content) or degree of saturation and suction (negative pressure) within a soil. It is the basis for prediction of other soil parameters under unsaturated conditions, such as the hydraulic conductivity. It can be described from two perspectives: drying of a soil or wetting of a soil. The resulting curves are not the same as there is some hysteresis, however, soils are subjected to both wetting and drying and therefore both curves should be determined (Figure 4). In most cases, the SWCC data presented are those derived from progressive drying of a soil sample (by application of increased negative pressures).

The soil suction as quantified in terms of relative humidity is commonly called total suction. Total suction has two components namely matric and osmotic suction. Matric suction is defined as the difference between the pore-air pressure (u_a) and the pore-water pressure (u_w) (Fredlund and Rahardjo, 1993 and Fredlund and Xing, 1994). Osmotic (solute) suction on the other hand is defined as the "partial pressure of water vapour in equilibrium with a solution identical in composition with the soil water, relative to the partial pressure of water vapour in equilibrium with free pure water" (Fredlund and Rehardjo, 1993). At suctions greater than about 1 500kPa (approximately 150m of negative pressure), the total and matric suctions can be assumed to be equivalent (Fredlund and Xing, 1994). For the purposes of this discussion, no differentiation is made between the two.

If a soil sample is initially saturated, the moisture in the voids is retained against low suction (Figure 4). As the suction increases, the tension forces holding water in the voids are unable to hold water in the larger pores and air is able to enter. The suction at which this first occurs is the air entry pressure (for consistency in interpretation of this value, tangents are drawn to best fit the three sections of the curve; the first intersection is the air entry value). Further increases in suction rapidly drain moisture from the soil to the residual water content (the second intersection of tangents).

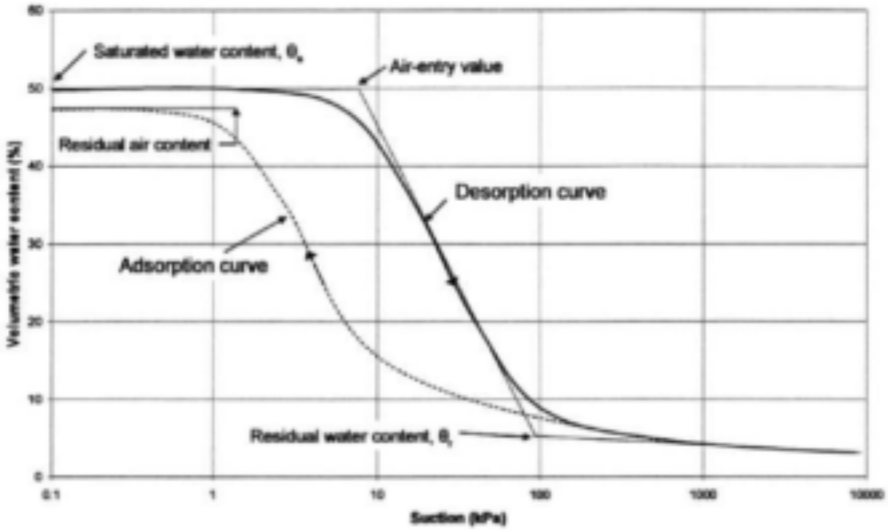


Figure 4: Typical SWCC for a silty soil (after Fredlund and Xing, 1994)

The wetting or adsorption curve does not return to the saturated water content of the soil at low suction values (Figure 4). A residual amount of air is left in the pores (residual air content). It is reported that hysteresis is less pronounced for coarse grained soils than finer grained soils (Yang et al., 2004b). In addition, hysteresis of uniform soils is less than that of less uniform soils (Yang et al., 2004b). SWCCs for soils vary. In general, finer soils have higher initial water contents at saturation and higher air entry values. A statistical analysis of a large data set indicated that the hydraulic properties of soils are related to their textural properties (Cosby et al., 1984). It is reported that the suction corresponding to zero water content is essentially the same for all soils; a suction slightly below 10^6kPa from laboratory tests (Croney and Coleman, 1961) and theoretical evaluations (Richards, 1965).

Empirical equations are used to fit soil SWCCs to laboratory data (a detailed history of the development of various models is presented in Barbour, 1998). Two equations are presented here: the van Genuchten model (1980) and the model of Fredlund and Xing (1994). The model of Fredlund and Xing is used in the finite element model *SoilCover* for modelling of alternative covers in later sections of this report. The van Genuchten model is commonly used in the literature (Webb, 1997, Stormont and Morris, 1998, Stormont and Anderson, 1999, Khire at al., 2000 and Miller et al., 2002). Both are sigmoid curves fitted using four parameters and give better estimations of the SWCC than non-sigmoid curves (Leong and Rahardjo, 1997a).

The van Genuchten model uses curve fitting parameters α, n and m as shown below.

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

where:

θ	is the volumetric water content
ψ	is the corresponding suction
θ_s	is the volumetric water content at saturation
θ_r	is the residual volumetric water content
α, n and m	are curve fitting parameters.

The effect of the three fitting parameters is described by Leong and Rahardjo (1997a). Parameter α shifts the curve to the left and right, relative to the suction on the x-axis. The curve is rotated about the halfway point between the air entry value and the residual water content (using the points of intersection shown in (Figure 4) by the value of n. Parameter m rotates sloping portion of the curve and the lower plateau (last tangent in (Figure 4). The model of Fredlund and Xing (1994) is used with a correction factor and is shown below:

$$\theta = \left[\frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{1000000}{\psi_r}\right)}\right] \frac{\theta_s}{\left\{\ln\left[e + \left(\frac{\psi}{a}\right)^n\right]\right\}^m} \qquad \textbf{Equation 2}$$

where:

ψ_r is the suction corresponding to the residual volumetric water content

a, n and m are curve fitting parameters.

The first term in square brackets is a correction factor. When ψ_r is equal to 10^6 kPa, then the correction factor is zero and the water content is also equal to zero (Fredlund and Xing, 1994). This is based on the observations of Croney and Coleman (1961). The parameters a, n and m have effects corresponding to α, n and m of the van Genuchten model on the position and shape of the curve (Leong and Rahardjo, 1998).

Leong and Rahardjo (1998) found that the Fredlund and Xing (1994) equation best fitted data sets during comparative modelling. However, they note that ψ_r should not be interpreted as the suction corresponding to the residual water content, θ_r, although this was the interpretation presented by the original authors. Leong and Rahardjo (1997a) further favour the form of the equation with the correction factor equal to one, based on sensitivity analysis.

The laboratory testing procedure required to determine SWCCs is very slow, particularly for very fine-grained soils such as clays, although a new testing method by Khanzode et al. (2002) can be used to obtain rapid results. Estimating the SWCC from particle-size distributions has also been investigated (Gupta and Larson, 1979 and Fredlund et al., 2002). The model by Gupta and Larson (1979) included bulk density explicitly, while Fredlund et al., (2002) used a packing factor derived from a neural network trained on published data for clays. A useful model based on basic geotechnical properties is proposed by Aubertin et al., (2003). The values required include the effective diameter (D_{10}) and uniformity coefficient (Cu) that can both be obtained from a particle-size distribution; liquid limit (L_L); void ratio (e) and soil grain density (G_s). SWCCs used in later sections of the report were derived from laboratory testing.

Application of four SWCCs to soils of varying compaction levels by Miller et al. (2002) indicated that there was poor correlation between predicted and measured residual water contents. There was also a discrepancy between models in water content prediction in the 0 to 100kPa range where no measurements were taken. Models should thus not be extrapolated past the measured range of suction values. In general, the water content at the same suction head increased with increased compaction effort and was also lower for soils compacted wet of optimum. As the clay content and plasticity index of the soil increased, so the air entry value also increased. The impact of compaction was greater for high plasticity soils than for low plasticity soils. A reasonable correlation was found between SWCCs for soils compacted in the laboratory and in the field, however this was not the case in tests by Prapaharan et al. (1991).

Coal discard has dual porosity: flow can occur between particles (macropore flow) or through the porous particles (micropore flow). A similar situation of dual porosity of sand and diatomaceous earth mixtures has been investigated by Burger and Shackelford (2001) a) and b). They found that the data could be best represented by splitting the data at the point where the macroscopic porosity appeared to have been completely desaturated and the micropores began to drain under increasing suction. SWCCs were then fitted to the two sections of data. The best fit to the dual porosity mixtures was visually assessed to be the van Genuchten model, although a Fredlund and Xing (1994) model using 8 fitting parameters (instead of the four discussed earlier) also showed a good fit. This procedure was followed for determining the SWCC of the coal discard.

Predicting hydraulic conductivity of unsaturated soils

A general misconception that was held for decades was that water flow in soils occurred only in the saturated zone and capillary fringe zone (Barbour, 1998). It has, however, been recognized that flow occurs under unsaturated conditions. The unsaturated hydraulic conductivity of a soil is a unique function of the water content of the soil (Fredlund et al., 1994).

Direct measurement of unsaturated hydraulic conductivities at varying suctions has associated problems. These include: the long time required to obtain the data, especially a very high suction values; measurements must be very accurate because of the low flow rates; an osmotic suction gradient may develop between the soil and the water used in the evaluation and finally as the suction increases the sample may shrink (Leong and Rahardjo, 1997b). Simms and Yanful (2004) also reported that changes in pore volumes occurred during direct measurement of both the unsaturated hydraulic conductivity and SWCC.

Given the complexities of direct measurement of unsaturated hydraulic conductivities, semi-empirical correlations are often used to derive a function of unsaturated hydraulic conductivity (Meerdink et al., 1996). Again, only two of these models are discussed. The first is the Mualem-van Genuchten model and the second is that of Fredlund et al. (1994). As with the SWCC, the Mualem-van Genuchten model is frequently used, while the Fredlund et al. (1994) model is adopted in *SoilCover*.

Van Genuchten (1980) developed a closed form equation to describe the relationship between suction and hydraulic conductivity. The SWCC described earlier, was substituted into a model developed by Mualem (1978) to derive the expression of relative hydraulic conductivity shown below. The relative hydraulic conductivity is the ratio of the hydraulic conductivity at the required suction to the saturated hydraulic conductivity.

$$K_r(\psi) = \frac{\left\{1-(\alpha\psi)^{n-1}\left[1+(\alpha\psi)^n\right]^{-m}\right\}^2}{\left[1+(\alpha\psi)^n\right]^{m/2}}$$ **Equation 3**

where:

K_r is the relative hydraulic conductivity function ($K_r = K_\psi / K_s$)

α, n and m are the fitting parameters from the van Genuchten (1980) SWCC

Fredlund et al. (1994) combined the SWCC described in the above section with a function derived by Childs and Collis-George (1950) that describes the relative coefficient of permeability in terms of suction. The resulting expression is presented below.

$$K(\psi) = \frac{\int_{\ln \psi}^{b} \frac{\theta(e^{y}) - \theta(\psi)}{e^{y}} \theta'(e^{y}) d\psi}{\int_{\ln \psi_a}^{b} \frac{\theta(e^{y}) - \theta_0}{e^{y}} \theta'(e^{y}) d\psi} \quad \textbf{Equation 4}$$

Where:

θ' is the derivative of the Fredlund and Xing (1994) SWCC with respect to ψ

y is a dummy variable of integration representing ln ψ

b is $\ln(10^6)$

ψ_a is the air entry pressure

Both van Geuchten (1980) and Fredlund et al. (1994) showed good fit between measured and predicted values of unsaturated hydraulic conductivities.

For two soils under investigation by Meerdink et al. (1996), the Mualem-van Genuchten model under predicted hydraulic conductivity by an order of magnitude at low suctions (<100kPa) and by more than four orders of magnitude at higher suctions (>1 000kPa). The Fredlund et al. (1994) model under predicted the function for one soil to the same extent as the Mualem-van Genuchten model, but the second soil it provided a reasonable estimate.

Meerdink et al. (1996) suggested that the reasons for the poor fit were that there was insufficient data to describe the SWCC adequately at low suction and that the models describe flow through a set of capillary tubes, which did not capture the complexities of flow through unsaturated soils. Chui and Shackelford (1998) also found that the Mualem-van Genuchten model under predicted unsaturated hydraulic conductivity (no comparative assessment of the Fredlund et al. (1994) model was presented).

Soils compacted at higher compaction effort (Modified Proctor effort) were found to have unsaturated hydraulic conductivities an order of magnitude lower than those compacted at lower compaction effort (Standard Proctor effort) at the same suction (Meerdink et al., 1994). Three soils were tested under unsaturated conditions. The moisture retained in all of the pores of two of the soils was fully mobilised during flow (Maraqua et al., 1997). However, for the third soil, only a proportion of the moisture was mobile and there was no mass transfer between the flowing water and immobile water (Maraqua et al., 1997).

SWCCs and the corresponding unsaturated hydraulic conductivity is used both for movement of moisture into covers and evaporation from soils (Yanful and Mousavi, 2003). Since both models presented here under predict flow under unsaturated conditions, alternative models could be assessed (Schaap and Leij, 2000) or model predictions should be compared with flume test or field data for proposed cover designs.

2.3 Store-and-release covers

Conventional covers rely on a resistive or barrier layer (clay, GCL or geomembrane) to limit moisture ingress into waste or mine discard (Albright et al., 2003 and Zornberg et al., 2003). Recent studies have been initiated to consider the effectiveness of covers that rely on water-storage mechanisms (Albright et al., 2004). Although the cited literature has focussed on store-and-release covers in the solid waste and hazardous waste arena, there is potential for their application in the mine waste industry in South Africa.

Store-and-release covers are also called monocovers because they consisted of a single layer of material to store moisture (Figure 5). Their main function is to limit rainfall infiltration into the waste. Store-and-release covers rely on evapotranspiration potential to remove soil water from the cover before it infiltrates the wastes and should have the ability to retain and store rainfall water in the cover and also promote upward movement of soil water.

A typical configuration for a store-and-release cover comprises a topsoil layer and a moisture retention layer. The topsoil layer consists of nutrient-rich soils to provide a growth medium for vegetation and to assist in evaporation from the soil surface. The purpose of the moisture retention layer is to retain and store infiltrating rainfall water and to promote upward movement of soil water by evapo-transpiration. The thickness of the layer can be chosen in such a way that it can be vegetated and that the root penetration does not extend into the required zone for storage. Root penetration should be prevented as preferential flow paths may form along the roots and influence the performance of the layer.

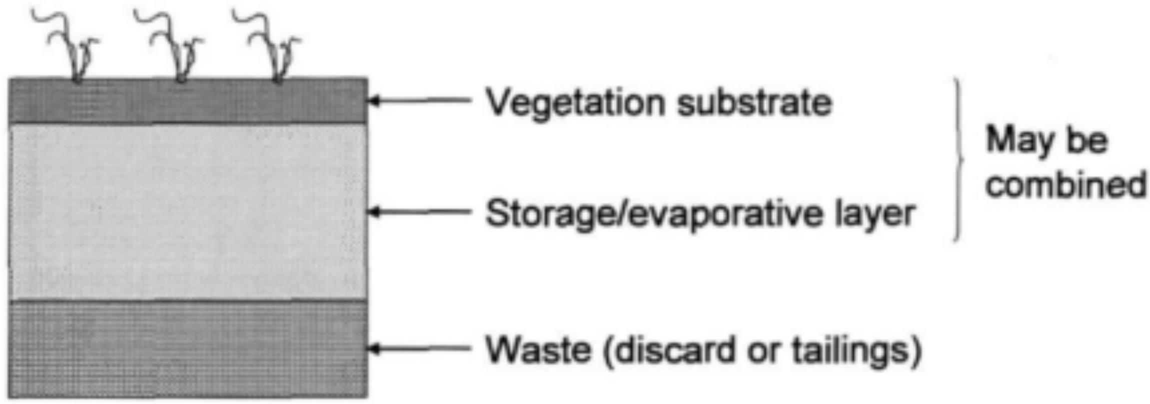


Figure 5: Schematic diagram of a store-and-release cover

Store-and-release covers are constructed of soils that have low susceptibility to desiccation cracking, for example, silts and low-plasticity clays (Zornberg at al., 2003). Although these soils have higher saturated conductivities than those used in resistive barriers, they are expected to perform better in the long term than conventional covers in arid and semi-arid climates. Design of these covers is site-specific as the storage potential of the cover must take into account the expected local weather conditions (Zornberg at al., 2003).

2.3.1 Moisture storage potential and material selection

The design of store-and-release covers depends on climatic conditions, soil properties and plant characteristics at the site (Albright et al., 2003). Where the growing season is short, the cover thickness needs to be increased to provide additional storage. Unlike resistive barriers that maximise overland flow, store-and-release barriers act as a sponge or reservoir to store moisture during precipitation events and then release it through evapo-transpiration (Zornberg et al., 2003). The covers rely on their low unsaturated hydraulic conductivities and void volume to aid moisture retention.

Stormont and Morris (1998) propose the following method for estimating the moisture storage potential of soil layers. The field capacity of a soil is the maximum amount of water that can be retained against gravity or free drainage. It is assumed that below the field capacity, the moisture is held in place by suction and that the drainage due to gravity becomes negligible. The amount of moisture that can be stored in any soil layer, ignoring capillary barrier effects, is then estimated as the integral of the volumetric water content at field capacity over its thickness. This moisture can be reduced by plants down to the permanent wilting point (PWP), which is typically defined as 1 500kPa (150m of negative pressure head) (Cassel and Nielsen, 1986). The available water capacity or net storage capacity is the integral of the field capacity minus the PWP over the layer thickness. If the plants reduce the moisture to the PWP during the growing season, then almost the full net storage capacity is available for moisture storage during the periods of plant dormancy and low evaporation. If the layer thickness is much greater than the plant rooting depth, moisture moving past the rooting depth is difficult to draw from the cover.

Store-and-release covers require low maintenance and can be constructed from a variety of materials (Zornberg et al., 2003). If required for cover stability in steep sections, geogrid reinforcements can be included (Zornberg et al., 2003).

In general, reference in the literature was made to silts or low plasticity clays without detailed material specifications. Cover designs were based on numerical modelling that included sensitivity analyses. Parameters for candidate soils were used in various model runs to optimise thicknesses and choose the best performing soils. Zornberg et al. (2003) limited the soils to be used to CL (inorganic clays of low to medium plasticity), ML (inorganic silts and very fine sands), SC (clayey sands, poorly graded sand-clay mixtures) and SM (silty sands to poorly graded sand-silt mixtures) soils with the plasticity index between 8 and 30% and fines content of greater than 35%.

Based on sensitivity analyses, the initial water content was found to have little effect over the long term. In the first year of modelling for thick covers, percolation was predicted as the placement moisture drained. However, it is recommended that the soils be compacted at the optimum water content plus or minus 2% to achieve required densities, design saturated hydraulic conductivities and limit desiccation (Zornberg et al., 2003).

2.3.2 Case studies

In a series of comparative experiments, Albright et al. (2003 and 2004) considered the percolation rates through a variety of cover types under a range of climatic conditions. At the end of two years of monitoring, it was found that percolation through composite barriers (geomembrane over compacted fine-grained soil) was 1.4% of precipitation, while for conventional soil covers the percolation was 6-17% of precipitation in humid climates. In humid and sub-humid areas, percolation through the two monolithic covers was 16 and 17%. Percolation through one thin monolithic cover in the semi-arid to arid group was 11% while for all the other store-and-release covers the percolation ranged from 0-1% of precipitation.
In the case of the cover in the humid to sub-humid range that allowed 16% percolation, the reason given for the poor performance was that the poplar trees used there had not matured sufficiently to aid evapotranspiration during the first wet season. However, during the following season, the performance improved (Albright et al., 2003). The compacted clay cover at the same site transmitted 31% of precipitation. This was due to desiccation cracking that developed, in spite of the moist conditions at the site.

At the second site, the conclusion was reached that the storage potential of the thin store-and-release cover had been over-estimated during design. The thicker cover only transmitted less than 1% of the precipitation.

Testing undertaken on eight covers (each 13m wide by 100m long) is reported by Dwyer (1998) and Dwyer et al. (2001). The covers were all constructed in such a manner that half the cover sloped westwards while the other half sloped eastwards. One half was monitored under ambient conditions and the other half had sprinklers installed. The store-and-release cover under investigation comprised a 1.05m thick cover of which the bottom 0.9m was compacted, while the top layer was loosely placed as a vegetated layer. After the cover was seeded, a veneer layer of gravel was placed to reduce erosion (Dwyer, 2001). As the vegetation became established, the percolation rate decreased and fell below that of the composite cover which had 1.5m of compacted clay covered with geomembrane (punctured in places to represent average quality control measures at full-scale sites), a drainage layer and a 0.6m thick vegetation layer (Dwyer, 1998). After three years of monitoring, the store-and-release cover was performing better than any of the others, including the capillary barrier cover (Dwyer et al., 2001). The worst performing covers were the conventional subtitle D cover (0.15m loose topsoil over 0.45m compacted soil barrier with saturated hydraulic conductivity of 10^{-7}m/s) and a composite cover with a GCL replacing the compacted clay layer (saturated hydraulic conductivity $5x10^{-9}$m/s).

Zornberg et al. (2003) describe the parameter choices, modelling and sensitivity analysis for a cover design at a hazardous waste site. Conventional covers were considered inadequate due to stability concerns, folowing seismic studies. The investigation of appropriate thickness of the cover was made using *LEACHM* (Hutson and Wagenet, 1992). For the given climatic conditions, it was found that a 0.3m thick cover would result in less than 0.003m percolation per annum. Below this value, the percolation rates increased very significantly. Increasing the cover thickness above 0.3m did not significantly reduce the expected percolation. However, a 1.2m thick cover was chosen and was placed over a 0.6m foundation layer. A saturated hydraulic conductivity of less than $5x10^{-7}$m/s was specified and this could be achieved by the soils under consideration when placed at 90% maximum Standard Proctor and optimum water content plus or minus 2%.

A cover not termed a store-and-release cover by the authors, but constructed of soils fitting the parameters suggested by Zornberg et al. (2003) was described in Swanson et al. (2003). The cover comprised an uncompacted over a compacted glacial till. The soil was classified as SC-CL and well graded. The grading showed 23% cobble and gravel, 28% sand, 40% silt and 9% clay size fractions. A plastic limit of 17.4% and a liquid limit of 39.6% were reported. The uncompacted material density varied from 66% standard Proctor maximum density at the top of the constructed layer to 93% at the base. The saturated hydraulic conductivities were $5.7x10^{-9}$m/s and $2.0x10^{-10}$m/s for the uncompacted and compacted layers, respectively. The compacted and uncompacted layers were assumed to have three layers each and in the modelling, each of these layers was assigned a saturated hydraulic conductivity based on measured field matric suction values. Modelling with *SoilCover* gave reasonable results, compared to measured water content profiles and evaporation rates. The uncompacted layer was found to dry to 50% saturation while the compacted layer maintained 80% saturation.

Modelling predicted that the oxygen flux would decrease to 2% of the uncovered condition. Long-term predictions are that the percolation would range between 2 and 4% of precipitation. Although the cover soil met the requirements suggested by Swanson et al. (2003), the soil did not meet the criteria selected in Chapter 4 (based on a combination of literature sources) for checking soil suitability for use in store-and-release covers. In particular, the liquid limit and plasticity index plot above the Casagrande "A" line and is therefore considered to behave plastically. This is confirmed by the very low saturated hydraulic conductivities measured in the laboratory. The cover does therefore not fall within the definition of a true store-and-release cover.

Similarly, the Kilbarchan cells described in the study by Vermaak et al. (2002) and in Chapter 6 of this report were designed as store-and-release covers and capillary barrier systems. However, the soils used in the construction of the cells do not meet the criteria used in Chapter 4. At the time of construction, little literature information on suitable soil selection for store-and-release covers was available. The soil parameters for both soils used in the Kilbarchan experiments (the parameters were very similar) are discussed with reference to the four criteria set out in Chapter 4:

- The clay-sized fraction was approximately 30% (the criterion specified a maximum of 10%, although literature suggests a limit of 2%).
- The plasticity index and liquid limit plot above the Casagrande "A" line and therefore are considered to behave plastically. Further, when considering the potential expansiveness (in terms of clay percentage and plasticity index), they are in the "medium" range of expansiveness.
- The linear shrinkage is about 9% (greater than the suggested maximum of 5%).
- The coefficient of uniformity is much greater than 15 (the soils are therefore well graded as opposed to the desired uniform grading).

In addition, the laboratory saturated permeability values were in the order of 2×10^{-8} to 6×10^{-8} m/s. These were already tending toward the expected range for clays given the large clay-sized fraction.

The Kilbarchan covers therefore did not meet the accepted definition of store-and-release covers (covers of low plasticity silt or fine sand of uniform particle size with low linear shrinkage). However, the results showed that the breakthrough of acid into the percolating water was retarded compared to the uncovered coal discards and therefore AMD could be reduced even with that cover configuration.

2.4 Capillary barriers

As with store-and-release covers, the mechanism that governs moisture ingress into material below the cover is the unsaturated hydraulic conductivity. The functional component of a capillary barrier cover as considered in this project, consists of a fine-grained layer overlying a coarse layer (Figure 6). The thickness of the fine-grained layer may be chosen such that it can be vegetated without loss of required storage capacity in the layer, or a vegetated layer may be placed over it.

Capillary barriers are used in a variety of applications (cover systems for mine waste, municipal solid waste and even hazardous waste) and under varying climatic conditions. In dry climates, the fine-grained material is used to store moisture during precipitation events and allow evapotranspiration or drainage. In wet cover systems, the break in continuity in water contents achieved by contrasting fine and coarse material is used to maintain the moisture levels in the fine-grained (even clay) layers, by placing coarser layers above and below. The mechanism for moisture retention for both systems is the same.

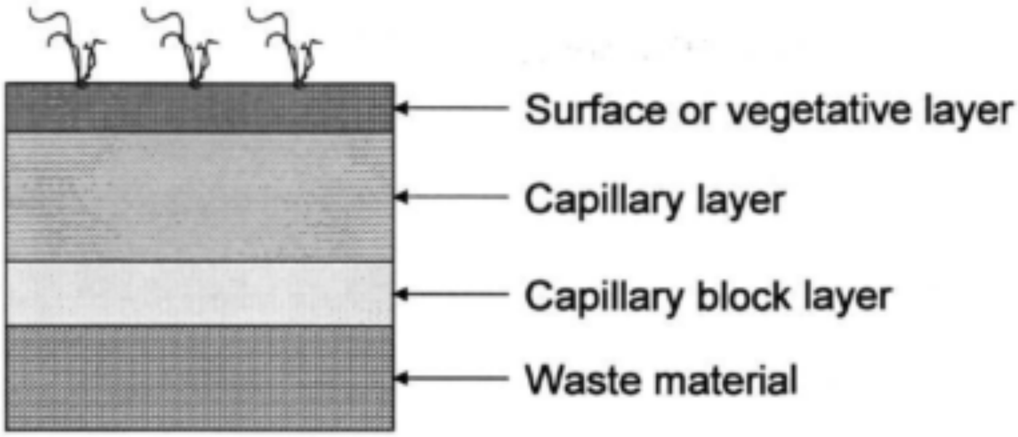


Figure 6: Schematic diagram of capillary barrier layers

The inclusion of a capillary layer is not only for limiting moisture ingress into discard, it can also be used to limit the moisture drawn up from lower lying layers. This is the mechanism used to limit evaporation from moisture retaining layers in wet cover systems (Section 2.1.2).

In dry climates, the use of moisture storage layers may not be feasible due to high evaporation rates, but the inclusion of a capillary barrier to limit upward migration of moisture may still be warranted. Toxins and salts drawn up from the discard by capillary action with evaporating moisture may prevent the establishment of sustainable vegetation cover. The use of a capillary break can eliminate this effect (Minerals Council of Australia, 1998).

2.4.1 Moisture storage mechanism and estimating moisture storage potential of capillary barrier cover systems

In general, the air entry value (the negative pressure at which a soil begins to desaturate) is lower for coarse-grained material than for fine-grained soils (Figure 7). The volumetric water content at both saturation and the residual water content for coarse material are also lower than those for fine-grained material. The design of a capillary barrier depends on this difference in moisture retention of materials of differing grain size (Smesrud and Selker, 2001).

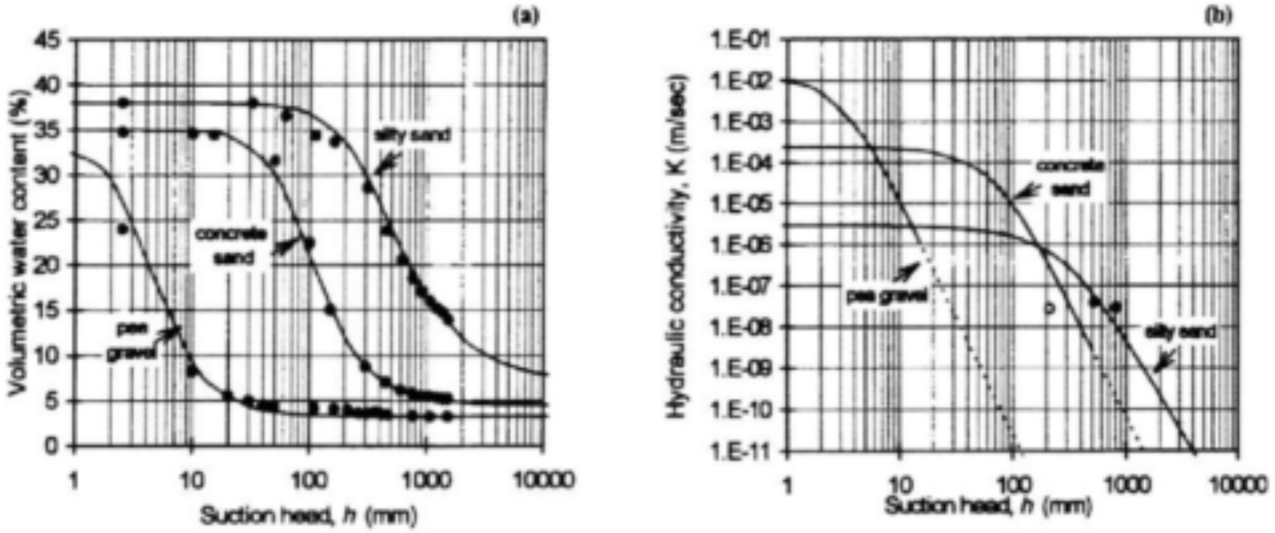


Figure 7: Graphs of measure and predicted soil water characteristic curves for three soils and corresponding unsaturated hydraulic conductivities derived using the Mualem-van Genuchten model (after Stormont and Anderson, 1999)

The capillary barrier cover will first be discussed from the perspective of a saturated system that is draining. At the water level in a discard, the pressure is equal to atmospheric pressure. With distance above the water table, negative pore pressure develops. Coarse materials are only likely to remain saturated to negative pressures of a few centimetres, while fine-grained soils remain saturated at negative pressures of a few meters (Gillham, 1984). At increasing distances from the water table, the negative pressure increases. Coarse material in a capping system is not able to retain moisture at these high negative pressures, due to its low air entry value. It therefore rapidly desaturates as the suction increases. At the residual water content of coarse-grained material, the hydraulic conductivity of coarse soil is low and little moisture is able to move through the layer, even though a downward gradient exists (Nicholson et al., 1989 and Morris and Stormont, 1997).

At the same suction at which the sand is already below saturation, the fine-grained soil remains saturated, because its air entry value has not yet been reached (Steinert et al., 1997).

Moisture is therefore retained in the pores and cannot drain into the coarser material below provided that there is no build up of positive pore pressure or preferential paths. It can either be drained laterally (and this depends on the diversion length, described later in this section) or be removed by evapotranspiration.

An alternative way of describing the mechanism of moisture storage by a capillary barrier cover system is to consider it in terms of the hydraulic conductivities of the two soils at similar soil suction values. The hydraulic conductivity of fine-grained soils even at high suctions is measurable, whereas that of coarse material is "immeasurably small" (Morris and Stormont, 1997). The moisture from the finer layer can therefore not flow into the coarser layer and will be stored in the finer layer. As moisture accumulates in the fine-grained layer, the suction is reduced and the hydraulic head of the fine-grained material is slowly increased. When the suction at the interface reaches the water entry value of the coarser layer, the hydraulic conductivity of the coarse layer is a finite, measurable value, equal to that of the finer layer. Moisture begins to move across the interface. As the suction decreases further, the hydraulic conductivity of the coarser layer rapidly increases above that of the finer layer and flow drains rapidly through the coarser layer. The air entry pressure of the fine-grained soil minus the pressure head at which the residual water content is reached in the coarse-grained layer represents the thickness of the fine-grained soil that could remain saturated (Nicholson et al., 1989).

As described in Section 2.3.1, the storage potential of a soil layer can be estimated from the field capacity and the permanent wilting point of plants. The presence of a capillary block layer, however, increases the effective storage capacity of the overlying layer (Stormont and Morris, 1998 and Khire et al., 2000). The method proposed by Stormont and Morris (1998) to determine the storage potential of the fine-grained capillary layer involves estimating the suction head in the top layer as the water breaks through into the coarse layer, and using this together with the soil water characteristic curve to determine a water content profile in the capillary layer. The method, which compared well with detailed numerical simulations, is briefly described below.

When starting from a dry condition, a wetting front will gradually develop downwards in the capillary layer during constant rate infiltration. The initial negative pressure head in the cover system (as a result of the height of the cover above the water table) is gradually increased with a corresponding increase in the hydraulic conductivity. When the wetting front reaches the interface with the capillary block layer, the coarse layer will block further downward flow if the pressure head in the fine-grained layer is greater than the water entry head of the coarse-grained layer (defined as the negative pressure head at which the coarse-grained layer will first admit water, Baker and Hillel, 1990). If a barrier is formed by the coarse-grained layer, the moisture in the overlying layer will redistribute itself. Evapotranspiration will create an upward flow gradient within the capillary layer that needs to be overcome for moisture to flow downward. Water will only pass into the lower layer if the suction head

associated with water from precipitation combined with the antecedent condition in the capillary layer reduces below the water entry head of the coarse layer (the water entry pressure has been estimated at half the air entry pressure of a soil, Bower, 1966). However, it has been observed in laboratory tests that condensation may develop within the coarser layer before breakthrough occurs (Stormont and Anderson, 1999 and Walter et al., 2000).
This is described numerically as follows:

$$SC = \theta_r b + (\theta_s - \theta_r)\int_0^b \left(\left\{ 1 + \left[\alpha \left(z + h_w^* \right) \right]^n \right\}^{-m} \right) dz \qquad \textbf{Equation 5}$$

where:

SC is the storage capacity

b is the layer thickness

h_w^* is the water entry pressure of the coarse layer

The numerical model above uses the curve fitting parameters for a drying SWCC. The SWCC for a wetting profile is different. At the same suction head, a soil that is wetted contains less water than one being dried, due to a hysteresis effect. Using the curve derived from progressive wetting would provide a more conservative estimate of storage (Stormont and Morris, 1998). This is important as the behaviour of a cover system is governed by complicated cycles of wetting and drying. A capillary rise open tube can be used to derive the wetting soil water characteristic curve for soils (Yang et al., 2004a).

At low water contents, where the soil is near its residual water content, isolated pockets of water develop (Choo and Yanful, 2000 and Yang et al., 2004a). These are not adequately modelled in numerical simulations, regardless of the pressure unsaturated hydraulic conductivity relationship used (Choo and Yanful, 2000).

Although breakthrough of moisture into the capillary block may occur during high infiltration, the barrier condition is restored to its pre-breakthrough condition once the downward flux of moisture slows (Stormont and Anderson, 1999). The advantage of this is that the cover system does not have any long-term loss of effectiveness as a result of breakthrough.

In addition to the moisture retention mechanism described, moisture can also be prevented from percolating through the capping system by increasing the slope of the cover and by slope shape (Steinert et al., 1997). As the slope of the cover is increased, the lateral drainage in the capillary block layer is also improved because the water is able to flow more quickly, although at some distance down the slope the combination of laterally moving moisture and additional infiltrating moisture can exceed the water entry head of the lower lying coarse material and breakthrough occurs (Morris and Stormont, 1997). Using convex shapes also improves lateral drainage as the flow field within the capillary layer diverges in the direction of the slope (Selker, 1997 and Steinert et al., 1997). Selker (1997) estimated that the use of a convex shape was able to double the diversion capacity of a capillary barrier system. Ross (1990) proposed a method for estimating the diversion capacity of capillary barriers. These estimations enable the appropriate positioning of drains along the slope as well as providing an estimate of the potential volumes of water at each of the drain positions. The equations developed for steady-state conditions are:

$$Q_{max} < \frac{K_s \tan\phi}{\alpha}$$ **Equation 6**

$$L < \frac{K_s \tan\phi}{q\alpha}$$ **Equation 7**

where:

Q_{max} is the maximum diversion capacity

L is the maximum effective length before breakthrough

K_s is the saturated hydraulic conductivity of the fine-grained soil

Φ is the dip angle of the interface of the capillary barrier system

α is a fitting parameter for a quasi-linear approximation of the fine soil

q is the infiltration rate

The value of α in the expression is assumed constant, but it is argued that this is not correct, especially near saturation (Steenhuis et al., 1991). Despite this limitation (and the proposed generalisation proposed by Steenhuis et al., 1991), the equations are used to estimate diversion capacity (Selker, 1997, Morris and Stormont, 1997, Kämpf et al., 1999, Khire et al., 2000 and Ursino and Cossu, 2001). Webb (1997) extended the derivation to include van Genuchten expressions for the coarse and fine-grained soils, thereby removing the limitation of the assumed constant value of α. The method integrates the horizontal flow over the layer thickness.

The effectiveness of capillary barriers can be improved by the introduction of a thin lateral transport layer between the capillary layer and the capillary block layer (Morris and Stormont, 1997). It was calculated that the diversion capacity of certain capillary layers was low due to their low hydraulic conductivities. By introducing a layer with relatively high lateral conductivity at the interface between the capillary and capillary block layers, the amount of moisture that can flow through the capillary barrier layer is increased without attaining the water entry value of the capillary block layer (Morris and Stormont, 1997).

Although many numerical simulations have been undertaken to prove the effectiveness of capillary barrier systems, the effectiveness may be less than previously assumed (Walter et al., 2000). This is because the diversion lengths calculated (using Ross (1990) or Webb (1997)) overestimate the diversion length and also do not adequately account for partial breakthrough (Walter et al., 2000). The designs should therefore be modified to accommodate some "factor of safety".

An additional consideration is the presence of microorganisms in soil profiles. Contrary to commonly observed decreases in microbial numbers and activity with depth, Lehman et al. (2004) found uniform (or even increasing) distributions with depth at excavated sections of field capillary barriers (less than 10 years old). They found that over the short period that the covers had been in place, no effect of the microbial action could be observed, but hypothesised that over the long-term, microbially produced surface-active substances could have an effect on the hydraulic performance of capillary barriers.

2.4.2 Material selection

Compatible material envelopes for the capillary barrier and capillary block layer are based on Terzaghi filter criteria (Terzaghi, 1943) and soil water characteristic curves of the two materials (Steinert et al., 1997 and von der Hude et al., 1999a). The greatest possible difference in grain size, based on filter criteria provides the most effective barrier.

Based on the theoretical evaluation by Steenhuis et al. (1991), the maximum diversion length is obtained when the water-entry pressure in the capillary block layer approaches zero, as the particle-size contrast becomes infinitely large. However, there are practical limits to the possible particle-size contrast. These include maintaining the textural integrity of the interface (filter criteria) and slope stability considerations (Smesrud and Selker, 2001).

Calculations by Smesrud and Selker (2001) showed that, although high particle size contrast are desirable to maximise the diversion length, particle-size contrasts greater than 5 are not necessary (where particle size contrasts are the ratio of the D_{50} of the finer soil to that of the coarser soil). Coarser, gravely sand was found to be a more effective capillary block layer and caused greater moisture storage in capillary barrier layers than did a medium sand (Yang et al., 2004a).

Materials considered suitable for use as a capillary block are required to have a fairly high saturated hydraulic conductivity as well as high unsaturated conductivities at low suctions in order to rapidly remove infiltrating material laterally to drains. Steinert et al. (1997) suggested that k_s be greater than 10^{-4} m/s and that sand with significant silt or clay content should not be used.

In order to optimise the effective storage of the fine-grained layer, appropriate material selection is required. Very fine-grained soils such as clays have large field capacities and the benefit derived from a capillary barrier is small (Stormont and Morris, 1998). Silty loam and sandy loam were found to show the greatest increase in storage capacity with addition of a capillary block when compared with sand and clay. Further, the storage capacity of the fine-grained layer was increased by the presence of a capillary barrier to a thickness of approximately 2m in the silty loam and the sandy loam but the effect was less in sand.

Khire et al. (2000) used numerical simulations to evaluate the effect of various design variables on the efficiency of capillary barriers. The model used was *UNSAT-H* (described in Fayer and Jones, 1990). As with *SoilCover*, the model used in later chapters of this report, *UNSAT-H* is unable to model sloping covers (Khire et al., 2000). The soils evaluated as potential capillary layers were silty sand (SM), nonplastic sandy silt (SM-ML), low plasticity silt (ML) and lean clay (CL). The coarser materials were a uniformly graded medium sand (SP) and a uniformly graded pea gravel (GP). At low suctions (<10kPa) the fine soils have lower hydraulic conductivities than the coarse soils when the soils are wet. However, when the soils are drier and the suctions high (>1 000kPa), the converse is true. Increasing the capillary layer thickness increased the moisture storage potential of the system and reduced percolation. It was, however, recommended that the thickness should not be extended to depths where the effect of the root zone was limited (Stormont and Morris, 1997). When the layer thickness of the capillary block sand (SP) was reduced from 0.75m to 0.45m, the percolation increased, although only by 5mm. For the pea gravel, the effect was even less.

The percolation through the fine grained soils (at the same thickness and using the same capillary block configuration) can be expressed as SM > SM-ML > ML > CL. This follows the decreasing hydraulic conductivities of the soils from SM to CL. For the very fine soils, the infiltration capacity of the soils is very low and precipitation is removed as runoff, and does to infiltrate at a high rate. The limitation of the CL clay is that it develops desiccation cracks (Section 2.1.1) and this causes preferential flow paths directly to the capillary block layer with its high hydraulic conductivity at low suctions. Further, the fine particles are easily washed into the coarse layer, reducing the effectiveness of the capillary block interface. The other soil types are therefore recommended for use, since the modelled percolation through these layers was very similar to that of the CL soil. The capillary block was enhanced by the use of GP soil when compared to the SP soil. A thickness of 0.3m was considered adequate for the capillary block layer.

The percentage of material finer than 0.1mm should be less than 8% for the capillary layer and should not contain active clays (von der Hude et al., 1999a). Grading envelopes after von der Hude et al. (1999b) for a combination of capillary barrier and capillary block are given in Figure 8. Suggested sources of the capillary break layer were given as crushed basalt, sieved sand or river sand, glass granules, or residues from coal burning in smelters. The material should be resistant to weathering and not friable (which may be a problem when using glass).

The minimum thickness suggested for the capillary block layer is 0.4m; however, they suggest that this can be replaced by a 0.02m thick layer composed of a geotextile mat filled with the chosen capillary block layer material since this can be supplied to site on a roll. It is noted that the properties of any vegetative layer should be chosen to aid the performance of the capillary barrier system and should not be less than 1.2m thick.

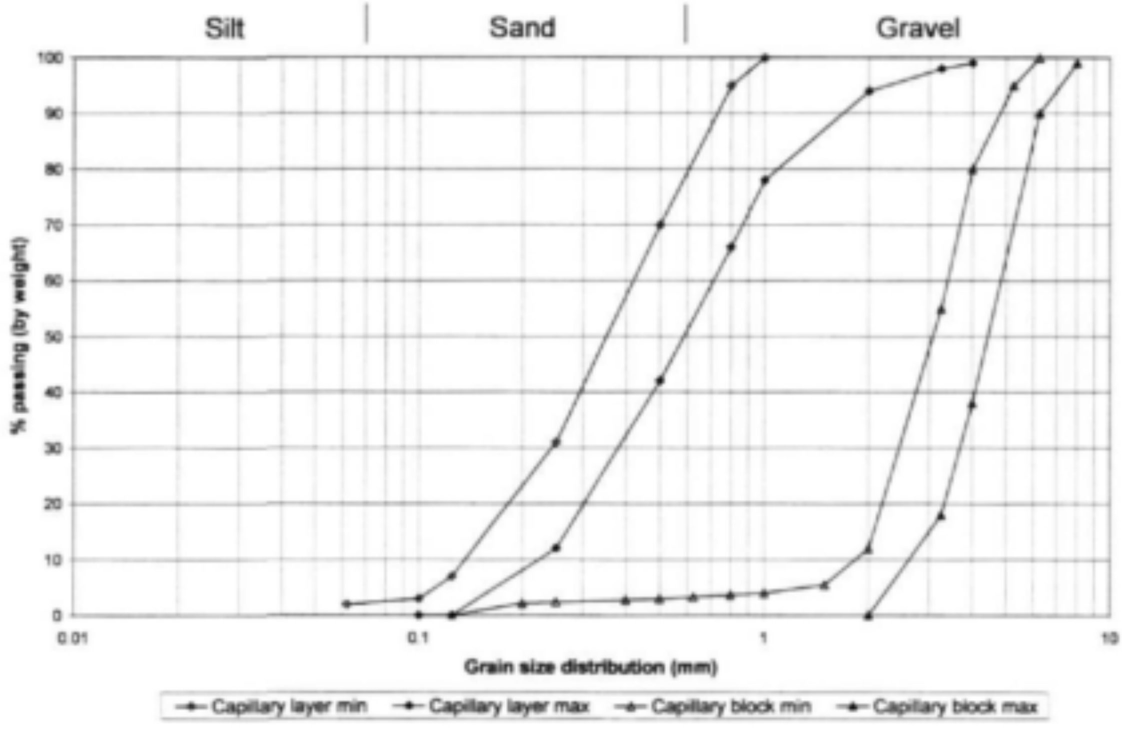


Figure 8: Particle size distribution envelopes derived from flume tests (after von der Hude et al., 1999b)

Capillary layers need to have large voids to aid lateral drainage, however, a sufficient size contrast with the capillary block layer below is required (Steinert et al., 1997, von der Hude et al., 1999a and Kämpf et al., 2001). In order to meet these contrasting requirements, Kämpf et al. (2001) suggested that the optimal soil type was a medium sand with a steep grain size distribution and a minimal fraction of fines below 0.5mm. The upper limit was set at 2mm grain size.

Aubertin et al. (1995) suggested that fine tailings could be used as a suitable source of the fine-grained material. However, this material is likely to be reactive. By combining the reactive tailings with appropriate neutralising material, the mixture could be used as the moisture retention layer between coarse layers (Lamontagne et al., 2000 and Fortin et al., 2000), such as the cover with capillary barrier described Nicholson et al. (1989) (Section 2.1.2).

Various authors have suggested that the use of geotextiles between the capillary and capillary block layer aids in maintaining a distinct interface between the two layers. This reduces fingering and loss of fine material into the coarser layer (Nyhan et al., 1990, Steinert et al., 1997 and Zischak, 1997). A further possibility to reduce the penetration of fines into the capillary block layer is to use two capillary barrier layers: a finer upper layer (sand sieved to obtain 0-1mm fraction) and slightly coarser lower layer (1-2mm sand fraction) over the capillary block layer (2-16mm size) (Ursino and Cossu, 2001).

A minimum slope for capillary barriers of 5% was suggested by Wohnlich (1991) while von der Hude et al. (1999a) specified 14% and Hoins (1999) recommended slopes greater than 18°. Based on the theory described in Section 2.4.1, no slope is required if the moisture is to be removed by evapotranspiration and the storage potential is designed to accommodate high infiltration from precipitation events. The maximum slope is determined from slope stability analyses. During infiltration, the negative pressure in the slope (which contributes to strength) is reduced (Zhang et al., 2004) and this should be considered in the stability analysis of covers.

2.4.3 Case studies

A variety of verification studies are presented in the literature. These include numerical simulations (Akindunni et al., 1991, Morris and Stormont, 1997, Stormont and Morris, 1998 and Khire et al., 2000), column tests (Stormont and Anderson, 1999, Choo and Yanful, 2000, Ursino and Cossu, 2001 and Yang et al, 2004a), flume tests (Steinert et al., 1997, Kämpf et al., 1999, Walter et al., 2000, Kämpf et al., 2001 and Tami et al., 2004) and field tests (Nyhan et al., 1990, Melchior, 1997, Zischak, 1997, Dwyer, 1998, von der Hude et al., 1999b, Dwyer, 2001, Schnatmeyer, 2002, Albright et al., 2003 and Albright et al., 2004). The discussion here is focussed on field verifications.

Tests conducted in a semi-arid climate showed that little or no percolation was able to penetrate the experimental cover, even at a plot with only 0.5% slope (Nyhan et al., 1990). Percolation rates for two plots were 0% and 2.6% of precipitation. The advantages noted by Nyhan et al. (1990) of the capillary barrier cover were that the capillary block increased the moisture storage in the capillary barrier layer. This in turn resulted in higher evapotranspiration. In addition, the higher moisture storage encouraged the establishment of a good vegetative cover that further enhanced moisture losses from the capillary block layer. The diversion capacity also enabled the removal of moisture through drains at the time of snowmelt.

Melchior (1997) described a study of several field plots under investigation in Hamburg, Germany. All test cells (10m x 50m) had a topsoil of sandy loam (0.75m) and a drainage layer (0.25m). The test plot with a compacted clay layer showed a significant decrease in performance over the five years of the study, despite the clay having relatively low potential for shrinkage when compared to other compacted clay barriers. The presence of preferential flow paths was confirmed through tracer studies. When GCLs used in two covers were examined after some years, bentonite had formed aggregates of about 10mm in diameter and there were 2mm wide gaps between them. The capillary barrier consisted of a 0.6m capillary layer (fine sand with 78% of particles in the 0.1 to 0.2mm range) and a 0.25m capillary block of sand and gravel (85% between 0.63 and 63mm). The system performed well until desiccation cracks developed in the compacted soil overlying the capillary layer. Subsequent infiltration was therefore concentrated along these cracks and did not enter the capillary layer as a wetting front as expected. Melchior (1997) suggested that well graded materials, silts, loams and clays were unsuitable for capillary layers. Well-sorted coarse sands were recommended for the capillary layer with gravel as the capillary block layer.

Comparing root penetration of a few cover types, Wagner and Schnatmeyer (2002) observed that roots penetrated the 0.75m thick protection layer and reached the clay layer, threatening the effectiveness of the barrier system over time. The percolation through the compacted clay barrier (without an overlying drainage layer) was 174mm in a year with 1 037mm of rainfall. Over the corresponding period, the percolation through the capillary barrier system was 152mm and the slope on the plot was only 5%. It was noted that the compaction of the protection layer in several layers led to the formation of interfaces along which lateral drainage occurred for most of the cover types.

The capillary barrier configurations tested by Dwyer (1998) and Dwyer et al. (2001) are complex designs and consist of numerous layers. For simplicity, they are shown in Figure 9 and Figure 10. The cover termed a capillary barrier by Dwyer (1998) and Dwyer et al. (2001) is composed of 0.3m topsoil and 0.15m upper drainage layer of sand (Upper drainage layer 1 in Figure 9) over 0.22m gravel (Upper drainage layer 2), a 0.45m thick compacted layer and a 0.3m sand layer (total cover thickness is 0.97m). The lower sand layer and compacted soil layer are considered the capillary barrier.

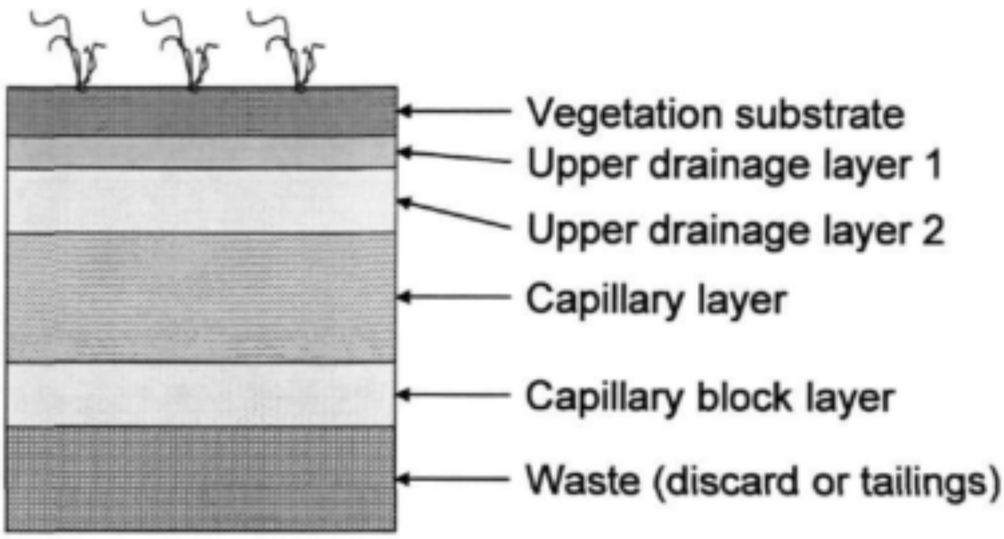


Figure 9: Capillary barrier system (after Dwyer, 1998 and 2001)

The anisotropic barrier (Figure 10), also relying on a capillary barrier, is composed of a 0.15m vegetation layer, 0.6m native soil, 0.15m of fine sand as an interface layer and 0.15m of pea gravel as the capillary block layer (total cover thickness is 1.05m).

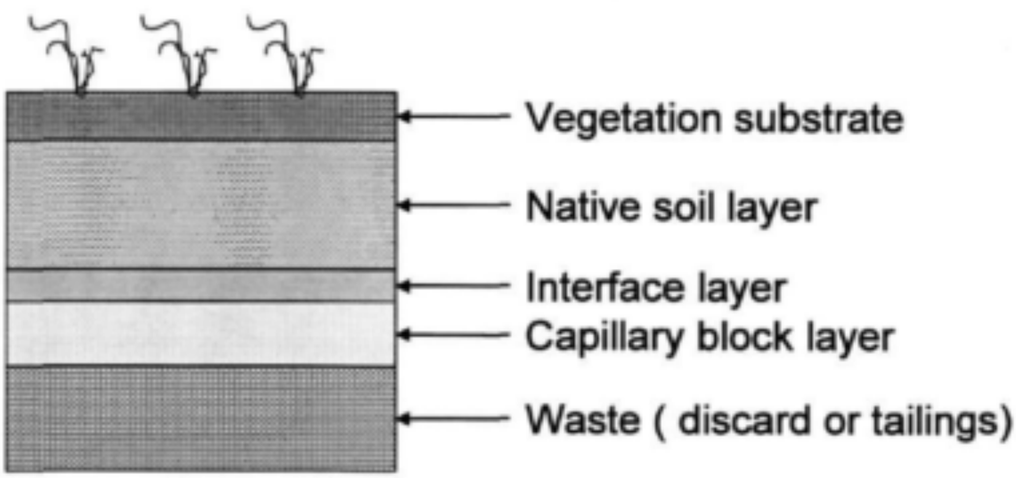


Figure 10: Anisotropic barrier (after Dwyer, 1998)

The test plots described by Dwyer (1998) and Dwyer et al. (2001) were located in an area of very low rainfall, with a total rainfall over three years of monitoring of only 482.5mm. The store-and-release cover (Section 2.3.2) performed slightly better than the capillary barrier system, but the anisotropic barrier performed even better. The efficiencies calculated for the monitoring period were: 99.9492%, 99.7440% and 99.9496% for the store-and-release cover, capillary barrier and anisotropic barrier, respectively. The store-and-release cover and the anisotropic barrier were of the same overall thickness, showing that the thickness of the fine soil layer can be reduced if a capillary block layer is introduced, and an improvement in barrier efficiency can be expected.

Landfill cover tests were carried out at ten locations across America, in different climatic regions (Albright et al., 2003 and Albright et al., 2004). At a site at Omaha (subhumid – humid climate), two capillary barriers and a conventional composite barrier were constructed. The composite cover consisted of a vegetative layer, geomembrane and compacted clay layer. During the first year, heavy precipitation was recorded. Percolation through the composite cover occurred during the first year (0.5% of precipitation over the two year monitoring period). As a result of the high rainfall, the storage capacity of both the thinner and thicker capillary barriers was exceeded. The storage capacity of the thinner capillary barrier was also exceeded in the second year. It was predicted that the vegetation would remove water to the wilting point, but the moisture levels in all three covers remained at 0.1m above the wilting point. Since less moisture was removed by the vegetation than predicted, the storage potential of the covers was reduced. Despite the problems, the percolation through the covers was 8.7% and 4.5% of precipitation for the thinner and thicker capillary barriers, respectively.

In the semi-arid and arid regions the capillary barriers performed very well. At a site in Polson, the capillary barrier system only allowed 0.32% percolation while the composite liner with geomembrane allowed twice that amount. The total rainfall for the monitoring period reported (Albright et al., 2003) was only 939mm.

Hupe et al. (2001) showed that capillary barriers could be constructed at a lesser cost than the cover system that included a compacted clay layer. The estimated cost for a conventional cover (vegetative layer, protection layer, drainage layer, compacted clay over a drainage mat) was 47 Euro/m^2 while the capillary barrier system (vegetative layer, slightly and heavily compacted protection layer, capillary layer, capillary block layer) was expected to cost 35 Euro/m^2.

In Mpumalanga, precipitation occurs mostly during the summer months, coinciding with the plant growing season. Therefore the thickness of the cover should be designed to store all moisture during the winter periods to ensure that no percolation through the cover occurs. On the side slopes of discards, the lateral diversion capacity should be investigated to determine spacing of drains (if required).

2.4.4 Summary of working principles of cover designs considered in research

- Store-and-release covers main function is to limit rainfall infiltration into the waste. Store-and-release covers rely on evapo-transpiration potential to remove soil water from the cover before it infiltrates the wastes and should have the ability to retain and store rainfall water in the cover and also promote upward movement of soil water.

- Capillary barrier is similar to store-and-release covers it that a capillary break is used to prevent rainfall from infiltrating the mine waste. Differing from store-and-release covers, capillary barriers, capillary barriers drain water from the covers before it enters the waste.

3 ASSESSMENT OF EXISTING COVERS

3.1 Background

A component of this research project entailed assessment of performance of a number of existing rehabilitated coal discard dumps in both Mpumalanga and KwaZulu-Natal.

The objective of the assessment of existing dumps was to ascertain whether the design applied to coal discard dumps during rehabilitation has influenced the performance of the dumps after completion of rehabilitation.

At the request of the mining companies on whose property a number of the rehabilitated dumps are located, comparison and critique of individual dumps has been avoided, with discussion confined to the performance of an approach to capping discard dumps, rather than discussion of performance of individual dumps.

3.2 Rehabilitation approaches assessed

The rehabilitation of coal discard dumps in South Africa has progressed from a "do nothing" situation in which old end-tipped dumps were not rehabilitated to a situation where extensive engineering of dumps takes place during construction and operation of a dump, or the dump is reshaped following decommissioning as part of the final rehabilitation and closure process.

Current rehabilitation approaches all involve the covering of coal discard with soil and vegetation of the soil cover.

The rehabilitated coal discard dumps assessed fall into one of the following categories, namely:

3.2.1 Terraced dumps

These dumps have been constructed in terraces of varying vertical height and bench width. Benches are designed to slope inward to prevent spillage of water over the front face of the terrace. Water is either taken off the dump in constructed reinforced drains of various forms, or alternatively is retained on the bench in shallow paddocks. In the latter case, the bench surface contains numerous small cross walls which prevent lateral flow of intercepted water. The dumps are soil clad and vegetated. The terrace slopes are typically steep, and close to the angle of repose of coal discard (about 36°). Terraced dumps are generally rehabilitated concurrent with dump development; with rehabilitation of the terrace generally commencing only when deposition on that terrace is complete and construction of the next terrace has commenced.

3.2.2 Reprofiled "whaleback" dumps

These coal discard dumps have been reshaped or reprofiled as part of the rehabilitation process. Typically the dumps were old end tipped discard dumps, with slopes at angle of repose. Reprofiling has entailed dozing down of the discards material to a final slope of 1:5, although at some dumps steeper slopes do occur (up to 1:3) over the whole or a part of the dump. No erosion control measures are present other than a well vegetated cover. Water runs off the dump down the full length of the slopes and discharges to the environment at the toe of the dump.

3.2.3 Reprofiled dumps with "spiral drainage"

These dumps are similar to reprofiled whaleback dumps in that the discards have been reshaped, typically to a slope of 1:5. However, a spiralling drain is cut into the reprofiled discard material to create a drain that leads water off the dump in a controlled manner. The fall in the drains is in the order of 1:200. Water falling on the dump surface runs down the vegetated slope until intercepting and entering the cross cutting spiral drain. Dumps are clad with soil and vegetated. The spiral drain discharges runoff water to the environment, typically across an area reinforced to provide protection against erosion.

3.2.4 Combination of approaches

In many instances the final rehabilitated dumps reflect a combination of the three broad approaches described below, as dictated by conditions on site which include:

- footprint area available for reshaping of the discard dump,
- whether the slope of the adjacent natural ground accommodates the planned rehabilitation approach,
- cost of implementing a particular approach,
- availability of materials for capping and soil cladding and
- shape of the original discard dump to be rehabilitated.

In these instances, the performance of the individual components of the dump were assessed. For example, in a dump that comprises both a terraced and whale backed sides, the performance of the terraced and whale backed parts of the dump have been separately assessed.

3.3 Methodology

In carrying out this assessment the intention has not been to conduct detailed monitoring of aspects such as vegetation performance because such performance monitoring needs to be conducted over time to demonstrate stability or change. A "snapshot in time" provides little real value in terms of assessing long-term performance.

The basic premise applied during the assessment has therefore been to attempt to evaluate the dump in a manner that allows the following questions to be addressed:
Given the shape and cover type selected for a given dump:

- How effective has the vegetation cover been in preventing erosion?
- How effective has the dump shape or geometry been in preventing erosion?
- How effective has the cover been in limiting infiltration? and
- Is there evidence of degradation in the cover through salt migration?

The dumps assessed are as follows:

Dumps	**Location**
Terraced dumps	
• Vryheid Coronation Colliery, No 2 dump	KwaZulu-Natal
• Vryheid Coronation Colliery, No 3 dump	KwaZulu-Natal
• Natal Anthracite Colliery, Boschhoek dump	KwaZulu-Natal
• Landua 3 dump	Mpumalanga
Reprofiled, Whale back dumps	
• Talana dump	KwaZulu-Natal
• Vryheid Coronation Colliery, No 3 dump	KwaZulu-Natal
• Springbok Dump	Mpumalanga
Reprofiled dumps with Spiral drainage	
• Ermelo Colliery, Ermelo Dump	Mpumalanga
• Witbank South dump	Mpumalanga

3.4 Findings

Key observations made are briefly discussed below:

3.4.1 Performance of Terraced Dumps

Vegetation performance

On all terraced dumps assessed the grass cover appears to be performing fairly well. All dumps assessed were more than ten years post rehabilitation.

The loss of soil from terrace slopes however is a concern as it suggests that the soil cover will continue to erode slowly to a point where cover vegetation will fail. In most instances soil loss is not through gully formation, but rather through sustained wash off of soil from the steep terrace slopes.

Dump shape and geometry

There is evidence that the steeper slopes of terraced dumps are susceptible to erosion and in a number of sites breakthrough to the underlying discard was observed. Soil loss appears to be due to erosion off the terrace slope with consequent thinning of the soil cover, rather than slip failure of the soil cover. In certain of the dumps assessed the original soil cover thickness had decreased by 50% over a ten to fifteen year period.

Soil washed off the steep terrace slopes does not wash right off the dump, but settles out under lower flow conditions on the benches. This results in the path of water flow on benches moving away from the toe of the terrace slope towards the outer edge of the bench. In some examples observed the flow path is mid way between the toe of the terrace slope and the lip of the bench, posing a risk of overtopping during high rainfall events (Figure 11).

One of the advantages of this type of dump is that it blends in with the landscape.

Cover and infiltration

Settling of soils on terrace slopes after placement and when soils are saturated frequently leads to cracking through the soil cap to the underlying discards. Such cracks run parallel to the slope and are most common at the top of a terrace slope. These cracks short circuit the passage of runoff water through the soil cap to the underlying discard.

Lateral cracks at the top of the terrace slope may also provide a ready conduit for air to the underlying discards. This poses a risk in terms of burning and will contribute to enhanced rates of oxidation in discard materials with negative consequences in acid rock generation in dumps with an ARD risk.

Evidence of degradation in cover

All dumps showed evidence of localised salinisation.

In general, the depth of soil cover is considerably less on terraced dumps than on either of the reprofiled dump forms. This is the consequence of difficulty in handling of soils on the steep terrace slopes.

Figure 11: Diagram indicating risk to terrace dump benches due to accumulation of eroded soil (yellow vs. brown line) which results in runoff flow movement away from the base of the terrace slope (blue solid line vs. stippled line)

Figure 12: Slumping of the soil cover and erosion frequently result in exposure of underlying coal discard at the top of terrace slopes. Solid brown line indicated soil cover at placement. The fill represents the actual soil cover ten years after rehabilitation

In dumps on which trees (*Eucalyptus* sp.) were growing, there was noticeable die back of the grass cover around individual trees. Within these localised areas, there is also evidence of salinisation suggesting that the uptake of water by the trees influences the cover vegetation by reducing the moisture available to grasses and, through exclusion of salts at the tree root – water interface, concentrating salts in the upper capping soils in proximity of trees on dumps.

3.4.2 Reprofiled dumps – whaleback

Vegetation performance

All dumps assessed had good vegetation covers, although isolated areas were evident where vegetation stress or dieback was evident, associated with seepage from the dump. In general the vegetation communities present on the reprofiled slopes were comprised of a number of grass species in addition to those sown.

A good basal cover was evident on all whalebacked slopes. No gulley formation was observed. All whaleback dumps assessed showed some soil loss to erosion as evidenced by "stepping" down-slope of the base of tuffed grass species suggesting either loss of soil down slope, or consolidation of soils on the slope.

As would be expected, topsoil quality appears to have a significant effect on vegetation performance on whale back reprofiled dumps. The limiting elements may be a combination of compaction (sub-soils) and low fertility.

Dump shape and geometry

In this form of rehabilitation the surface runoff water flows down the full slope length to discharge at the toe of the slope. In certain instances the slope length of whale backed dumps exceeded 100m at a slope of 1:5. Even on these long slopes there was no evidence of gulley formation.

The stability of these long slopes was protected at the time of planting by the incorporation of rows of rhizomatous grasses (strips of kikuyu hand plants, *Cynodon* hand plants, or thin strips of instant kikuyu lawn) at close intervals.

The cover on certain KwaZulu-Natal dumps in which a form of breaker layer had been placed was extremely good. Vegetation on similar dumps in the vicinity is performing less well, however the differences may relate, to a greater extent, to the quality of soils used in capping than to the presence of a breaker layer. It must be noted that the breaker layer referred to has not eliminated localised saline breakthrough near the foot of the slope. In many cases the saline conditions even occur higher up on the slopes and in some cases even close and on top of the whale backed dumps.
A typical observation on die back areas:

- No or poor grass cover, sometimes the grass died off but the old tuffs remained.
- No or very little re-growth, irrespective the grass species (*Rhodes, Ercurvula* or *couch grass*).
- In the case of recently die back areas, the dead grass tuffs still hold the soil intact, but in areas where the die back took place more than three years ago, there is clear evidence of erosion (lowering of profile compared to the rest of the area, erosion gullies, sheet wash etc.).
- Two (and sometimes three) distinct soil conditions were present in all areas where the vegetation died back. Gray-brown or yellow-brown-gray soils, typical of the soft pithite and or the semi-saturated horizon below the plinthite[4], were noted in the topsoil layer. Typical dark gray soil with red-brownish streaks and mottles were pronounced. Iron-

[4] A humus-poor, sesquioxide-rich horizon that hardens irreversibly to ironstone hardpans or aggregates with repeated wetting and drying. (Buol et al., 1997, Soil Genesis and Classification, Iowa State University Press)

concretions (from the glayed horizon and soft plinthite) were oxidized (Fe^{2+} change to Fe^{3+}) resulting in the hardening of the soft concretions at the soil surface. This was associated with acidification (pH<4) of the soil and eventually Aluminum (Al) toxicity. As a result the vegetation was severely damaged and died off over a period of time. Once this happened, soil erosion became a problem. Salination (well above the average electrical conductivity of surrounding natural soils) and acidification (pH<4) of either the whole topsoil profile or very close to the soil surface (indicating a toxic condition in the root zone) were noted. In the cases where salinisation were noted:

  - it is obvious that Al-toxicity (together with the salination if it is too high) could cause the die back,
  - salination and acidification may not appear on the surface, but are present in the bottom part of the topsoil profile, indicating an upward movement,
  - the coal discard material below the topsoil contains some sulphides/sulphur or saline and acidic properties (the latter two are an indication that the coal discard material weathered/decay extensively before placing or oxidation took place after placing and capping with topsoil) and
  - in one incident Fe-rich shale material was used together with the top soil and the shale was exposed to atmospheric conditions. The Fe^{2+} in the shale oxidized after exposure resulting in acidic conditions.

- In the aread where the grass cover was still in excellent condition but located within 5m radius of die back areas, the above described conditions were not encountered in the topsoil or underlying coal discard.

Cover and infiltration

Reprofiled slopes steeper than 1:5 do not perform as well as slopes of 1:5. The poorer vegetation performance and higher erosion from these steeper slopes appears to be influenced by both more arid soil conditions (less infiltration on steeper areas) and hotter slopes in north facing areas.

No evidence of cracking or micro cracking was observed on reprofiled slopes, suggesting that very little "short cutting" of runoff occurs.

Evidence of degradation in cover

All reprofiled whale back dumps assessed showed localised salinisation of cover materials. The incidence of saline patches of cover soil was however limited and was typically associated with small wet seeps from within the dump.

3.4.3 Reprofiled dumps – spiral drainage

Vegetation performance

On dumps where soil depths were shallow, breakthrough to the underlying coal discard was observed in places. Observations with regards to thin soil covers were separated into two categories based on their means of establishment namely construction and erosion. In the case of the latter, remnants of roots and other organic carbon material in the remaining soil were noted, an indication of original properly established vegetation but changed conditions causing dieback (acidification by means of oxidation of subsurface soil horizons or acidification by means of diffusion. In both cases a breakthrough to the underlying discard material was pronounced.

Dump shape and geometry

Top soil thickness on dumps assessed varied from greater than 0.75m to less than 0.30m. Slopes were in the vicinity of 1:5.

The spiral drains however have been cut into the reshaped dumps after completion of re-profiling. This practice results in steeper slopes immediately above a drain, at the foot of the drained slope. Erosion damage to these areas where water flow velocity increases was common.

Cover and infiltration

The dumps assessed showed good resistance to erosion on the reprofiled slope. At the point where the spiral has been cut into the slope however there was consistently evidence of erosion. Similarly, in limited instances there was evidence of erosion on the down slope wall of a drain where the slope angle is typically steeper.

There was no evidence of cracking or micro cracks within the dump cover layer.

Evidence of degradation in cover

The dumps assessed differed considerably in performance. On dumps where soil cover depth was in excess of 0.50m, the cover performance was good.

In all dumps assessed, however, seepage and salinisation was evident in localised areas associated with thinner soil depths where the drains cut into the slope.

4 SOIL IDENTIFICATION

4.1 Introduction

Store-and-release covers (or evaporative covers) and store-and-release covers with capillary barriers were investigated by the research team as possible alternatives to current cover types for coal discards. Soils from the Mpumalanga region were considered for suitability for use in these cover types. Criteria suggested in the literature for soil selection were used to identify possible sources in Mpumalanga. Initial laboratory testing was used to refine the set of soils under investigation. Various soil characteristics required for numerical modelling were determined for the selected soils.

4.2 Background on alternative covers under investigation

Store-and-release covers are cover systems that store moisture during precipitation events and allow evaporation of stored moisture during dry periods. The objective of these covers is to minimize the ingress of moisture into the coal discard or waste underlying the cover material.

These covers have been proposed to replace covers that are prone to desiccation and erosion. An important aspect in rehabilitating coal discards is the potential formation of acid mine drainage (AMD) (Section 2.2.1). Covers should therefore not only limit moisture ingress, but should also slow the movement of oxygen (Section 2.2.2) and thus minimize the formation of AMD. It can be argued that if there is a very low moisture flux, then the products of oxidation will not be removed from the discard dump and it is likely to form a stable zone of oxidized material.

Soils suitable for use in store-and-release covers should have the potential to retain moisture against gravity and have a low saturated hydraulic conductivity if a lateral drainage component is to be used (Section 2.3). A balance is required between the pore volumes and permeability. The soils thought most suited to store-and-release covers are silts to fine sands (Zornberg et al., 2003). It is important that the soils have low linear shrinkage limits in order to avoid formation of cracks during drying. Moisture retention potential is based on the SWCC (Section 2.2.3).

Capillary barriers are covers of fine material overlying a coarser material (Section 2.4). Moisture is retained in the fine material and moisture movement into the coarser layer is limited by the moisture retention characteristics of the two layers. There is a continuity of suction across the interface of the two soils. Fine soils are able to effectively retain moisture at high suction values, and this causes a discontinuity in water content across the interface. The storage potential of store-and-release covers is enhanced by use of a capillary break layer (coarser material) below (Nicholson et al., 1989).

The coarser, capillary break layer is chosen according to Terzaghi filter criteria (Steinert et al., 1997 and von der Hude et al., 1999a). If this were not done, the fine material would fall into the voids of the coarser material, and "fingering" or "wicking" would occur. These are preferential pathways for moisture movement across the soil interface.

The same feature of these soils that limits moisture ingress into discards is also the aspect that reduces the oxygen flux. Moisture is retained in the fine soils against fairly high negative pressures or suction. During and after a rainfall event the pores of the soil are partially filled with water. It requires very high suction values to remove this water, and therefore the covers do not dry out rapidly. Air flows more slowly through partially filled voids than voids in dry soils. While the cover is partially saturated, oxygen fluxes are low.

An alternative to soils is the use ash from coal stations in the area. The benefit would be two-fold: ash requiring disposal would be used beneficially and ash may reduce the production of AMD. Ash has a high buffering capacity and could therefore reduce acidity of infiltrating moisture. Ash samples were collected for laboratory investigations regardless of the criteria set out in Section 4.4.

4.3 Sample collection

Using very broad criteria, a desktop study was able to indicate soils in the Mpumalanga region that might be suitable for use in the alternative covers under consideration. The soils required could be grouped into two categories namely fine soils for use as evaporative covers or capillary layers and coarse material for the capillary block layers. The initial criteria are given in Table 1.

Table 1: Initial sample selection criteria

Fine soils	Coarse soils
Silt to fine sand (clay-sized if not active – to be confirmed in modelling)	Sand to fine gravel
Uniform particle size	Uniform particle size
Low linear shrinkage	Low linear shrinkage
Less than 2% clay (to be confirmed in modelling)	Less than 2% clay
Low organic fraction	Low organic fraction
Low carbonates	Low carbonates

From the initial desktop study it was found that there would be no soils in the area of interest that met the criteria for the coarse soils. Eleven samples were, collected at the Kleinkopje mine near Witbank (July 2003) for further assessment for use as the fine grained layers in the covers (Appendix 1). The South African Soil Classification name (Soil Classification Working Group, 1991) and the Unified Soil Classification names are given for each sample in Table 2. Sample numbers will be adopted henceforth as the geotechnical properties of the soil samples determine the suitability for use in the alternative covers. The unsuitability of any sample does not necessarily imply that all soils of the same origin are unsuitable.

Table 2: Sample types collected

Sample number	Soil Type: South African	Unified Soil Classification (according to laboratory results)
1	Avalon	Silty sand
2	Bainsvlei	Sandy clay to silty sand
3	Clovelly	Sandy clay
4	Dresden	Sandy clay
5	Glencoe	Silty sand
6	Glenrosa	Silty sand
7	Griffon	Silty sand
8	Hutton	Silty sand
9	Katspruit	Sandy clay
10	Longlands	Silty sand
11	Pinedeen	Silty sand

4.4 Initial criteria for soil selection and initial sample selection

The criteria for store-and-release covers and the capillary (storage) layer of capillary barrier systems are essentially the same in that the function of these layers is to store moisture in void spaces against gravity. No distinction was therefore made between these two layer types in the soil selection criteria. According to Khire et al. (2000) soils best suited for use as capillary (storage) layers are silts to fine sands (low plasticity silt, non plastic silty sands and silty sands) while Kämpf et al. (2001) suggest that medium sands with the main grain size in the range 0.2mm to 2mm. Steinert et al. (1997) also suggested that sands with significant silt or clay content were unsuitable. Further, it has been suggested that the soils should have less than 2% clay (by dry mass) and display low linear shrinkage. Given these rather contradictory requirements (Sections 2.3.1 and 2.4.2), it was decided that a variety of soils would be tested further.

The criterion of "less than 2% clay" relates to the plasticity of the material and its tendency to shrink when dried. Clay minerals, in particular montmorilonites, swell when hydrated and shrink when dried. This induces cracks in clay layers (either covers or liner systems) and waste or discard is not adequately isolated from the environment. However, not all fine particles in the clay-sized fraction of soils are necessarily clay minerals. Samples containing clay minerals can be moulded moist. No plastic limit could be found for Samples 1, 5, 6, 8 and 11 when using the soil fraction passing the 0.425mm sieve (Appendix 2). The same samples also displayed no linear shrinkage. These two facts would imply that the clay-sized fractions of these samples were not composed of clay minerals and therefore the samples could still be suitable for use in the covers under investigation.

Table 3 summarizes the reasons for exclusion of samples from the proposed further testing regime. Criteria for exclusion were as follows:

1) Fraction of clay-sized particles > 10%

2) PI and LL plot above Casagrande "A" line (NP means Non-Plastic)

3) Linear shrinkage > 5%

4) Coefficient of uniformity > 15

These criteria are proposed in order to aid material selection.

Table 3: Summary of values used in decision-making

Sample	Clay-sized particles (%)	LL; PI (%)	Linear Shrinkage (%)	Coefficient of uniformity, Cu	Further Testing	Reason for exclusion
1	4	NP; NP	0	7.9	Yes	
2	8	19; 6	2	100	No	4
3	9	22; 8	3.5	295	No	2; 4
4	15	21; 8	3.5	ND	No	1; 2; 4
5	5	NP; NP	0	12.0	Yes	
6	4	NP; NP	0	11.1	Yes	
7	7	16; 4	1.5	31.2	No	4
8	5	NP; NP	0	14.2	Yes	
9	7	23; 8	3.5	132	No	4
10	13	16; 3	0.5	ND	No	1; 4
11	5	NP; NP	0	14.0	Yes	

Criterion 1 limits the clay-sized fraction to less than 10%. This is higher than the suggested 2% in the literature, but as discussed previously, may be too stringent since not all the fine materials consist of clay minerals. A limit is, however, required, in order to avoid fine material moving into the capillary block (for those covers with capillary block layers). Further, very fine particles will fill the void spaces between larger particle sizes.

Criterion 2 excludes soils that are classified as clays and are likely to behave as clays under repeated wetting and drying.

Criterion 3 limits the linear shrinkage of the materials. Materials with high shrinkage will develop cracks during drying. The efficacy of the cover is compromised if cracks open since preferential flow can occur through these pathways.

Soils with coefficients of uniformity (Cu) below 10 are generally considered to have uniform grading (Craig, 1997). *Criterion 4* has been chosen to be slightly less restrictive, but the performance of the soils with Cu values in the range 10 to 15 should be evaluated carefully after more extensive testing.

Soils to be used for capillary block layers must be chosen in accordance with the grading of the overlying soil. Terzaghi (1943) filter criteria based on the grading of the finer material to be retained can be used to generate the grading envelope of the capillary block layer. This could only be done once the soils to be used as the storage layer had been chosen based on further laboratory testing. The greatest improvement in moisture retention in the capillary layer is achieved when the capillary block layer is as coarse as possible within the confines of the filter requirements (Kämpf et al., 2001 and Smesrud and Selker, 2001).

Samples 1, 5, 6, 8 and 11 were considered potentially suitable for use in store-and-release covers as well as store-and-release covers with capillary blocks, based on four initial selection criteria. In addition, fly ash from a power station was also evaluated. Further tests performed on the soils are described in the Section 4.5.

4.5 Detailed Selection tests

The tests described in this section were required to further refine the sample selection criteria. The test data were also incorporated in numerical models such as *SoilCover* to predict cover performance. Soil parameters required as input variables for *SoilCover* are as follows:

- soil-water characteristic curve,
- soil density,
- initial water content of soil,
- porosity or specific gravity and
- saturated hydraulic conductivity, k_s.

Soil-water characteristic curves describe the water content of soils at varying matric suction values (Section 2.2.3). This defines the unsaturated hydraulic conductivity and the potential of the soil to retain moisture against gravity or suction pressures. One of the techniques to derive these curves is the pressure plate test. Curves can be fitted to the data using equations of Brookes and Corey (1964), van Genuchten (1980) or Fredlund and Xing (1994) (Section 2.2.3).

The soil density and initial water content are specified by the design engineer when designing a cover system. The soil density has a direct impact on both saturated and unsaturated conductivities (Daniel and Benson, 1990 and Miller et al., 2002). Soil density and placement water content are specified in terms of a percentage of the maximum Standard Proctor density to be achieved and the water content at which the material is to be placed in order for some (nominal) compaction to be achieved in the field. Although it has been argued that soil covers in South Africa are commonly placed by end-tipping of material down slopes with some re-grading by dozer, that does not obviate the need for the design engineer to specify a compaction density and placement water content that must be achieved. It is an issue related to quality assurance. Compaction tests are thus required for design purposes to obtain information regarding the maximum dry density and optimum water content. Standard Proctor tests were developed to enable specifications of compactions on slopes at earth dams where only fairly low compaction is possible. For soil covers placed on slopes, as for earth dams, it is difficult to apply a high compaction effort, which is the reason that the Standard Proctor test has been specified in preference to the Mod AASHTO test or Modified Proctor test for soils in this investigation.

The soil-water characteristic curve and saturated hydraulic conductivity are used together to predict a function for moisture conductivity of unsaturated soils. Since the soils to be tested were predominantly sandy, permeability tests were performed in a triaxial cell to measure the saturated hydraulic conductivity.

The pressure plate tests, permeability tests and flume tests were all carried out at the same placement density in order for the data to be used together for predictive purposes. Samples were tested at the optimum water content and at 90% Standard Proctor maximum dry density. For Samples 1 and 8, additional tests were performed at 85% and 95% Standard Proctor maximum dry density.

The last test parameter required as input data for *SoilCover* is the specific gravity of the soils. This simply measures the density of the solid particles relative to the density of water. It is used to determine the volume of voids in the soil. This in turn determines the ease with which water or air can move through the soil.

5 SOIL ANALYSIS

5.1 Introduction

A selection of soils from the Mpumalanga region was considered for use in store-and-release covers and capillary barriers. These types of covers function differently to conventional compacted clay covers. The basic function of compacted clay layers is to limit infiltration due to the compacted clays very low hydraulic conductivity. As discussed in Section 2.1.1, one of the problems with clay covers is the increase in hydraulic conductivity, which results from repeated cycles of wetting and drying. Initially, the high plasticity of the clay allows some degree of self-repair when the dry clay is re-hydrated. However, the cracks that form in the structure are not completely eliminated when the clay re-hydrates and this rapidly leads to a loss of integrity of barriers constructed from clays.

Store-and-release covers retain water in interstitial pores during rainfall events and this moisture is released by evaporation during dry periods. Since the material used for these barriers has low linear shrinkage, there is no problem of cracks opening during desiccation. The moisture storage potential of these covers can be increased by placing a coarser, capillary block layer below the storage layer, as discussed in Section 2.4. A discontinuity of water content develops at the interface as a result of the differences in moisture retention at the same negative pore pressure (suction). It is thought that store-and-release covers may offer a suitable alternative to compacted clay covers under the climatic conditions in Mpumalanga.

5.2 Soil data collected

From the initial desktop study it was found that there would be no soils in the area of interest that met the criteria for the coarse soils. Eleven samples were, however collected from the Kleinkopjie mine (near Witbank) and assessed in July 2003 for further detailed investigation for use as the fine grained layers in store-and-release covers and as the capillary layer in capillary barriers. The soils were compared to a set of criteria to identify which of the samples were considered most suitable for use, as discussed in Chapter 4. Criteria were based on parameters affecting performance of this cover type, as reported in the literature. Cut-off values from the literature were, however, relaxed to consider a scope of soils.

Five soils (Samples 1, 5, 6, 8 and 11) were considered most suited to the set criteria and were subjected to further testing. It is important to note that it is the characteristics of the samples, not the soil types that are being considered. These samples cannot be considered as representative of all Avalon or Hutton soils etc., but are single samples of these types collected in the field. It is more appropriate to consider the soils in terms of the Unified Soil Classification system.

These samples were subjected to the following additional testing:

- particle size analysis,
- specific gravity testing,
- determination of Atterberg limits,
- Standard Proctor compaction testing,
- determination of saturated hydraulic conductivity (samples prepared at 90% maximum Standard Proctor dry density and optimum water content),
- pressure plate testing to generate SWCCs (samples prepared at 90% maximum Standard Proctor dry density and optimum water content) and
- Saturated hydraulic conductivity and the SWCCs were also determined for Samples 1 and 8 at 85% and 95% maximum Standard Proctor dry density and optimum water content.

Sample 11 was eliminated as a result of a large proportion of organic matter in the sample. This was observed during the second phase of particle size analysis and therefore the other tests were not conducted. Large amounts of organic matter in the sample were considered unsuitable for both store-and-release covers and capillary barrier systems as the organic matter would decay and change the performance of the covers systems. In addition, organic material in soils may lead to problems during compaction as the organic material may absorb moisture preferentially.

Additional SWCCs and saturated hydraulic conductivity values were obtained for Samples 1 and 8. The characteristics for these soils had already been evaluated at 90% maximum Standard Proctor dry density and additional tests were performed at 85 and 95% maximum Proctor density respectively. These additional values allowed consideration of the effect on cover performance if degrees of compaction differing from the specified 90% Standard Proctor maximum dry density were achieved.

One of the problems with poorly rehabilitated coal discard dumps is the formation of acid mine drainage. This occurs as a result of oxidation reactions within the discard (Section 2.2.1). A sample of ash was obtained from Duvah Power station to assess its suitability in store-and-release covers and capillary barriers. The ash is alkaline and may limit the formation of acid mine drainage by acting as a chemical buffer. The sample was subjected to the same testing protocol as all the soil samples. The data are presented in Appendix 3 and 4.

5.3 Results

Table 4 contains a summary of initial conditions and soil parameters used in *SoilCover* simulations.

The impact of the clay-sized fraction in Sample 1 is evident in the saturated permeability which is an order of magnitude lower than that of the coarser Sample 8, both at 90% Standard Proctor maximum dry density. The fine fractions of both soils were however found to be non-plastic, a very important consideration when choosing soils for evaporative covers. This characteristic would enable the cover to accommodate differential settlement without the formation of tension cracks in the cover.

Soil-water characteristic curves describe the ability of soil to retain moisture within its structure while subjected to a negative pressure or suction. In practice, suction is the result of evaporation drawing moisture from the soil or gravitational forces drawing water down through the soil profile. Soils have varying ability to retain moisture under unsaturated conditions. The air entry value is the point on the soil-water characteristic curve where desaturation begins (Section 2.2.3). Coarse soils generally have lower air entry values than finer soils that are more able to retain water under suction pressures (Section 2.2.3 and Figure 7). This is evident from Figure 13, comparing Samples 1 and 8, both at 90% Standard Proctor maximum dry density. The air entry value for Sample 1, with the higher fraction of fine particles, is higher than that of Sample 8 both at 90% Standard Proctor maximum dry density.

Generally, as the degree of compaction of samples increases, so the air entry value increases, as shown for Sample 1 in Figure 14. This is in agreement with results presented by Meerdink et al. (1996) and discussed in Section 2.2.3. As a result of the increased compaction density, it is more difficult to draw water through the soil because pores between particles are smaller and therefore the capillary tension forces are greater. When considering suitability of soils for store-and-release covers, a balance is required between the soil's ability to retain moisture and the size of voids. If the voids are very small, the volume of moisture that can be retained is high, although flow through the layer may be low. It is an advantage to store some moisture in the cover to reduce air entry into the coal discard, but it should be held against gravity and moisture should not flow freely into the coal discard below. This optimisation can only be predicated by simulations (e.g. *SoilCover* and *HYDRUS2D*) and laboratory experiments such as flume tests.

The air entry value for the most heavily compacted specimen (95% Standard Proctor maximum dry density) of Sample 8 is very low. Simon Gawu, who performed the test, indicated that the sample had not been fully saturated at the start of the test (this can only be discovered at the end of the test when water content values are back-calculated). The corresponding soil-water characteristic curve is therefore not suitable for simulation purposes and should be repeated. In addition, as shown in Figure 15, the soil samples had decreasing moisture retention ability as the degree of compaction increased. This is contrary to the expected increasing moisture retention expected.

The ash sample from Duvah power station in Mpumalanga had high water content when collected. As soon as the sample was disturbed and placed in the sample bag, free water collected on the surface of the sample. It was thought that the ability of the undisturbed material to retain large amounts of water would prove useful for store-and-release covers. However, a potential problem is that the water would drain rapidly from the layer if any disturbance occurred, such as settlement of coal discard below the cover. Water would then potentially drain into the discard. In addition, the ash had a high gravimetric water content at saturation, but the air entry value from the soil water characteristic curve was only 4.9kPa, lower than the other soils under consideration, except for one. Once the suction exceeded the air entry value, the ash rapidly desaturated (Figure 16).

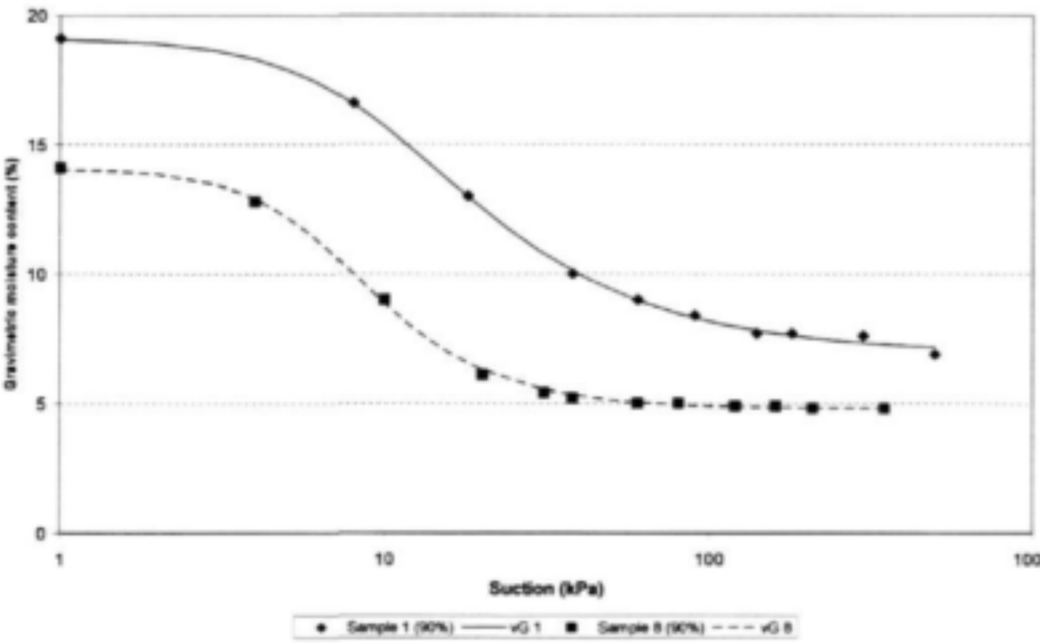


Figure 13: Soil-water characteristic curves from laboratory data for Samples 1 and 8

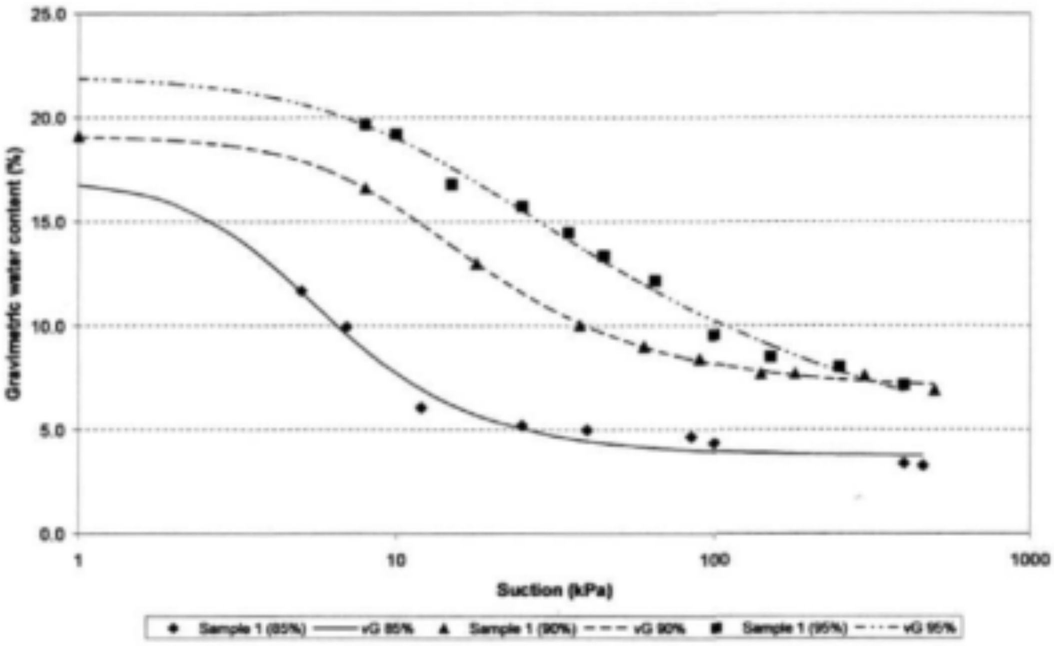


Figure 14: Soil-water characteristic curves from laboratory data of Sample 1 at different degrees of compaction

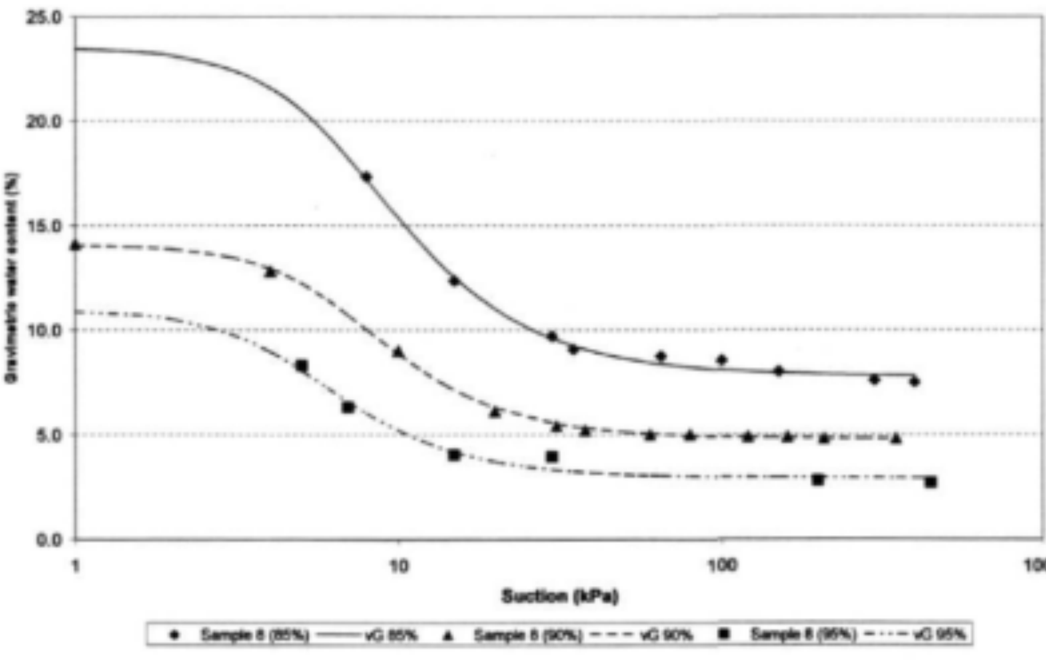


Figure 15: Soil-water characteristic curves from laboratory data of Sample 8 at different degrees of compaction

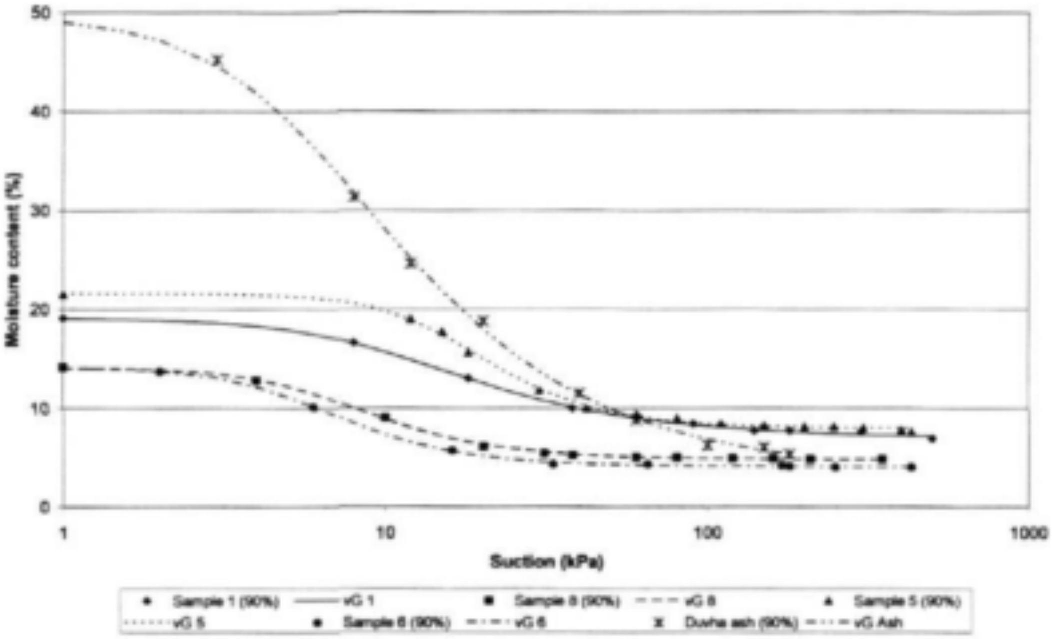


Figure 16: Soil water characteristic curves of soil samples and ash at 90% maximum Standard Proctor dry density

Table 4: Values and soil parameters

Parameter	Soil 1	Soil 1	Soil 1	Soil 5	Soil 6	Soil 8	Soil 8	Soil 8	Ash
Degree of compaction (relative to Standard Proctor maximum dry density)	85%	90%	95%	90%	90%	85%	90%	95%	90%
Dry density (kg/m^3)	1670.3	1768.5	1866.8	1791	1692	1700	1800	1900	1075
Water content (%)	9.5	9.5	9.5	9.3	10.0	9.3	9.3	9.3	
Porosity	0.37	0.333	0.296	0.324	0.359	0.361	0.323	0.266	
Saturated permeability at 50kPa effective stress (m/s)	1.7×10^{-8}	1.7×10^{-8}	4.0×10^{-8}	4.1×10^{-6}	1.1×10^{-6}	1.5×10^{-6}	2.4×10^{-6}	3.1×10^{-6}	
Specific gravity	2.65	2.65	2.65	2.68	2.64	2.66	2.66	2.66	2.36
Air entry value (kPa)	3.5	10.4	12.2	16.5	5.6	7.0	6.9	4.9	5.9

6 KILBARCHAN MONITORING

6.1 Introduction

In 1999, Wates Meiring & Barnard (now Golder Associates Africa), members of the coal mining industry and the Department of Water Affairs and Forestry initiated a project to continue the monitoring programme at the experimental site (Vermaak et al., 2002). It was felt that the continuation of monitoring would contribute greatly to a better understanding of the long-term performance of soil covers. The project terminated in December 1999. In 2000, it was decided that the monitoring programme at Kilbarchan should form part of the Mine 20/20 initiative under the guidance of Coaltech. Coaltech funded the now completed monitoring programme in co-operation with the Department of Water Affairs and Forestry.

The main objectives of soil covers should be to limit water infiltration into coal discard or spoils, thereby impeding oxygen ingress, and to inhibit the growth of large iron-oxidising bacteria populations. In this way, leachate volumes are significantly reduced and the quality of leachate is improved because of lower sulphide oxidation rates.

The Kilbarchan experiment attempted to compare the advantages, disadvantages and cost implications of various rehabilitation techniques, create some consensus regarding design philosophy and methodology of soil covers, evaluate the performance of soil covers in terms of limiting rain water infiltration. It was one of the first detailed research experiments in South Africa where soil covers have been researched and used for the mitigation of coal discard and development of a clear understanding of the flow mechanisms in the top unsaturated soil layers of a natural soil cover on micro scale. The results of the experiment was used to model recharge accurately and to protect water resources.

6.2 Monitoring Program

Ten experimental cells were constructed with each cell having a surface area of $100m^2$. The cells were separated from each other by means of 1m thick compacted (93% Mod AASHTO at optimum moisture content) clay walls (Bezuidenhout et al., 2000 and Vermaak and Bezuidenhout, 2003). The cells were extensively instrumented (Figure 17) to record the parameters that govern unsaturated flow and leachate quality on a weekly basis. The following parameters were recorded during the life of the experimental site:

- climatic conditions,
- outflow,
- water content,
- oxygen and carbon dioxide concentrations and
- leachate quality.

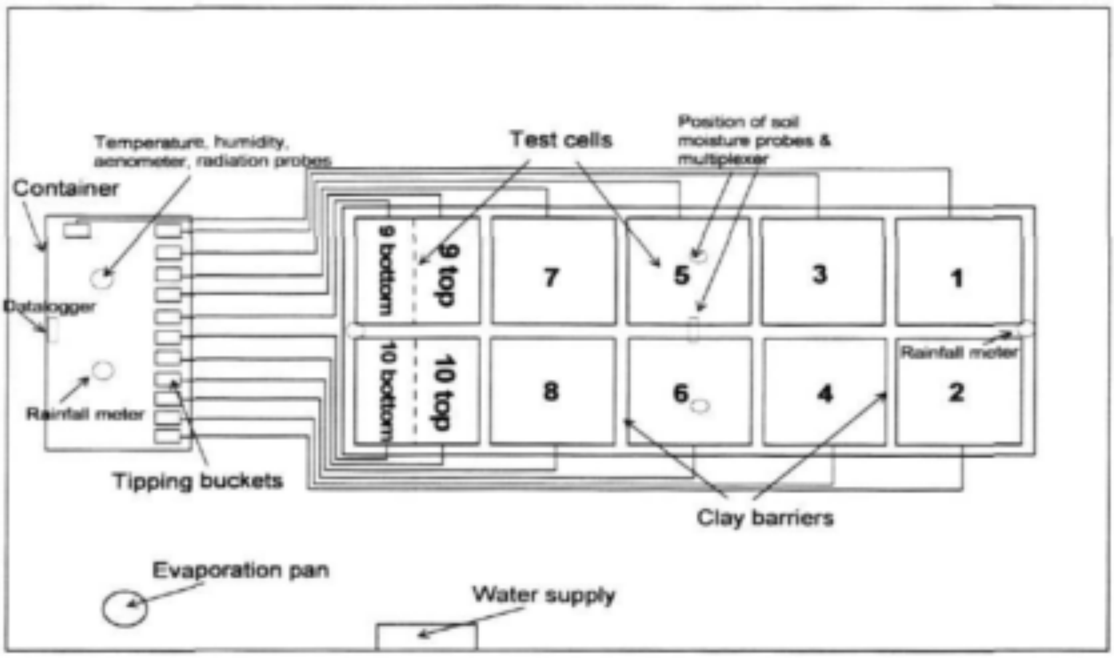


Figure 17: Layout of experimental site (after Vermaak and Bezuidenhout, 2003)

Five monitoring periods can be distinguished since the commissioning of the project in 1993:

- February 1994 – September 1997

Monitoring that formed part of the first WRC project (Wates et al., 1998). Meteorological data was captured using a data logger and the outflow; water quality and gas readings were measured.

- October 1997 – April 1999

Monitoring conducted after the conclusion of the first WRC project (Vermaak et al., 2002). The monitoring team continued weekly monitoring but the meteorological equipment was not maintained and resulted in data loss.

- May 1999 – December 2000

Monitoring that formed part of this WRC project and funded by some members of the coal mining industry (Vermaak et al., 2002). All equipment was repaired and additional equipment installed.

- January 2001 – August 2002

Monitoring funded by some members of the coal mining industry. All equipment was repaired and additional equipment installed.

- September 2002 – May 2005

No mayor changes have taken place since September 2003.

Field monitoring was conducted by Mr Yoshan Nehro of the Department of Water Affairs and Forestry (DWAF), Dundee office, in a similar fashion to that conducted from commissioning of the project in 1993, comprising weekly measurements of rainfall, A-pan evaporation and monthly datalogger readings of outflows and leachate quality sampling. DWAF also contributed to the general maintenance of the site by regularly cutting grass and supplying water to the experimental site as required.

6.2.1 Problems encountered during the monitoring period

Several problems were encountered during the monitoring period that affected the data collected:

- The mechanical counters used for measuring outflow were subject to wear and tear and were also affected by the corrosive environment. At the start of the second WRC project, several mechanical counters were found to be out of order, which affected the continuity of data from the first to the second WRC project. The mechanical counters were replaced on a regular basis during the second WRC project.
- The mechanical counters frequently showed unreliable readings due to wear. These unreliable results were easily identified as they showed huge increases in outflow over the other cells. The unreliable results were filtered from the outflow database.
- It was observed that "double-tipping" frequently occurred, caused by the bucket bouncing off the mechanical counter during tipping. Outflows may thus have been over-estimated but the frequency of "double-tipping" meant that they could not be filtered from the database. Preliminary observations on "double-tippling" suggest that outflow may have been over-estimated by approximately 10%.
- Some of the equipment had to be replaced during the second WRC project. These included the datalogger (damaged by lightning), gas analyser (broke down) and the wind sentry-set (theft). The solar panel, also stolen, was not replaced. The temperature and humidity sensors required repair after they were first damaged by lightning and then by vandalism.
- There was a veld fire at the experimental site during August 2000. The PVC pipes, in which the leachate flowed to the tipping buckets, and the signal wire between the datalogger and multiplexer were severely damaged. This resulted in data loss of outflow, water quality and volumetric water content, measured by the soil water probes. The equipment was subsequently repaired.
- Site visits revealed that burrowing animals damaged several of the test cell surfaces. The burrowing holes were mainly in the uncovered Cells 1, 2 and 3 and could have resulted in increased outflow. The animals have since been controlled and the holes refilled and compacted.

6.3 Outflow analysis

Table 5 provides a summary of the configurations of the respective cells. Eight of the cells (1 to 8) represented the top section of a rehabilitated discard dump with a slope of 1%. This is the smallest slope that would be used in the rehabilitation of a discard dump (Vermaak and Bezuidenhout, 2003). Cell 9 was constructed with a 10% slope while Cell 10 with a 20% slope. Three of the cells were constructed without any cover (Cells 1 to 3). The influence of compaction, soil type and cover thickness was also investigated.

A discussion of the result of the experiment follows.

6.3.1 Uncovered cells (Cells 1, 2 and 3)

The highest outflow rates were measured in the uncovered Cells 1 to 3 where average outflow rates of between 25% and 33% of MAP were measured. This can be attributed to the particle size distribution of the fine coal discard used in the experiment, which consisted of gravely sand sized particles as compared with typical coal discard consisting of a sandy gravel and gravel sized particles. The fine coal discard possesses a slightly higher storage capacity and therefore allows more soil water to be removed by evaporation. However, the outflow rates are particularly high when compared with natural recharge rates which vary from 3% MAP for the South African coalmining region (Hodgson, 2000) to 10% for areas underlain by dolomite (Bredenkamp, 1999).

Table 5: Summary of cell configuration

Cell	Layers top to bottom	Slope (%)
1	No cover, unvegetated, uncompacted spoils	1
2	No cover, unvegetated, compacted spoils	1
3	No cover, vegetated, uncompacted spoils treated with lime	1
4	0.3m uncompacted Avalon, vegetated, uncompacted spoils	1
5	0.5m compacted Avalon, vegetated, uncompacted spoils	1
6	0.3m uncompacted Avalon, vegetated, 0.7m compacted Estcourt, uncompacted spoils	1
7	0.3m uncompacted Avalon, vegetated, 0.7m compacted Avalon, uncompacted spoils	1
8	0.7m uncompacted Avalon, vegetated, 0.3m compacted Estcourt, uncompacted spoils	1
9	0.3m uncompacted Avalon, compacted, vegetated, 0.7m compacted Estcourt, uncompacted spoils	10
10	0.3m uncompacted Avalon, vegetation, 0.7m compacted Estcourt, uncompacted	20

Outflow through the uncovered cells varies considerably over the monitoring period. The outflow measured for the 1995/1996 rainfall season is more than six times higher than that measured for the 2000/2001 rainfall season. The outflow generated during 1995/1996 actually exceeds the total rainfall of the 2000/2001 rainfall season. It appears therefore that outflow is not related linearly to rainfall. The outflow during the wet 1995/1996 rainfall season represents 37 to 45% of MAP whereas the outflow during the dry 2000/2001 rainfall season represents 16 to 20% of MAP. A higher percentage outflow occurs during wet years and a lower percentage outflow occurs during dry years.

The highest outflow rates were measured in Cell 1, comprising uncompacted fine coal discard, followed by Cell 3, comprising treated and vegetated fine coal discard and then Cell 2, comprising compacted fine coal discard. The higher outflow rates for Cell 1 was expected, firstly because the storage capacity of the uncompacted fine coal discard is lower than that of the compacted fine coal discard of Cell 2 and secondly because the vegetation assisted water removal through evapotranspiration from Cell 3. In addition, it was observed that a number of holes were made in the cell by burrowing animals and rainwater could therefore short-circuit the fine coal discard. The burrowing holes were destroyed from time to time to eliminate that problem.

The outflow rates from Cell 2 were the lowest of the uncovered cells, largely because of the increased storage capacity of the compacted fine coal discard. Rainfall water is retained in the compacted fine coal discard from where a portion of soil water is evaporated.

6.3.2 Single layered covers (Cells 4 and 5)

The results show that outflow rates are significantly lower for cells that have been provided with a soil cover. The outflow rates for Cell 4 which has only a 0.3m soil cover, are an average 18% of MAP compared with the 30% of MAP for uncovered cells. However, the outflow rates are significantly higher in comparison with other covered cells. When designing infiltration-limiting covers, one would typically aim to reduce rainfall infiltration to about 5% of MAP. In this respect, this cover fails to meet the infiltration target and is therefore ineffective in limiting infiltration into the fine coal discard.

An average outflow rate through Cell 5 (0.5 m compacted Avalon soil cover) of 13% of MAP was recorded which was less than those of Cell 4. This is only slightly more than the outflow rates of Cells 6 and 9, both of which have been provided with complex cover systems. However, the outflow rates are still significantly higher than the target for infiltration-limiting covers of 5% of MAP.

With the exception of the rainfall years, 1994/1995, 2000/2001 and 2002/2003, outflow rates for Cell 4 exceeded 20% of MAP. A possible explanation for the low outflow rates for 1994/1995 is that the soils and fine coal discard were placed in the cell in a dry state and that the rainfall was soaked up by the soils and coal discard during that year, resulting in minimal outflow. The lower outflow rates for the 2000/2001 rainfall year is due to the low rainfall of that year and the fact that reference evaporation was four times higher than rainfall, meaning that a greater part of the soil water could be removed from the cover. However, the outflow rates were relatively high, even in the dry 2000/2001 year, indicating that the cover is not effective in limiting rainfall infiltration.

The outflow rates for Cell 5 are similar to those of Cell 4, with relatively high outflows of between 12 and 21% MAP for all rainfall years except 1994/1995 and 2000/2001. Unlike Cell 4, the soils of Cell 5 were compacted, thereby increasing the soil's air entry value and its soil water retention capabilities. Cell 5 is in effect a store-and-release cover in which the fine coal discard is a capillary break and the compacted soils are the storage medium. However, the high outflow rates indicate that the storage in the cover is inadequate to store the rainfall volumes, resulting in breakthrough.

It is interesting to note that the outflow rate for the dry 2000/2001 rainfall year represents only 2% of MAP. This indicates that, for dry years, the storage capacity is adequate to store rainfall water and the cover is effective in limiting rainfall infiltration but, in years of higher rainfall, the storage capacity is exceeded. The results suggest that the cover configuration might be adequate for climates with annual rainfall less than 500mm/a. Similar to Cell 4, it is believed that the low outflow rates for the 1994/1995 rainfall year were the result of soils and fine coal discard being placed in position in a dry state, and that rainfall was soaked up by the soils and coal discard during that year, resulting in minimal outflow.

6.3.3 Double layered covers (Cells 6 and 8)

Outflow rates for double layer covers are significantly lower than those for the uncovered cells, with outflow rates being 30% to 40% of those of covered cells. However, these rates are more than twice as high as the target of infiltration-limiting covers of 5% of MAP. The outflow rates for Cell 6 (0.3m uncompacted Avalon soils overlying 0.7m compacted Estcourt soils) and Cell 8 (0.7m uncompacted Avalon soils overlying 0.3m compacted Estcourt soils) were on average 12% of MAP and 9% of MAP respectively. These outflow rates are particularly high in comparison with Cell 7, which also has a 1.0m in thick cover, but has outflow rates of less than half of those of Cells 6 and 8. The outflow rates are also not significantly lower than those of Cell 5, which has only a 0.5m thick cover. The comparatively high outflow rates of Cells 6 and 8 suggest that their cover configurations are ineffective in limiting rainfall infiltration and that infiltration rates can be significantly reduced by changing their configuration to that of Cell 7.

Cells 6 and 8 were originally designed to be infiltration barriers in which the compacted Estcourt would act as the infiltration barrier and the Avalon used as topsoil with the functions of providing a growth medium for vegetation and protecting the Estcourt soils against desiccation. It was unfortunately found that the properties of the Estcourt soils are not conducive for use as an infiltration barrier. The field saturated hydraulic conductivity (1.73 x 10^{-7}m/s) is 17 times higher than the specified saturated hydraulic conductivity for infiltration barriers (1.0 x 10^{-8}m/s). A more stringent value of 1.0 x 10^{-9}m/s is often required for infiltration barriers of capping layers (Benson and Koerner, 1997). Infiltration barriers are rendered ineffective if the specified saturated hydraulic conductivity is not achieved.

The actual saturated hydraulic conductivity of the covers is significantly higher than that measured by laboratory tests, possibly because of inadequate compaction during construction of the cover. This highlights the importance of quality assurance during the construction of infiltration barriers.

Cells 6 and 8 were not provided with drainage layers. The percolation rates into infiltration barriers are significantly higher for covers that do not have drainage layers. It is believed that rainfall water accumulated and infiltrated the compacted Estcourt soils resulting in higher outflow rates.

6.3.4 Store-and-release cover (Cell 7)

Although this cell was designed as a store-and-release cover based on available information at the time, the material selection does not match the criteria now more commonly suggested (Section 2.3 and Chapter 4). Cell 7 has proved to be by far the most efficient cover, with average outflow rates of less than 5% of MAP and therefore meeting the target of infiltration-limiting covers. The outflow rates are approximately 10% of the outflow rates of the uncovered cells and 50% of the next best performing non-sloped cover, Cell 8.

Cell 7 consists of 0.3m uncompacted Avalon soils overlying compacted Avalon soils and has a typical configuration of store-and-release cover systems (Bews et al., 1997). Rainfall water infiltrates the cover and is stored in the uncompacted and compacted Avalon soils. The fine coal discard acts as a capillary break, limiting water infiltration into the discard. Soil water is then removed by means of evapotranspiration processes.

The compacted Avalon soils increase the retention capabilities of the cover, thereby ensuring that water does not flow into the fine coal discard, as is the case with Cell 8. The cover is 1.0m in thickness, which proves to be adequate in storing infiltrating rainfall water, even in wet years. In addition, the whole cover is constructed with Avalon soils, which ensures hydraulic continuity throughout the cover and for all soil water contents. The Avalon soils do not act as a capillary break for upward-moving water, as is the case with Cells 6 and 8. The results indicate that annual outflow rates vary considerably for the different rainfall years with a maximum of 10% of MAP for the wet 1995/1996 year to almost zero outflow for the dry 2000/2001 year. Outflow rates are also not directly related to rainfall, with an outflow of 1% of MAP recorded for the wet 1996/1997 year and 5% of MAP for the below-average 1998/1999 year. This indicates that, similar to Cell 6, outflow is not only related to the volume of annual rainfall but also to rainfall intensity and frequency.

For the wet year, most of the rainfall occurred in December and January, thereby allowing insufficient time for the water to be removed by means of evapotranspiration. Breakthrough occurred and rainfall water percolated into the fine coal discard. In contrast, rainfall spread throughout the season allows soil water to be removed by means of evapotranspiration.
The results also showed that outflow was almost completely prevented during the dry 2000/2001 rainfall year. The cover was adequate to store-and-release all of the rainfall water that infiltrated the cover during that year.

6.3.5 Sloped covers (Cells 9 and 10)

The outflow results for the cells with sloped covers are mixed, with Cell 9 (10% slope) performing relatively poorly and Cell 10 (20% slope) performing satisfactorily. The average outflow rate for Cell 9 is 12% of MAP, which is slightly higher than that of the double layer cells and slightly lower than that of Cell 5. The average outflow rate for Cell 10 is 6% of MAP, which is the second best performing cover after Cell 7.

Both sloped covers have similar configurations to Cell 6 (0.3 m uncompacted Avalon soils overlying 0.7m compacted Estcourt soils). Because the covers are sloped, it is believed that capillary barrier flow processes govern outflow and that soil water flows through the cover and accumulates at the interface between the compacted Estcourt soils and fine coal discard. The soil water then flows down-slope towards the bottom part of the sloped cells.

To measure the effects of capillary barrier processes, the sloped cells were designed to intercept soil water from the interface between the Estcourt soils and fine coal discard. The outflow from the interceptors discharges to Tipping buckets 9 (top) and 10 (top) but no outflow was recorded in either bucket during the monitoring period. This suggests that the diversion length for the compacted Estcourt soil is less than length of the cover (10m) and that breakthrough occurred before it reached the interceptors, resulting in infiltration into the fine coal discard.

For non-sloped cells, soil water accumulates along the fine coal discard interface and is then removed by evaporation processes. For sloped cells, soil water moves down-slope, accumulating water as it flows along the fine coal discard interface, resulting in breakthrough. One would therefore expect that breakthrough would occur more readily in sloped cells and outflow rates would therefore be higher compared with non-sloped cells. That would explain the higher outflow rates of Cell 9 compared with Cell 6, even though they have similar cover configurations.

This does not explain why the outflow rates are lower for Cell 10, which has a similar configuration to Cell 9 but with a steeper slope. It is possible that run-off on Cell 10 is significantly higher than that of Cell 9 and also the non-sloped cells. One would therefore expect lower infiltration rates and lower outflow rates for that cover. This is in contrast with conventional infiltration theory, which states that the top centimetre of soil would first need to become saturated before run-off is generated. The run-off quantities for gradual slopes would therefore be similar to those of steep slopes provided that ponding did not occur. Run-off would, however, accumulate faster on steep slopes. It is possible that run-off was generated on the unsaturated soils of Cell 10 and resulted in higher run-off.

Explanations for the difference in outflow rates for the sloped cells remain inconclusive. One needs to form a better understanding of capillary barrier processes before satisfactorily explanations can be given. One also needs to form a better understanding of infiltration and run-off processes on steep slopes to interpret the outflow results of the sloped cells.

6.3.6 Explanation of outflow rates

Even though the covers on Cells 6 and 8 failed as infiltration barriers, the outflow results indicate that the covers act as store-and-release covers. The fine coal discard acts as a capillary break, thereby limiting infiltration into the fine coal discard. The compacted Estcourt soils act as a storage medium in which infiltrating soil water is retained before being released by means of evapo-transpiration.

However, as mentioned earlier, the Avalon soils overlying the Estcourt soils also act as a capillary break, limiting upward movement of soil water and entrapping soil water in the Estcourt soils. With subsequent rainfall events, the soil water content increases in the Estcourt soils and results in breakthrough and infiltration into the fine coal discard. The covers therefore not only failed as infiltration barriers, but are also shown not to be effective as capillary barrier systems.

It is believed that the 0.7m uncompacted Avalon soils in Cell 8 provided storage for infiltrating rainfall water for average and dry years, which was then removed by evapo-transpiration. However, the hydraulic characteristics of uncompacted Avalon soils are not conducive to soil water storage during wet periods and soil water therefore percolates through both Avalon and Estcourt soils and infiltrates the fine coal discard before evapo-transpiration can remove water from the cover.

The outflow rates for Cell 6, comprising 0.3m uncompacted Avalon soils overlying 0.7m compacted Estcourt soils, are more difficult to interpret. High outflow rates were measured for the wet season but relatively low outflow rates were measured for the almost equally wet season. Outflow rates for the average rainfall years were higher than those of Cell 8 and exceeded those of Cell 5 for the dry season. This highlights the complexity in predicting outflow rates for a particular cover and its dependence on specific climatic characteristics.
It is believed that the high outflow measured during the wet season can be attributed to the fact that most of the rainfall occurred during the months of December and January. Soils remained near saturated, resulting in rapid infiltration into the fine coal discard. Little rainfall occurred in February and March, resulting in drying out of the overlying Avalon soils and entrapment of soil water in the compacted Estcourt.

Rainfall in the wet season, however, was spread throughout the season. There was adequate time for much of the infiltrating water to be removed by evapo-transpiration processes. In addition, the continuous rainfall prevented the Avalon soils from drying out, thereby ensuring that the soils were not a barrier to upward movement of soil water. The cover was therefore more effective in releasing water via evapo-transpiration than in the wet season. By implication, the storage potential of the layer was therefore exceeded during wet spells, but was adequate for low rainfall periods.

In contrast to Cell 8, which has 0.7m thick Avalon soils to provide storage for infiltrating rainfall water, Cell 6 has only 0.3m of Avalon soils after which it infiltrates the compacted Estcourt soil below. For average and dry rainfall years, rainfall water infiltrates the Estcourt soils but is prevented from being evaporated because of the dry, less conductive Avalon soils above. Outflow rates for dry and average rainfall years are therefore higher compared with those of Cell 8.

6.4 Analysis of concentration vs time of selected chemical species

Table 6 presents a summary of key trends in chemical parameters reflected in the time series plots.

Table 6: Summary of key trends in leachate quality data

Uncovered Cells: Cells 1, 2 and 3
An acid breakthrough occurred in Cell 1 during the latter part of 1997. This is reflected in a sharp decrease in pH (over a two-week period) and perhaps indicated that secondary precipitation of minerals either was prevented or flushed from the discard.
An increase in Fe concentration was recorded (due to lower pH conditions) properly catalysed by bacterial reactions and the oxidation of Fe^{2+} to Fe^{3+}, lowering the pH even further.
The pH decrease in Cells 2 and 3 during 2001 seems to have broken through the buffering processes associated with secondary minerals (CO_3 and hydrated Al compounds). The pH ranged from 3.9 - 4.9 for Cells 2 and 3 respectively.
Both Cells 2 and 3 showed a gradual decrease in alkalinity and increase in Mn and SO_4 concentration due to the lower pH.
The Ca concentration in all three cells stayed relative constant at approximately 500mg/l regardless of a change in pH. This could be attributed to gypsum solubility that controls the concentration of Ca and SO_4 in solution.
Single Layer Soil Covered Cells: Cells 4 and 5
Cell 4 turned acidic in February 2000.
Increase in the Fe concentration is a result of pyrite oxidation processes that took place.
An increase in Mg, Mn and SO_4 concentration levels reflect the increase in acidic conditions.
The constant Ca concentration is mainly due to the solubility of gypsum.
Cell 5 does not show any signs of acid breakthrough.
A slight increase in Mg and SO_4 levels might be indicative of the start of acidification.
Multi Layered Soil Covered Cells: Cells 6, 7 and 8
A very stable chemical trend is represented in these cells. SO_4 and Fe indicate no concentration change, as pH values stayed neutral at 7.7 in Cell 6 and 8.3 and 7.4 in Cells 7 and 8 respectively.
Multi Layered Sloped Soil Covered Cells: Cells 9 and Cell 10
Cell 9 showed signs of acidification in the beginning of 2002, with an increase in metals, Mg and SO_4 concentrations. Both the top and bottom samples seem to reflect the same chemistry since early 2001.
Cell 10 turned acidic in April 2000 and shows an increase in Mg and SO_4 concentration levels over time. Both the top and bottom samples seem to reflect the same chemistry since early 2001. Acidification at this steeper sloped cell needs to be explained.

7 NUMERIC MODELLING & COVER DESIGN

7.1 Introduction

Current best practice for discard dump rehabilitation requires the placement of a cover. The objectives of these covers may vary from site to site, but generally include:

- dust and erosion control,
- chemical stabilisation of acid forming wastes (through control of oxygen ingress),
- contaminant release control (through control of infiltration) and
- provision of a growth medium for the establishment of sustainable vegetation.

Typically, the performance objectives for discard dump covers are tied to specific design objectives that relate to objectives such as reducing net percolation and oxygen ingress, vegetation types/mixes and vegetation basal cover. However, in order to get closure for a waste facility with respect to the minerals act, the performance of a particular cover will also be measured with respect to surface and groundwater impacts and impact reduction.

The design or optimisation of a cover for a discard dump should therefore take account of specific design objectives aimed at achieving a required and Acceptable Risk Level in the receiving surface and groundwater environment.

7.2 SoilCover

The finite element modeling software *SoilCover* (SoilCover, 1997) was used to assess alternative cover scenarios for flat (or nearly flat) surfaces. This model is a coupled heat and mass transfer, saturated-unsaturated model, which combines soil conditions with atmospheric conditions. *SoilCover* is capable of predicting actual evapotranspiration from the soil profile. The model input parameters include daily climate parameters (air temperature, relative humidity, pan evaporation, and precipitation) as well as soil parameters (SWCC, k_s and hydraulic conductivity function).

SoilCover allows the computation of the resulting net flux of pore water (expressed as mm or inches per year) across the interface of a cover and mine rock for a given time period (typically based on one calendar year or hydrologic year). This net flux is commonly referred to as the "net percolation" of the cover system. *SoilCover* is a one-dimensional mode and it is implicitly assumed that the soil profile is horizontal and all soil water movement is vertical. Therefore, modelling results apply only to flat or nearly-flat surfaces.

SoilCover uses "formulas" similar to most models, which simulates the physics of a liquid phase in porous media. The soil surface evaporative flux is controlled by the difference in atmospheric and soil water vapour pressure, which makes it applicable to South African conditions. The *SoilCover* theory was verified against laboratory column observations in sand, silt and clay materials.

Vegetation plays a significant and dynamic role in the evapotranspiration process (Saxton, 1982). A vegetative uptake source term method is combined with a shade, or cover factor term. The method used by *SoilCover* accounts for the effects of canopy cover, root depth and density, and water stress. Lack of available plant water and/or high evaporative demands will cause most plants to biologically react by closing stoma, reducing transpiration and reducing metabolic reactions (Saxton, 1982). Under continued and increasing stress the plant will reach its wilting point. The wilting point results in leaf drop and tissue death (Saxton, 1982). Between 100kPa and 1 500kPa the plant limiting factor is reduced linearly as a function of the log of matric suction. The actual plant transpiration reaches zero at a value of suction equal to 1 500kPa. Figure 18 illustrates a typical relationship used by *SoilCover* to calculate the plant limiting factor.

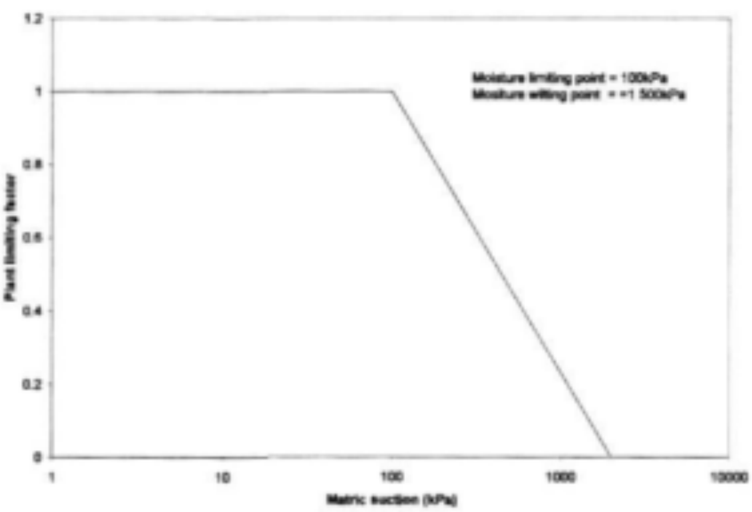


Figure 18: Plant Transpiration Reduction Versus Log Suction at the Root Centroid Node

Tratch (1995) verified the *SoilCover* vegetation algorithm by modelling an evapotranspiration experiment that was carried out in a carefully controlled environmental chamber. The experiment was similar to the Wilson (1990) column study except, in this case, plants were allowed to grow and the leaf area index and root depth were monitored. It was found that:

- Plant growth reduces evaporation.
- Potential evaporation is equal to the sum of transpiration and actual evaporation.

- Plant transpiration decrease once the soil suction values exceed the moisture limiting point.

The oxygen flux is derived using Fick's law for diffusion of oxygen. The diffusion coefficient is calculated using either the Millington and Shearer (1971) or Nicholson (1989) method.

7.3 Recharge Modelling

Recharge through a soil cover is dependent on a number of factors. These include meteorological or weather related factors, the type of soil used, the thickness and configuration of the soil cover. High net evaporation levels and the use of soil covers to act as store-and-release systems have great potential to sustainably reduce infiltration and oxygen ingress into coal discard dumps, ultimately reducing the seepage impact from discard dumps. The aim of a store-and-release soil cover is to retain the water that infiltrates through its surface. This stored water can then be released back into the atmosphere through natural processes i.e. evaporation and transpiration. The effectiveness of a soil cover to limit recharge and oxygen ingress is largely determined by its ability to retain water and the physical properties of the soil.

Unsaturated flow is complex and it is influenced by a host of soil and meteorological parameters such as the amount of sunshine the cover receives, the wind speed and humidity. The behaviour of water, once it has infiltrated below the surface of the cover, is dependent on the depth of the vegetation roots, and the soils ability to hold onto water under negative pore pressures. Many of these parameters are difficult to measure. Rainfall depths are often the only available meteorological data. Detailed soil parameters are difficult to measure, and estimates are usually made about their porosities and other general factors such as moisture retention properties. *SoilCover* was developed with these difficulties in mind. It utilises parameters that are easy to measure or estimate.

The unsaturated flow of *SoilCover* was calibrated for South African conditions by using the results of the experimental study of natural soil cover in rehabilitation of opencast mines and waste dumps in South Africa at Kilbarchan, a Water Research Commission (WRC) research project (Vermaak et al., 2004). The best performing (<5% MAP) store-and-release cover comprised a 1m thick layer (0.3m compacted Avalon, covered by an 0.7m uncompacted Avalon). The thicker (0.7m) uncompacted Avalon layer had a better store characteristic for infiltrated water, which was later released through evapotranspiration and therefore performed better. The fact that the cover was constructed only from Avalon soil, created a hydraulic continuity, which made the profile perform more efficiently as a store-and-release cover than thinner profiles.

7.4 Model Set-up

7.4.1 Single year simulations

A number of configurations of evaporative covers were simulated using *SoilCover*. Two soil types (Soils 1 and 8) with two different thicknesses were considered. A referenced coal discard thickness of 0.3m was assumed for the modelling. As a comparison, 0.5m and 1m coal discard thickness were also investigated. It was necessary to include some depth of coal discard since suction continuity across the soil/discard interface is likely to lead to discontinuity of moisture across the interface.

The soils were both modelled at 1m and 0.5m thick using climatic data for the calendar year 2000 only. The climatic data was obtained from the Kleinkopje mine; also the site from which samples were obtained. Soils were simulated at 95%, 90% and 85% Standard Proctor compaction at their optimum water contents. Table 4 contains a summary of initial conditions and some soil parameter data for the simulations. The impact of the clay-sized fraction in the Soil 1 is evident in the saturated permeability, which is an order of magnitude lower than that of the coarser Soil 8. For the Soil 1 the 90% Proctor dry density was 1 768.5kg/m^3 at water content of 9.5% (all water contents are reported as gravimetric water content values). Soil 8 had a dry density of 1 800kg/m^3 and water content of 9.3%. Soil water characteristic curves at these densities were determined in the laboratory using a pressure plate apparatus.

Retention characteristic data derived at 90% Proctor for Soil 1 showed that the soil had a higher saturated water content than Soil 8. Further, Soil 1 had an air entry value of 10.4kPa while the corresponding value for the Soil 8 was 6.9kPa (Table 4). Figure14 shows the soil water characteristic curves for the two soils with best-fit van Genuchten curves. Soil 1 retained water more effectively than Soil 8 at all measured values of applied suction. At the residual water content there was also a significant difference between the two. The saturated hydraulic conductivity of Soil 1 was significantly lower (1.7x10^{-7}m/s) than Soil 8 (2.4x10^{-6} m/s).

Freeze/thaw cycles were omitted. The influence of vegetation on the liquid moisture flux at the interface with the coal discard in a cover design was modelled. Vegetation was varied from none to excellent. The leaf index area of grass was applied with a six month growing season and 50mm root depth.

A concern with the *SoilCover* model is the use of the Fredlund and Xing curve to describe the soil water characteristic curve. Figure13 shows the van Genuchten curves of Soils 1 and 8, which are both reasonably good fits to the laboratory data. The Fredlund and Xing curve on the other hand (Figure19), extrapolates the data to negligible water content vales at high suctions. The laboratory data indicate a flattening out of the curve, i.e. only very small decreases in water content are expected at higher values of suction.

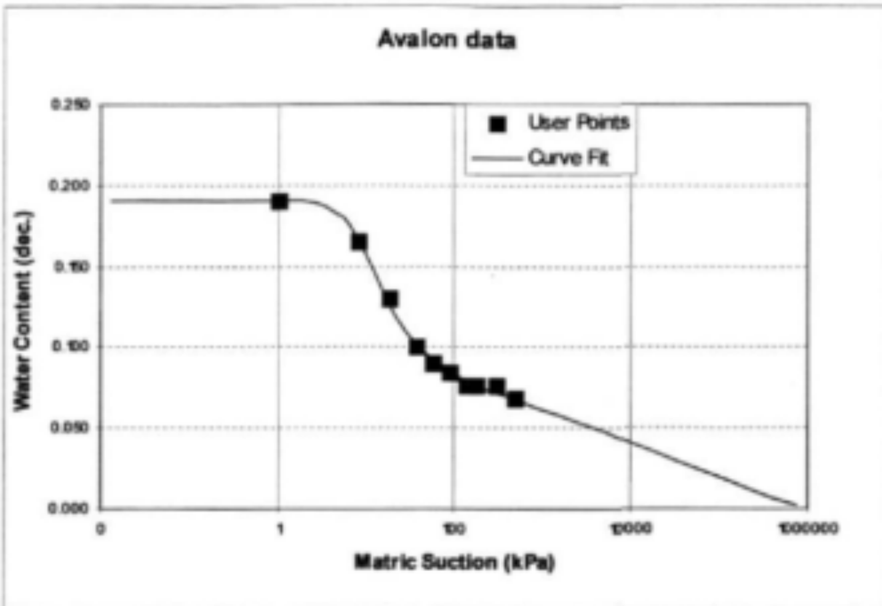


Figure 19: Soil water characteristic curve for Soil 1 with Fredlund and Xing curve as fitted by *SoilCover*

A reference cover configuration of 90% Standard Proctor density soil cover with no vegetation overlying 0.3m coal discard, was adopted. The 0.5m thick Soil 1 cover had a liquid moisture flux of 37mm at the interface with the coal discard while that of Soil 8 allowed 145mm of moisture to pass. Similarly, the 1.0m thick Soil 1 allowed 29mm of moisture through into the discard and the Soil 8 149mm. In both cases the flow through the Soil 1 cover was less than for the Soil 8. Generally it is expected that a thicker cover would have the potential to store more moisture during wet spells and allow evaporation, but in the case of the Soil 8 the thinner cover appeared to be more effective in reducing moisture flow into the coal discard. When considered together with the saturated permeability values, it is not surprising that less moisture flow occurred through the Soil 1 than the Soil 8 cover. It can be concluded that the Soil 1 type has potential to be suitable, at a preliminary investigation stage, for use in evaporative covers. Table 7 provides a summary of the single year simulations.

Table 7: Summary of *SoilCover* model runs

Soil	Configuration	Degree of soil compaction (%)	Vegetation			
			None	Poor	Good	Excellent
1	1m soil; 0.3m coal discard	90	Homa11	Homa11p	Homa11g	Homa11e
	1m soil; 0.5m coal discard	90	Homa15	-	-	-
	1m soil; 1m coal discard	90	Homa11	-	-	-
	1m soil; 0.3m coal discard, capillary break	90	Homa11c	-	-	-
	1m soil; 0.3mm coal discard	95	Homa11D	-	-	-
	1m soil; 0.3m coal discard	85	Homa11L	-	-	-
	0.5m soil, 0.3m coal discard	90	Homa15	Homa15p	Homa15g	Homa15e
	0.5m soil; 0.5m coal discard	90	Homa55	-	-	-
	0.5m soil; 1m coal discard	90	Homa51	-	-	-
	0.5m soil; 0.3m coal discard, capillary break	90	Homa15c	-	-	-
	0.5m soil; 0.3m coal discard	95	Homa15D	-	-	-
	0.5m soil; 0.3m coal discard	85	Homa15L	-	-	-
8	1m soil; 0.3m coal discard	90	Homh11	Homh11p	Homh11g	Homh11e
	1m soil; 0.5m coal discard	90	Homh51	-	-	-
	1m soil; 1m coal discard	90	Homh15	-	-	-
	1m soil; 0.3m coal discard, capillary break	90	Homh11c	-	-	-
	1m soil; 0.3m coal discard	95	Hamh11D	-	-	-
	1m soil; 0.3m coal discard	85	Homd11L	-	-	-
	0.5m soil; 0.3m coal discard	90	Homh15	Homh15p	Homh15g	Homh15e
	0.5m soil; 0.5m coal discard	90	Homh55	-	-	-
	0.5m soil; 1m coal discard	90	Homh51	-	-	-
	0.5m soil; 0.3m coal discard, capillary break	90	Homh15c	-	-	-
	0.5m soil; 0.3m coal discard	95	Homh15D	-	-	-
	0.5m soil; 0.3m coal discard	85	Homh15L	-	-	-

P poor vegetation
L 85% Standard Proctor density
g good vegetation
D 95% Standard Proctor density
e excellent vegetation
c capillary break

At the interface between soil and coal discard, a discontinuity in water content exists in all the simulations. This is an indication that the coal discard acts as a breaker layer or capillary barrier and assists the moisture retention in the above-lying soil cover layer. This improves the efficiency of the soil as an evaporative cover material.

The depth of the coal discard layer was varied between 0.3m, 0.5m and 1m. When considering the water content profiles, it became evident that the water content at the base of the discard did not change from the initial value. The moisture flux of Soil 1 at the interface between the discard and cover, was unaffected by discard depth while that of Soil 8 was only slightly influenced. The thickness of the layer required for a good estimate of actual field conditions is not known. It is expected that a moisture profile in the field will develop in the discard and will reach an equilibrium condition between the moisture infiltrating from the cover and background moisture values in the discard. It is not evident whether keeping the boundary moisture fixed in the simulation has an influence on the flux through the soil cover above the discard.

The influence of vegetation on the liquid moisture flux at the interface with the coal discard in a cover design was modelled. It was found that vegetation does influence the performance of a cover, increasing the effectiveness of a cover to limit rainfall infiltration and increasing evapotranspiration, as the quality of the vegetation increases from a poor to a good and excellent vegetated cover (Table 8). The improvement in cover performance due to vegetation in terms of absolute reduction in through flow rate was more evident in the Soil 8 covers (improving from 145mm to 36mm during the year) than the Soil 1 covers (improving only by some 5mm). However, the Soil 1 covers remain the most efficient in all vegetation scenarios.

The influence of density on the cover performance has been investigated by changing the model runs to represent the soil water characteristic curves obtained from the laboratory, at 85%, 90% and 95% Standard Proctor. Two cover configurations namely 0.5m and 1m thick soil cover with no vegetation overlying 0.3m coal discard were adopted. It was found that the cover performance of Soil 1 in terms of limiting moisture infiltration was best at 85%, then 90, followed by 95% density. Soil cover 8 performance on the other hand, (from best to worst) were 90%, 95% and 85% (Table 8). These results are indicative of the subtle relationship between water retention characteristic and hydraulic conductivity in the performance of soil covers. While the conductivity of Soil 1 is low, the larger pore size distribution afforded by the 85% proctor material enhances water storage and, at the same time, limits ingress of water into the discard layer. The smaller pore space of the denser material makes this a less efficient option, particularly in the shallower scenarios. Soil 8, on the other hand, has a higher hydraulic conductivity together with an open pore structure in the 85% proctor material and thus allows the most water through the profile. The 90% proctor provides the best cover for this material, being the best combination of hydraulic conductivity and pore size distribution for this particular soil.

Finally, the influence of a capillary break was investigated. Once again, vegetation was omitted and a reference soil density of 90% was adopted. It could be noted from Table 8 that the addition of a capillary break almost halved the infiltration of moisture through Soil 1.

The effect was more pronounced with Soil cover 8. Despite this dramatic reduction in moisture infiltration of Soil 8, Soil 1 the moisture infiltration of Soil 1 was still less. The cover performance in terms of discharge through the cover, Soil 1 was consistently better than that of Soil 8.

Table 8: Summary of model run results

Soil	Configuration	Degree of soil compaction (%)	Water flux (%Annual Rainfall) out of the soil, into the discard[5]			
			Vegetation			
			None	Poor	Good	Excellent
1	1m soil; 0.3m coal discard	90	1.2	1.2	1.1	0.9
	1m soil; 0.5m coal discard	90	1.2	-	-	-
	1m soil; 1m coal discard	90	1.2	-	-	-
	1m soil; 0.3m coal discard, capillary break	90	0.5	-	-	-
	1m soil; 0.3m coal discard	95	3.1	-	-	-
	1m soil; 0.3m coal discard	85	1.1	-	-	-
	0.5m soil; 0.3m coal discard	90	1.4	1.2	1.0	0.7
	0.5m soil; 0.5m coal discard	90	1.4	-	-	-
	0.5m soil; 1m coal discard	90	1.3	-	-	-
	0.5m soil; 0.3m coal discard, capillary break	90	0.7	-	-	-
	0.5m soil; 0.3m coal discard	95	2.8	-	-	-
	0.5m soil; 0.3m coal discard	85	1.4	-	-	-
8	1m soil; 0.3m coal discard	90	22.4	14.2	10.0	5.6
	1m soil; 0.5m coal discard	90	21.6	-	-	-
	1m soil; 1m coal discard	90	20.2	-	-	-
	1m soil; 0.3m coal discard, capillary break	90	4.0	-	-	-
	1m soil; 0.3m coal discard	95	26.2	-	-	-
	1m soil; 0.3m coal discard	85	28.2	-	-	-
	0.5m soil; 0.3m coal discard	90	22.4	14.4	11.4	8.3
	0.5m m soil; 0.5m coal discard	90	20.8	-	-	-
	0.5m soil; 1m coal discard	90	19.1	-	-	-
	0.5m soil; 0.3m coal discard, capillary break	90	2.7	-	-	-
	0.5m soil; 0.3m coal discard	95	22.1	-	-	-
	0.5m soil; 0.3m coal discard	85	23.3	-	-	-

[5] Annual rainfall (2000) =647mm

7.4.2 Analysis of representative climatic period

Water flow through a soil cover was optimised to 0.5% MAP by varying the cover thickness and configuration. It should be noted that this might not be representative of the cover performance as only a single year was simulated. The weather data for this year may not necessarily be representative of that of a longer period of time. Additional analysis, simulating a period of 15 years was thus carried out.

Following the results of the event (single year) analysis, it was decided to investigate the performance of the 0.5m thick Soil 1 cover for several consecutive years. A 0.5m thick soil cover as opposed to a 1m cover was selected as the cover performance of the former was only slightly less than the latter, while the construction cost would be significantly reduced by a thinner soil cover. The influence of vegetation was completely ignored in the analysis.

The coal discard did not appear to influence the infiltration water flux of Soil 1 and consequently, a depth of 0.3m was assumed for simulations.

The analysis aimed at assessing the influence of compaction and capillary barrier on the infiltration of a cover over a prolonged period of time. Results were compared with that of a reference soil cover (0.5m Soil 1 cover, compacted to 90% Standard Proctor density). Three scenarios were investigated namely:

- 0.5m Soil 1, 90% compaction
- 0.5m Soil 1, 85% compaction
- 0.5m Soil 1 with a capillary barrier, 90% compaction

Since the weather data for a single year may not be representative of long term behaviour, as it may include extreme events, simulations were carried out using a 15 year record (1978 to 1993). Once again the climatic conditions of Kleinkopje mine were employed for the numerical analysis. These were obtained from the weather bureau. Daily temperature, radiation, humidity and wind speed data were obtained from gauges 0478 808 7 and 0478 867 7 in Bethal, the nearest available weather station. The data were collected for January 1978 to December 1993. The data set was not complete and consequently a patching exercise had to be carried out on the data before it could be used.

For the purpose of clarity, the patching procedure will be explained using the data from one month as an example. The maximum air temperature measured in October 1964 was used as an example:

- The daily temperature data for October 1964 was added together to give a monthly total of 706,1°C.

- The number of days, during this month, over which temperature measurements were made, was 27. On three days during this month, no measurements of temperature were taken.
- The daily average temperature for that month was calculated by dividing the monthly total by the number of days for which measurements were taken (706,1 / 27) = 26,15°C.
- The daily average values were calculated in this fashion for all the months in the data set. During some months no measurements were taken. The average value for these months was left out. The calculated average values for all the October months from 1964 to 2002 were then averaged. This average value was used to fill in any blanks for the temperatures in October. This exercise was repeated for all the months in a year, for all the measured parameters.

Figure 20 shows the annual precipitation for each year (bar chart) and discharge through the soil profile. It can be noted that the discharge of Soil 1 placed at a light compaction (85% Standard Proctor) was the highest. The standard cover at 90% proctor yield a lower through flow and the cover containing a capillary barrier yields the lowest discharge. On an annual average basis, the mean discharge through the light cover is 0.91% of the average annual precipitation, while that of the standard Avalon cover and capillary barrier cover are 0.70% and 0.21% respectively.

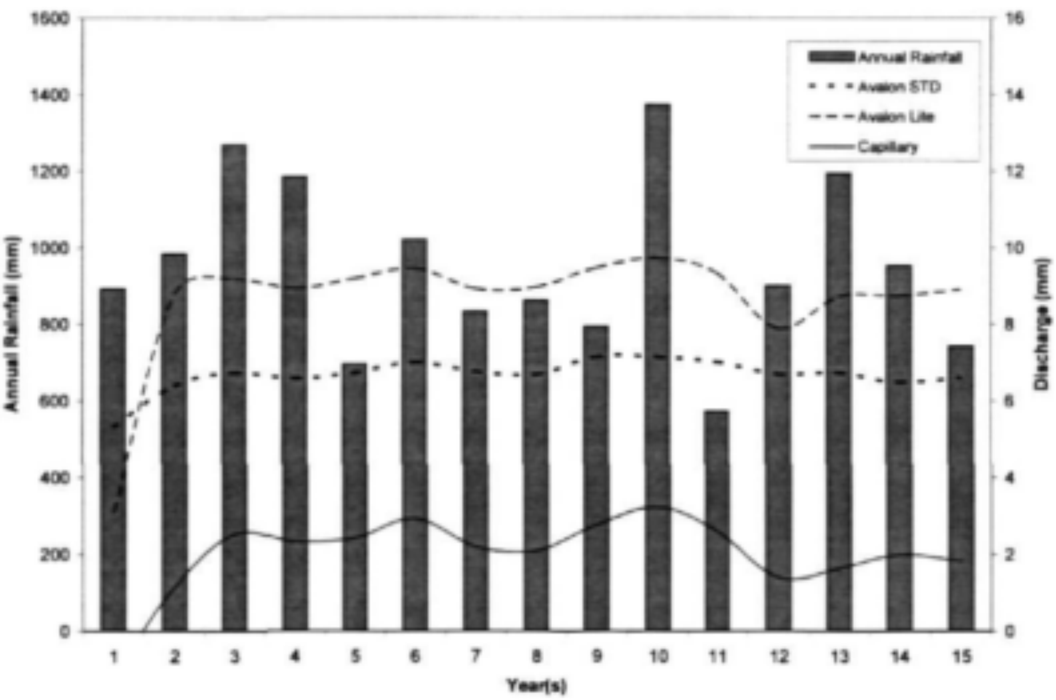


Figure 20: Results of the Soil 1 covers long term simulations, showing annual precipitation and the discharge through the cover into the discard

The numerical analysis, based on representative climatic data, indicated that a 0.5m thick soil cover of Soil 1 at 90% Standard Proctor density as well as one with a capillary break, performance in terms of water infiltration into the cover, were the best. The former however may be the favoured cover configuration as the addition of a capillary break increases the construction cost. Over the 15 year record, the average annual infiltration into the top surface of the soil cover of the standard and capillary barrier profiles was some 42mm/a (4.5% of MAP), while the light soil cover infiltration was 75mm/a (7.9% MAP). While the standard cover and the capillary cover allow similar infiltration into the cover over the long term, the discharge through the cover into the discard differs between these cover types. The average annual discharge through the cover into the discard over the 15 year simulation is 6.6mm/a for the standard cover but only 2.0mm/a for the capillary break cover. Hence the capillary break cover is more efficient in storing the infiltrated water and releasing this to the atmosphere. Clearly, the significance of these differences in discharge into the discard requires assessment as to their impact, prior to selection of the final cover design.

If the results of the event (single year) analysis could be extrapolated to the representative climatic analysis, it could be noted that the performance of Soil cover 1 could be further improved by vegetation (preferably good to excellent).

8 LABORATORY EXPERIMENT

8.1 Introduction

While computer simulations of cover performance enable a wide range of scenarios to be evaluated, observation of the runoff, infiltration and evaporation processes is useful in order to:

- determine the effect of slope on runoff and infiltration characteristics and
- test the validity of the computer simulations, where material properties and flow patterns may not conform to the theory on which the models are built.

This is particularly true if the observations can be made in a controlled environment. Therefore, a laboratory flume was constructed to test a layered soil/discard profile subjected to simulated rainfall at various slopes.

8.1.1 Flume structure

The flume was constructed from a frame of welded channels (0.1x0.05x0.005m) braced with angles (0.05x0.05x0.005m) in a box structure of 1.5m long, 1.2m wide and 1.2m deep, (Figure 21). The sides, ends and base were formed with 0.02m shutter ply bolted to the frame and sealed with a silicon sealant. The frame was mounted onto a 10 ton bearing and secured to a concrete plinth. The bearing was placed off-centre so that tilting of the flume could be effected by lowering one end on hydraulic jacks.

Drainage holes were drilled in the base of the flume and collection cups secured below the holes. The flume compartment was split in two down the long axis by inserting a dividing wall of shutter ply. This was done to allow a full profile to be tested with the volume of soil sample delivered from Mpumalanga. Runoff outlet holes were drilled into the downslope face at the final level of the top of the profile. Plastic drainage pipes were inserted into these holes to lead the runoff water into a gutter which discharged into a tipping bucket mechanism (Figure 21).

8.1.2 Rainfall simulator

The rainfall simulator comprised a flat water reservoir of 1.5x1.0x0.05m, constructed from sheets of Perspex with an inlet pipe, control ball valve and filter for water supply. The bottom face of the reservoir was drilled to receive 0.3mm ID, stainless steel needles at 0.04m centres, through which the simulated rainfall was generated. The rain simulator was tested by measuring the simulated rainfall intensity with automatic, tipping bucket rain gauges at various supply valve settings. The rainfall simulator was mounted onto a frame above the flume as shown in Figure 21. During the application of rainfall to the soil cover, a rain gauge was set up under the side of the simulator which did not discharge into the compartment being tested.

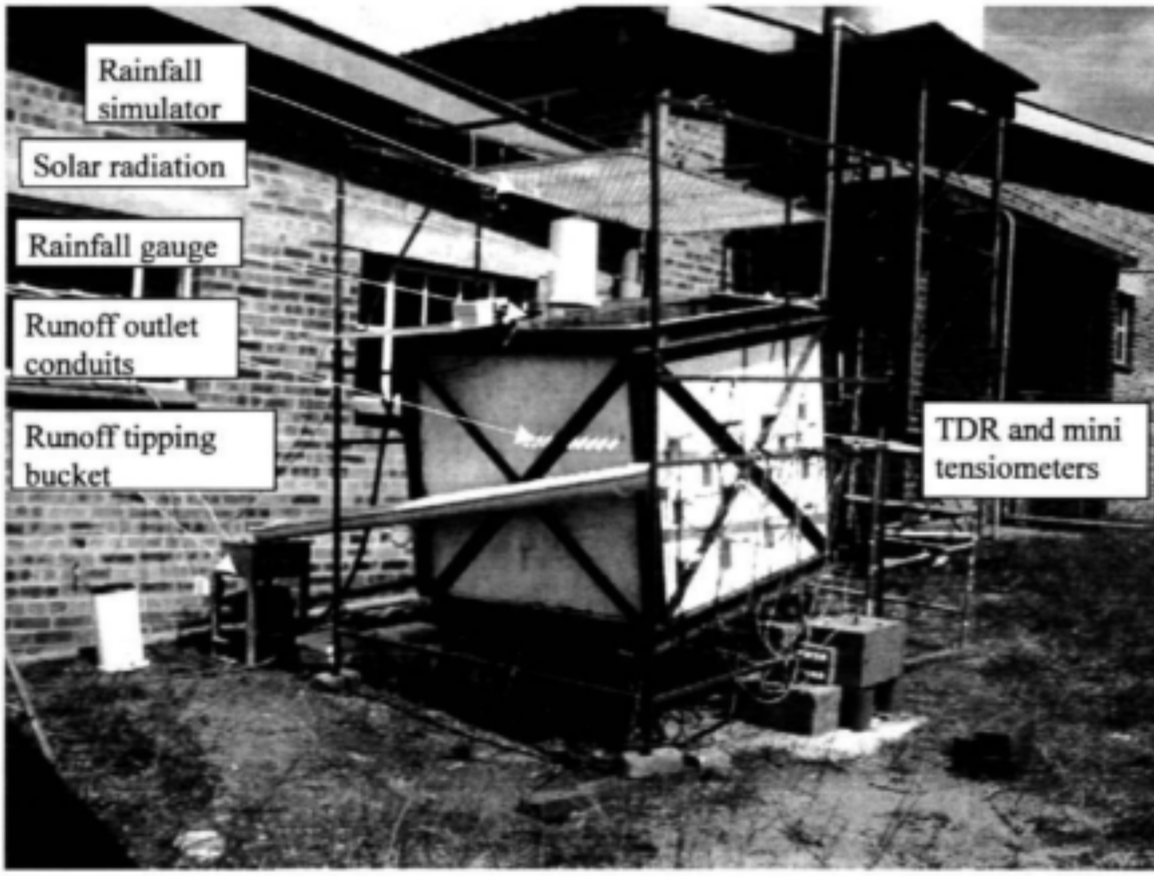


Figure 21: The experimental flume and rainfall simulator at the Ukulinga farm, University of KwaZulu-Natal

8.1.3 Instrumentation

Instrumentation was placed into the sample from the side in the pattern shown in Figure 22. A row of four soil water content and soil water matric potential sensors were positioned at 0.05m (Probes 1-4), 0.15m (Probes 5-8), 0.30m (Probes 9-12) and 0.54m (Probes 13-16) below the top of the soil layer (Figure 22).

Time Domain Reflectometry (TDR)

A Campbell Scientific Instrumentation TDR100 system was installed using 14 CS605 0.3m long, 3-rod probes. Positions 8 and 16 were not instrumented with TDR. The TDR100 system measures volumetric water content and electric conductivity of the soil by analysis of the time domain reflectometry of an electromagnetic wave in the probe. The TDR probes were inserted into the packed soil cover using a guide designed to keep the probe rods parallel. Two multiplexers were used to connect the probes to the TDR100 wave generator and reflectometry analyser. The TDR100 instrument was connected to a Campbell Scientific CR10X logger, which triggered the sampling sequence and recorded the water contents analysed in the TDR100 instrument. The sampling rate during rainfall events was set at 10 minutes and during evaporation periods, to 1 hour.

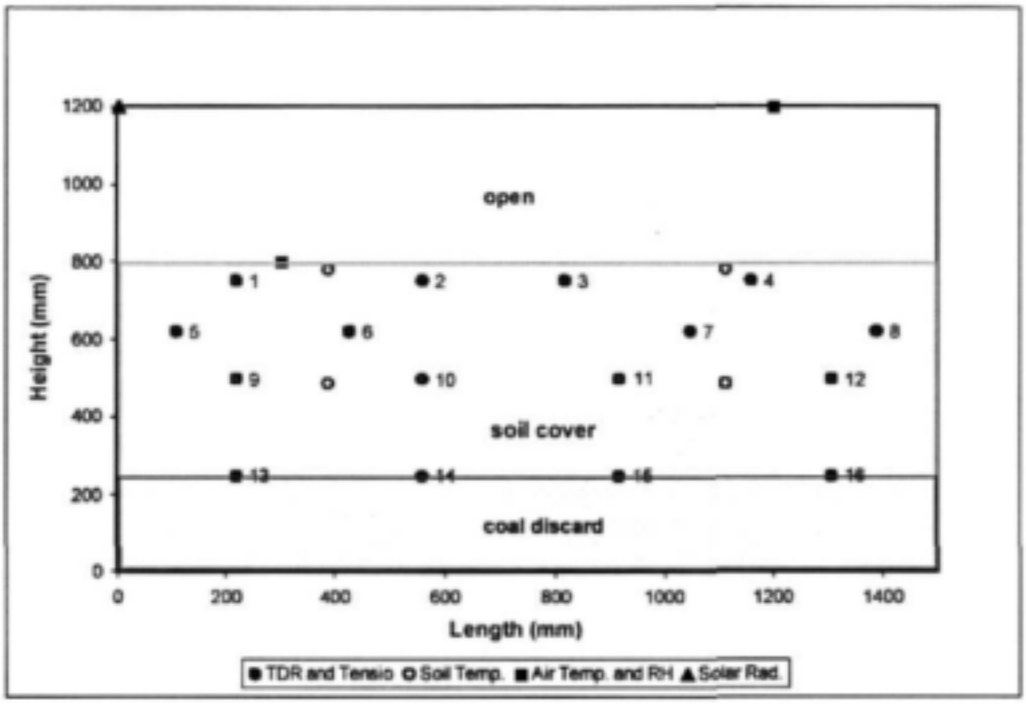


Figure 22: Layout of the cover profile and instrumentation (numbered markers refer to TDR and tensiometer probe positions in the compacted Soil 8) for the laboratory flume experiments

Miniature tensiometers

Miniature tensiometers comprised 6mm diameter, 20mm long, ceramic cups connected to 6mm diameter plastic hydraulic tubing. Each ceramic and tubing assembly was filled with de-aired water and connected to a differential pressure transducer. The ceramic was inserted into the side of the sample, a distance of 0.2m. The differential pressure transducer then recorded the negative pressure of the pore water in contact with the ceramic. The transducers were connected in sets of four, to HOBO voltage recording loggers. Sampling rates were set at 15 minutes.

Soil temperature

Soil temperature probes were inserted at two positions in sample as shown in Figure 22. At each position, soil temperature probes were placed immediately below the soil surface and at 0.3m below the surface. These temperatures were recorded at 15-minute intervals in HOBO loggers, throughout the experiment. However, the surface probes were removed during the rainfall simulation events and replaced immediately afterwards.

Air temperature and humidity

Air temperature and humidity were recorded on the surface of the soil and at the top of the flume compartment, 0.4m above the soil cover surface at the positions shown in Figure 22. The air temperature and humidity data were recorded to HOBO loggers at 15-minute intervals.

8.1.4 Cover material

The material supplied, comprised a reddish soil (Soil 8) and a coal discard. Textural analysis of the soil was performed on two sub-samples and is indicated in Figure 23. The soil material comprised

- Clay 10%
- Silt 30%
- Sand 60% fractions

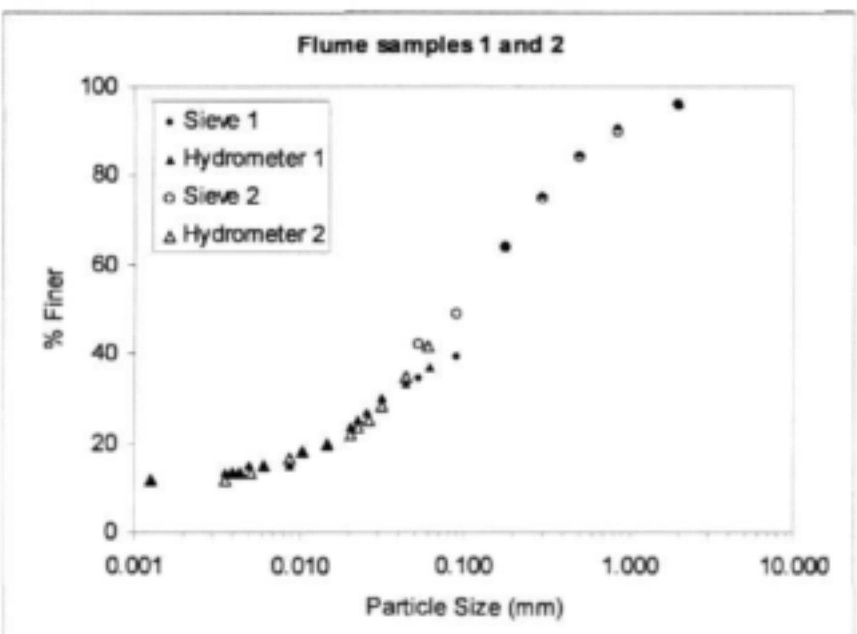


Figure 23: Textural analysis of the soil used in the flume experiment

The layered configuration desired was 0.3m coal discard and 0.5m compacted soil cover. However, there was only sufficient material to make up a 0.22m layer of coal discard and so the soil layer was increased to 0.54m to align with the instrumentation ports (Figure 23). The soil sample was supplied in plastic bags. The water contents of the soil in the bags varied from 15% to 28%. The soil was therefore mixed on a plastic sheet and allowed to dry before packing. The water content of mixed samples of the packed soil was 18%. The soil was weighed using a platform scale and packed in 0.1m lifts into the flume and compacted to a density of 1 800kg/m^3.

The sample was allowed to equilibrate for 7 days before the start of the first event. Fourteen days of drying and equilibration preceded the second event and a period 7 days observation of evaporation and equilibration followed the second event. Between the events, and during the evaporation monitoring period, cracks were noted on the surface of the material as indicated in Figure 24. The sample also shrunk slightly from the sidewalls and aluminium sheeting was used to prevent preferential flow into the space between soil and wall. The cracks and spaces were closed rapidly at the onset of the simulated rainfall events. The sample was protected from natural rainfall by placing a cover over the top of the flume during rain.

Figure 24: Cracks evident on the surface of the soil material after wetting events

8.2 Results of events and evaporation

Two events were simulated in the laboratory flume. The first, with the flume set at a slope of 1:50, comprised a rainfall event of 59.4mm and the second, with the flume at 1:5, comprised an event of 92mm. The events were applied with a low intensity initially, increasing slowly over the 50-minute duration of the events. Results of the runoff responses are presented in Table 9 and in Figure 25 and Figure 26.

Table 9: Summary of the laboratory flume simulated rainfall events

Cover slope	Rainfall (mm)	Runoff (mm)	Runoff factor (%)	Antecedent water content (%)
1:50	59	16	25	25
1:5	92	26	28	20

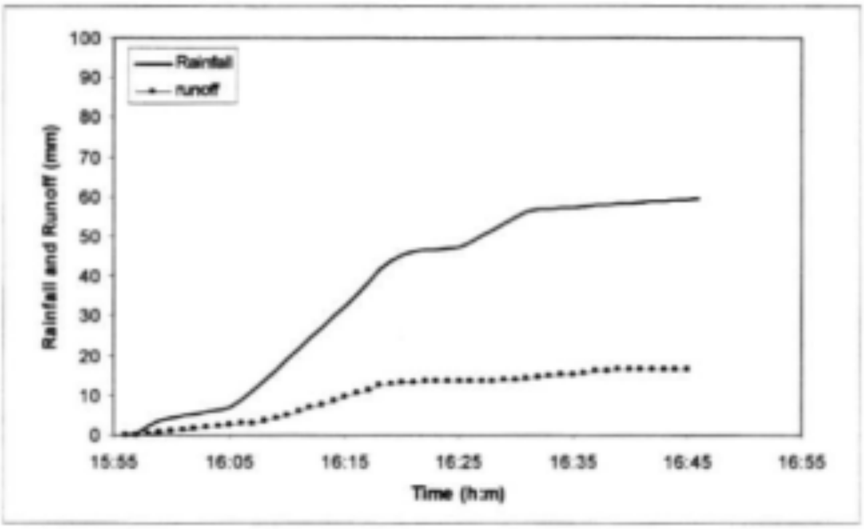


Figure 25:Measured rainfall and runoff of Event 1 in the laboratory flume

Despite the significant increase in slope between the two events, the runoff only increased from 25% of the rainfall in the first event (1:50 slope) to 28% in the second event (1:5 slope). The antecendent water content is lower (20%) in the second event than in the first (25%), so the initial infiltration rate would have been greater in the second event than in the first. There was no drainage observed at the base of the flume during or after each event. Hence, it can be concluded that the soil cover was effective in preventing deep discharge into the coal discard.

Significant erosion occurred during both events, but this was not quantified.

8.2.1 Soil water response: Event 1 (1:50 slope)

The soil water response to the application of rainfall in Event 1 is immediate in the top 0.1m as indicated by the response of TDR Probes 3 and 4 (Figure 25). The water content increases from 25% to 36% during the application of the rain. Deeper in the profile, the response is dampened and the increase is only from 28% to 33% (Probes 6 and 7, Figure 25). Below 0.2m the response in water content is small (Probes 11 – 15).

The tensiometers also respond immediately at the 0.1m depth (Tensiometers 1 to 3, Figure 26) rising from –3.m to close to 0m. Tensions begin decreasing again, after the cessation of the rainfall event during redistribution and evaporation. The response in the deeper horizons is slower and not as pronounced. Responses at the deepest two levels (Tensiometers 9 to 16) are surprising, considering the water contents do not change significantly at these depths. Nevertheless, this could be a characteristic of the water retention relationship of the soil at the wet end, where significant changes in matric pressure head could occur with negligible changes in water content. Alternatively, this behaviour could be due to the transfer of pneumatic pressure of the invading wetting front to the deeper soils.

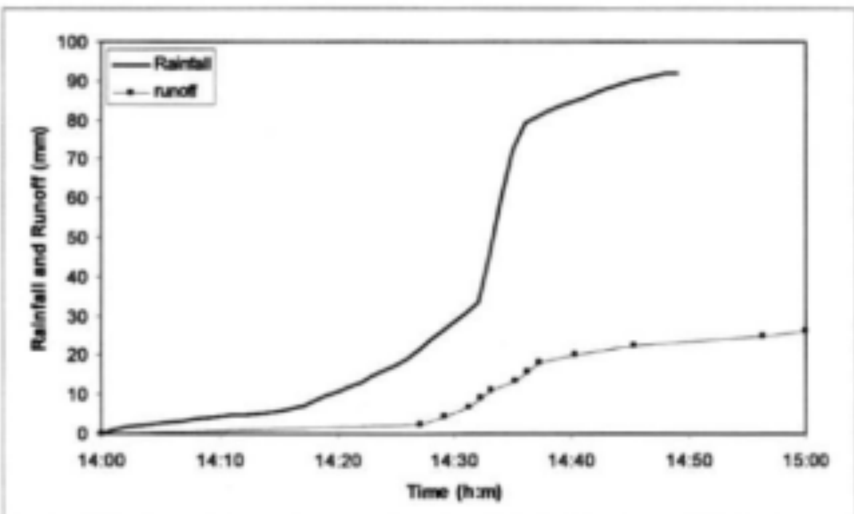
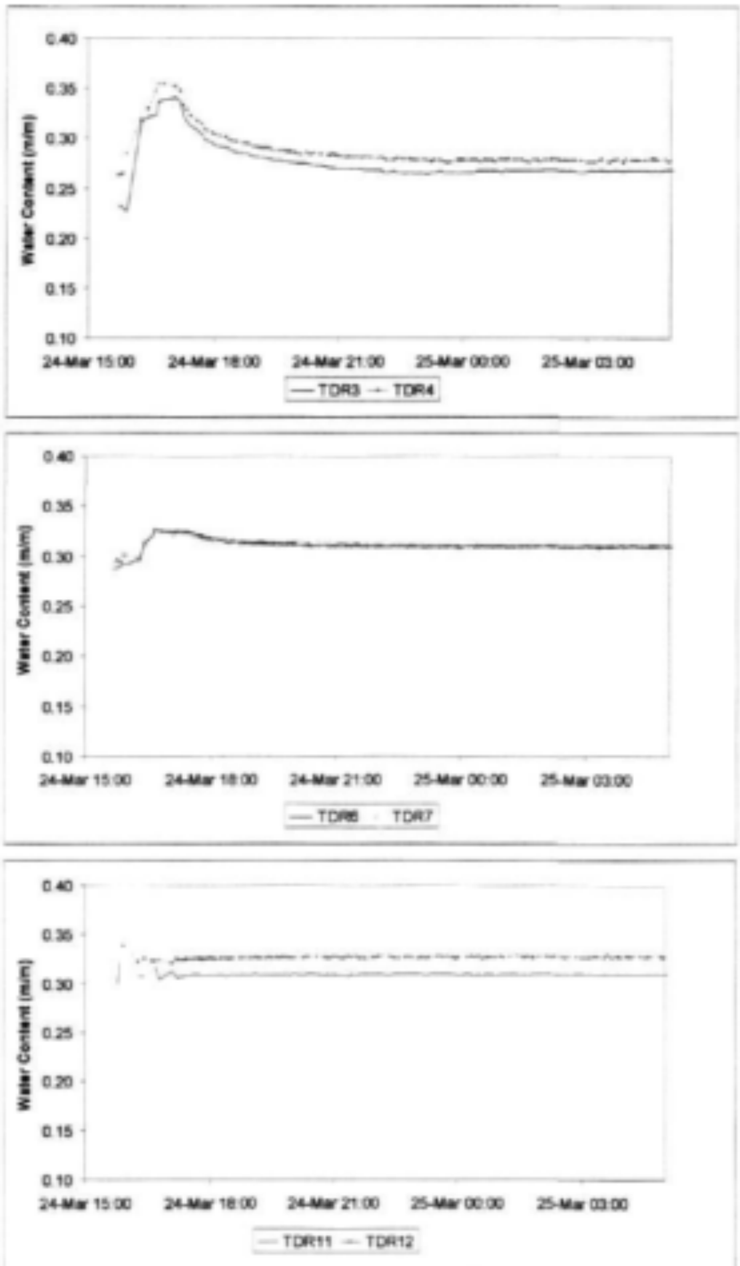


Figure 26: Measured rainfall and runoff of Event 2 in the laboratory flume

8.2.2 Soil water response: Event 2 (1:5 slope)

Similar behaviour is evident during the second event. The soil water response to the application of rainfall is again, immediate in the top 0.1m as indicated by the response of TDR Probes 3 and 4 (Figure 27). The water content increases from 20% to 29% during the application of the rain. Deeper in the profile, the response is dampened and the increase is only from 28% to 32% (Probes 6 and 7, Figure 27). Below 0.2m the response in water content is small (Probes 11 – 15), but increases slowly with time as water arrives deeper in the profile. At no time does the pressure in the deeper part of the profile become positive and hence no drainage is expected. Indeed, there was no drainage collected from the collection cups below the flume at any time during the experiment.

Tensiometer responses are similar to those in Event 1 and the drying can be seen by the daily decrease in matric pressures in the profile during the week following the event (Figure 28).



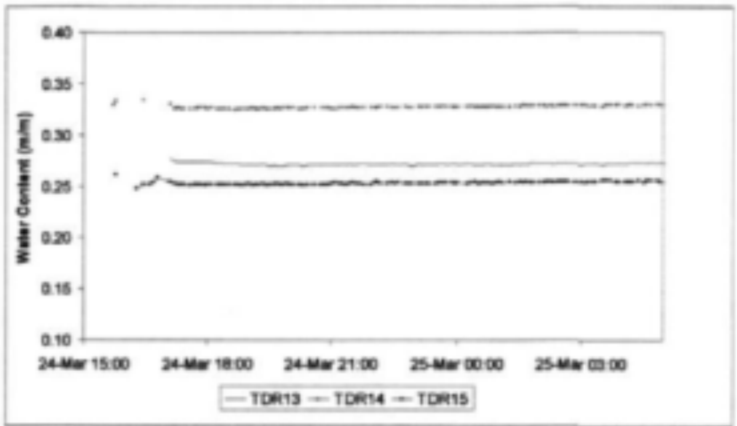
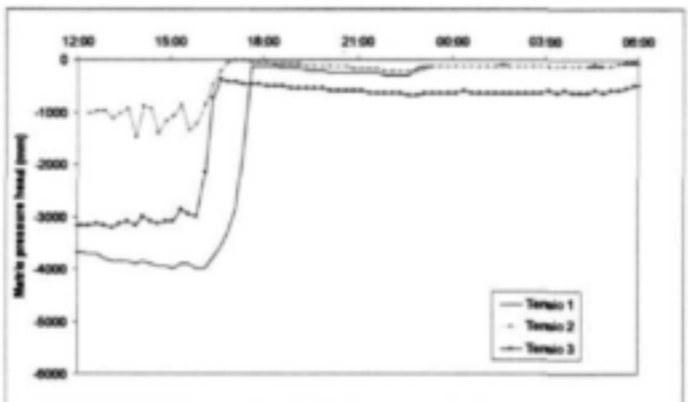
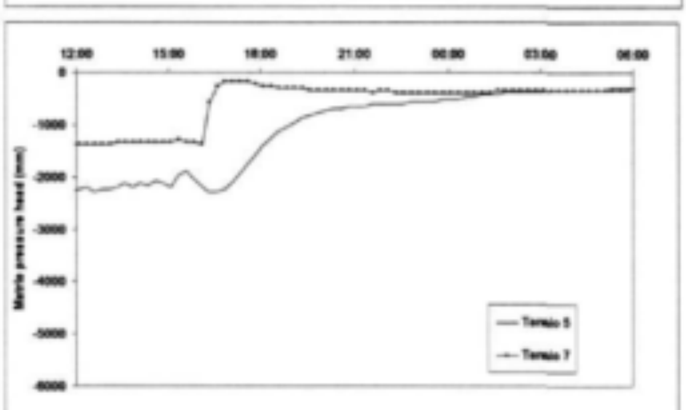


Figure 27: Soil water content response during Event 1 of probe sets at a) 0.05m b) 0.15m c) 0.3m and d) 0.45m





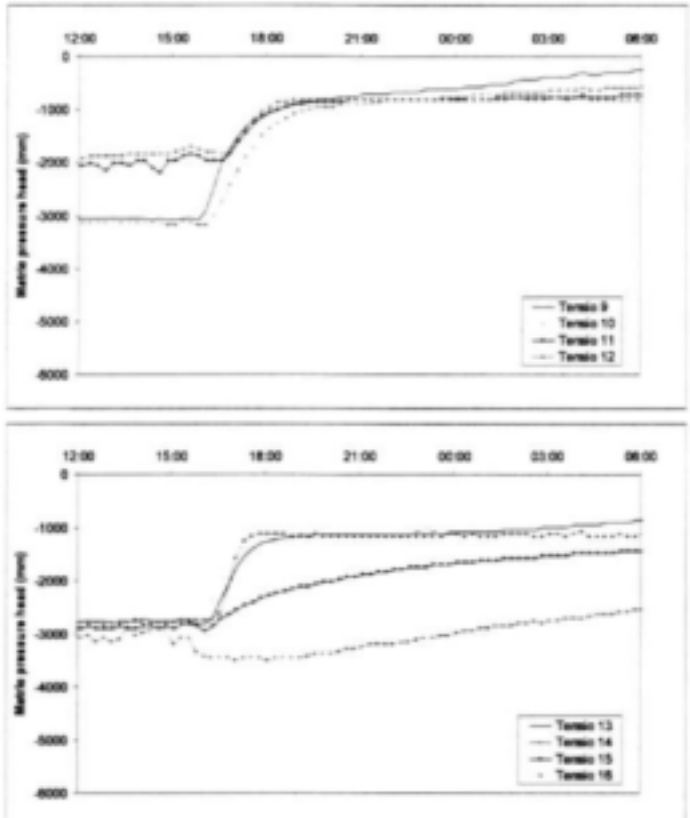
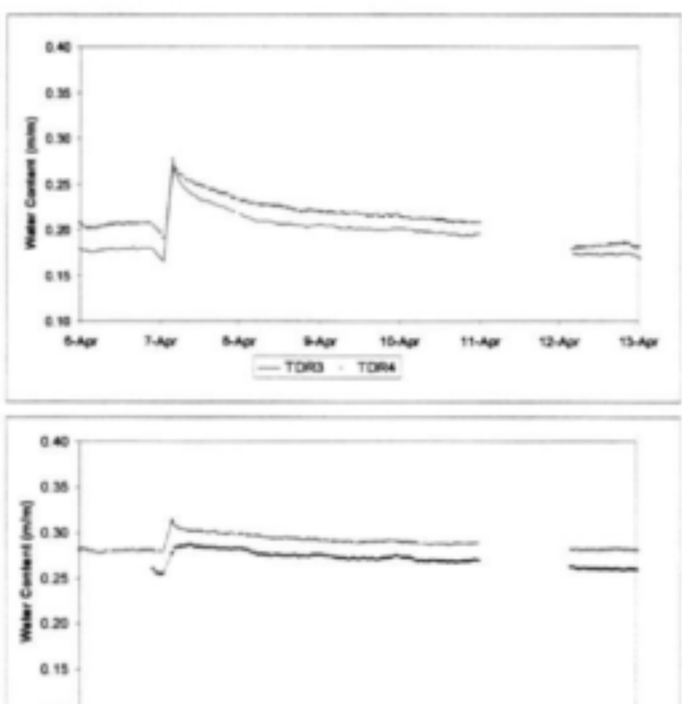


Figure 28: Soil matric pressure response during Event 1 of probe sets at a) 0.05m b) 0.15m c) 0.3m and d) 0.45m



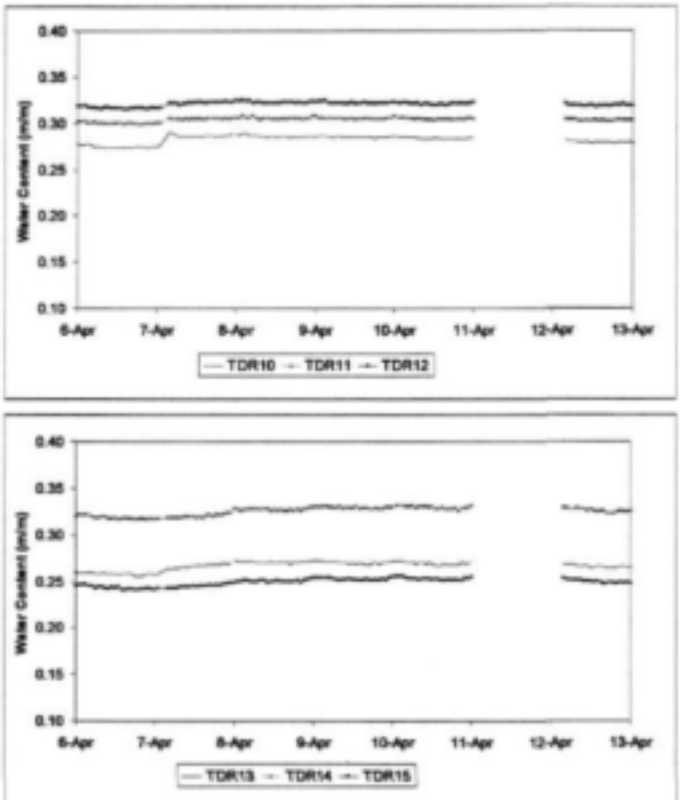
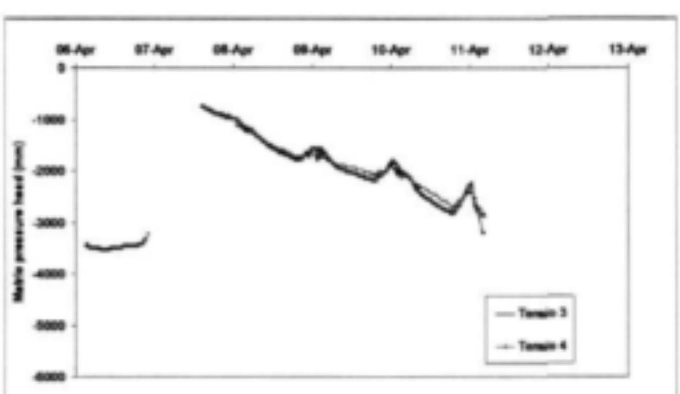


Figure 29: Soil water content response during Event 2 of probe sets at a) 0.05m b) 0.15m c) 0.3m and d) 0.45m



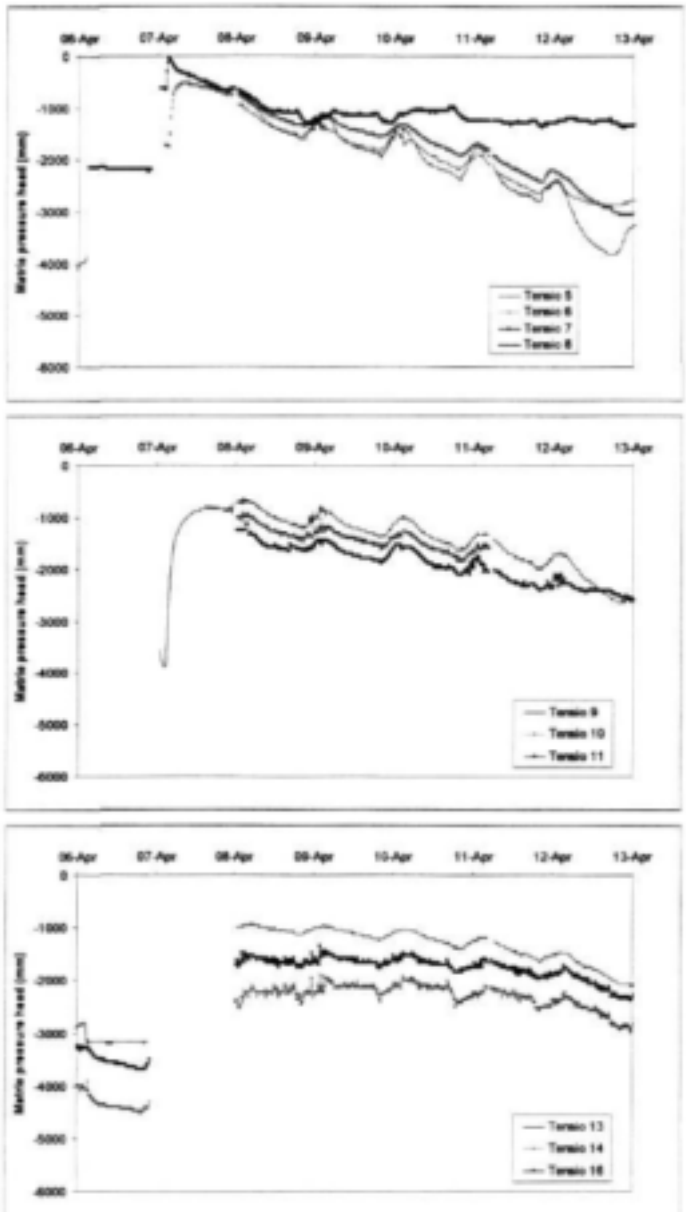


Figure 30: Soil matric pressure response during Event 2 of probe sets at a) 0.05m b) 0.15m c) 0.3m and d) 0.45m

8.3 Flume simulation

Event 2 of the experimental cover was simulated using the *HYDRUS2D* model. An atmospheric boundary condition was defined on the top surface and a free drainage boundary was specified below the coal discard. The initial conditions were specified as closely as possible to the observed initial status of the matric pressure heads and soil water contents (Figure 31). The rainfall/runoff response was controlled by the hydraulic properties of the soil and the evaporation rate was adjusted in proportion to observed temperature and radiation data until the observed matric pressure head responses were simulated faithfully during the drying phase.

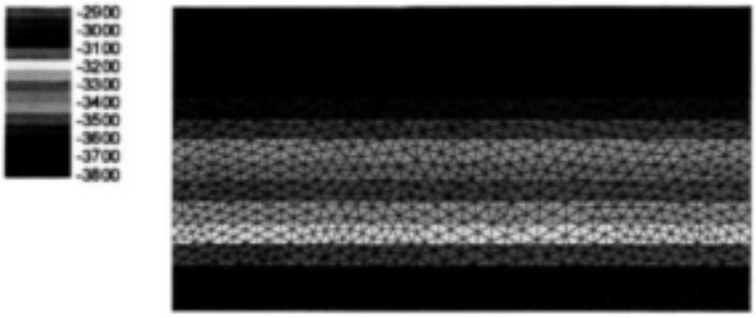
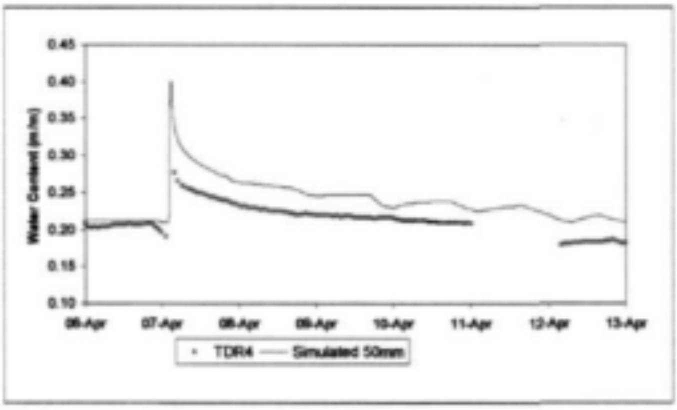


Figure 31: Initial conditions in the *HYDRUS2D* simulation, with soil matric pressure head varying from 2.9m at the base of the discard to 3.8m at the surface of the soil cover

The results of the simulation against observed data are shown in Figure 32 for water content and Figure 33 for matric pressure head. The simulated matric pressure head track the observed responses accurately at all levels (Figure 33). Diurnal fluctuations in the observed matric pressure head response are due to temperature variations in the water filled plastic tubing connecting the miniature ceramic to the pressure transducer. At night, the cool temperatures cause a decrease in matric pressure head while during the day the warmer temperatures relax the tension in the tube and this manifests as an increase in matric pressure head. In the simulated response, diurnal fluctuations are caused by redistribution of pressures near the surface during the night and drying in response to evaporation from the surface during the day. The rate of drying is clearly more rapid in the top layers than deeper in the profile. During the six days after the event, the matric pressure head reduces from 0m to –4m in the 0.05m depth layer, (Figure 33a), while the matric pressure head reduces from –1m to –2.7m in the 0.3m depth layer (Figure 33c). Simulated responses reflect this drying rate faithfully with daily simulated actual evaporation varying between 1 and 5mm.



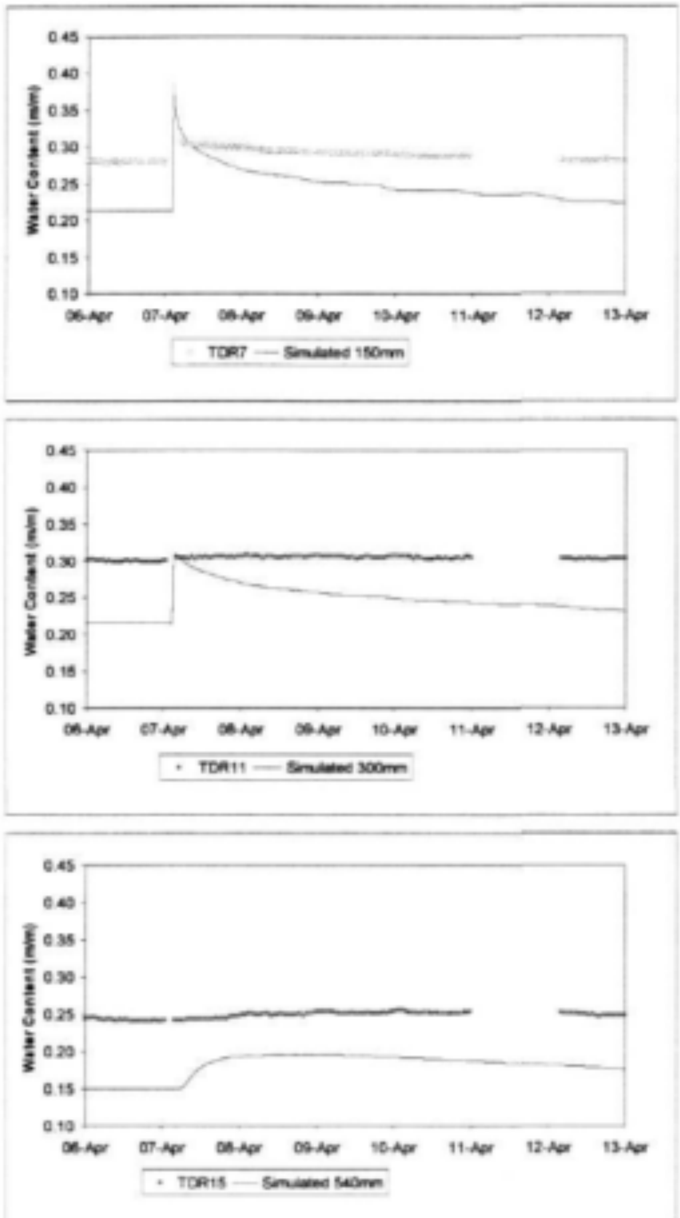


Figure 32: Simulated and observed water content response for Event 2 at a) 0.05m b) 0.15m c) 0.3m and d) 0.54m depths

Simulated water contents match the observed data only in the near-surface layer (Figure 32a). Observed water contents deeper in the profile prior to the event are significantly higher than the initial simulated water contents. The deeper observed water contents do not increase significantly during the event as is reflected in the simulated responses. At the 0.15m depth the water content increases from 28% to 32% during the simulated rainfall, while the simulated water contents increase from 21% to 37%. There is a slow decrease in observed water content at 0.15m depth during the drying period, but not as much as in the simulated response. At the 0.3m and 0.54m depths, the observed water contents increase gradually over the first three days after the event and then decrease in response to the drying at the surface.

This response is only evident in the simulated water contents at 0.54m depth (Figure 32d). The initial wetting up during and immediately after the event as simulated at the 0.3m depth is not evident in the observed water contents, (Figure 32c and d) although the observed initial water content (30% at 0.3m and 25% at 0.54m) is higher than the simulated initial water content (22% at 0.3m and 15% at 0.54m).

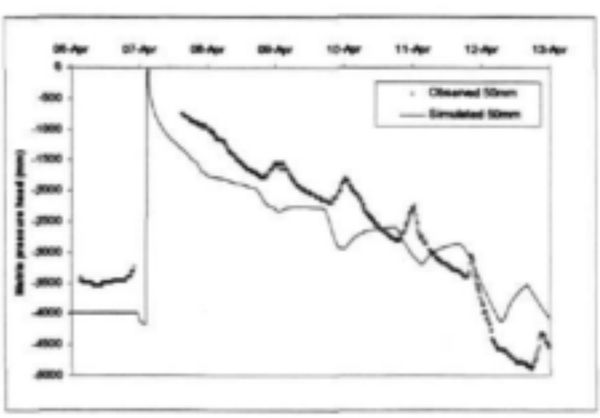
The lack of continuity between observed water contents and the matric pressure heads in the deeper layers could be due to inconsistencies in packing density of the material. The material in the deeper profile (below 0.15m), being packed to a higher density would retain water at a higher water content than in the less dense upper layers. The deeper layers would thus manifest higher water contents at the observed matric pressure heads than the upper layers. Denser deeper layers would also explain the small changes in water content during the event and drying phases, but significant variation in corresponding matric pressure. A single material type at all levels was used in the simulations.

8.4 General slope runoff analysis

While the *HYDRUS2D* model can be used to define a sloped profile, the runoff process is nevertheless determined by the hydraulic characteristics of the porous medium, not the overland flow characteristics. Hence, a comparative study of the *SoilCover* and *HYDRUS2D* simulations are not presented here. These models have been shown to be comparable in their ability to simulate cover profiles, (Noël and Rykaart 2003).

The relationship between runoff response to rainfall events and slope is not well known (Janeau et al., 2003, Fox et al., 1997 and Chaplot and Le Bissonnais, 2000). Some research shows a decrease in runoff with increase in slope due to crust formation of flatter slopes.

An assessment of the theoretical runoff rates on different slopes for different events was performed using an analytical technique. The hydraulic characteristics of the Avalon (Soil 1) and Estcourt soils of the Kilbarchan experiment were used in the analysis.



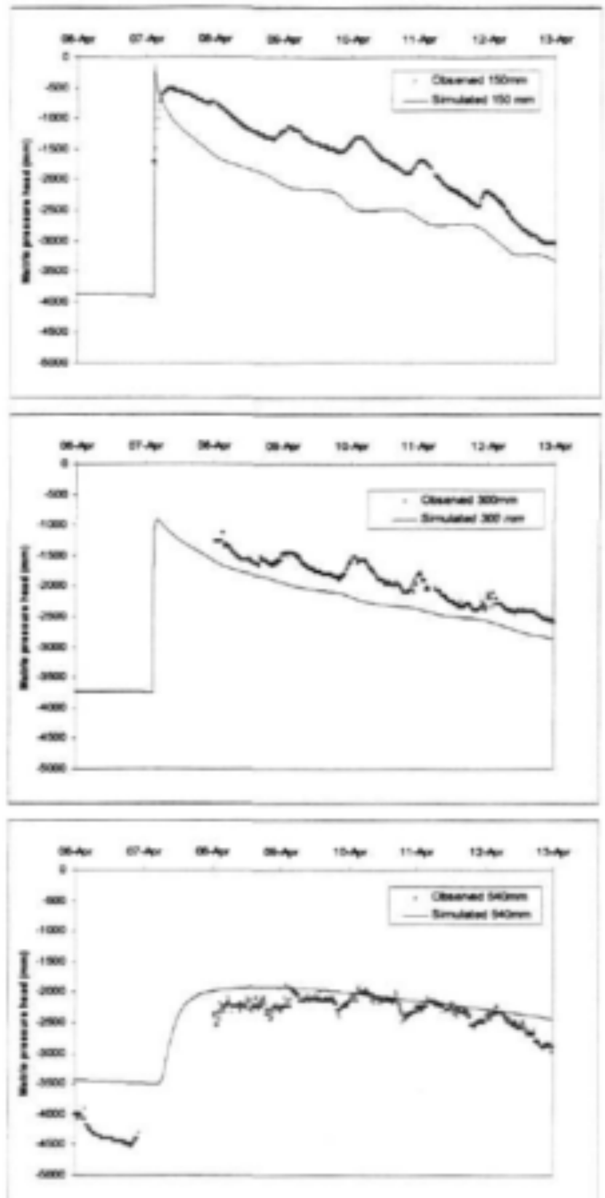


Figure 33: Simulated and observed matric pressure head response for Event 2 a) 0.05m b) 0.15m c) 0.3m and d) 0.54m depths

The slope runoff generation determines the amount of excess rain that will enter the profile as infiltration (Lorentz et al., 2004). First the slope is divided up into 2m segments. Then the time to ponding, t_p is calculated from the application of the Green-Ampt/Horton equation, (Morel-Seytoux, 1988), given as:

$$t_p = \frac{Ks(\theta_s - \theta_i)H}{i(i - Ks)}$$ **Equation 8**

where:

Ks is the saturated hydraulic conductivity (mm/h)

θ_s, θ_i is the saturated and initial water content in the profile

H is the capillary pressure head at the Green-Ampt wetting front (mm) and

i is the rainfall intensity (mm/h)

The infiltration rate, *f*, at each segment during any time interval, Δt, is given as:

$f = \mathrm{I}$ for $t < t_p$

$$f = Ks + \frac{1}{k\Delta t}(i_p - Ks)(e^{k\Delta t} - 1)e^{-k(t-t_p)} \quad \text{for } t > t_p$$ **Equation 9**

where:

$$k = \frac{8K_s}{(\vartheta_s - \vartheta_i)H}\left(\frac{1}{h}\right)$$

i_p is the rainfall intensity at the ponding time (mm/h)

The hydraulic head at the wetting front, *H*, is given, for a soil described by Brooks-Corey parameters (Corey 1977) as:

$$H = \frac{(2+3\lambda)}{(1+3\lambda)}\frac{h_b}{2}$$ **Equation 10**

The Brooks and Corey parameters will be estimated from the van Genuchten curve or retention characteristic data.

Once the time to ponding has been established, a mass balance of inflows and outflows to the elemental volume of water on the slope can be evaluated. For each time increment, rainfall excess, i_e, being the difference between rainfall intensity, *i* and infiltration rate, *f* after ponding is the inflow (or withdrawal after rainfall ceases and $i = 0$) of water to the surface water element (Figure 34). Upslope inflow, Q_n is also an input, while the downslope discharge, Q_{n+1} is the output. These discharges are balanced with the change in storage, governed by the flow height (or cross sectional area, *A*), which, of course, also controls the discharge. This balance is derived by Newton-Raphson iterative solution of the downstream cross-sectional area of flow for the current time step, $A_{n+1,t+1}$. To start the iterative solution, the most upstream cross sectional area and all initial cross sectional areas are taken to be zero.

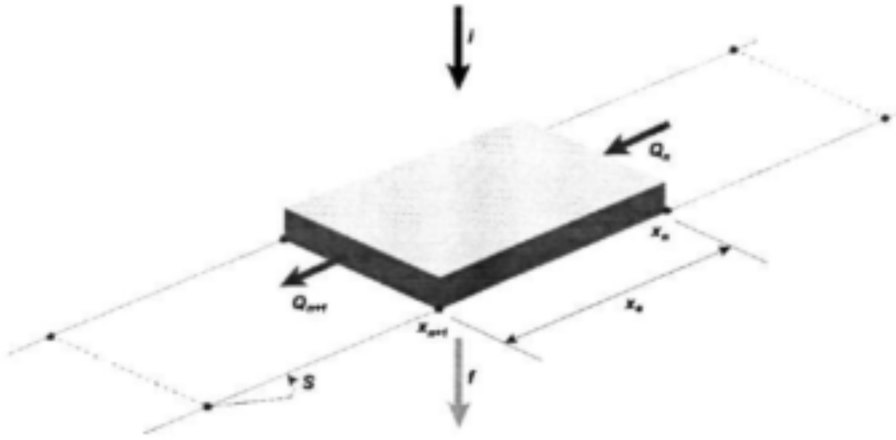


Figure 34: Schematic view of the kinematic, finite difference surface runoff algorithm showing the mass balance of a surface runoff element

The finite difference for of the continuity equation is used in the form:

$$\frac{A_{n+1,t+1}}{2} + Q_{n+1,t+1}\frac{\Delta t}{\Delta x_e} = \frac{A_{n,t} + A_{n+1,t} - A_{n,t+1}}{2} + Q_{n,t+1}\frac{\Delta t}{\Delta x_e} + i_e A_e \frac{\Delta t}{\Delta x_e}$$ **Equation 11**

where suffixes n and t refer to the upstream node and previous time step, respectively and n+1 and t+1, to the downstream node and current time step. A_e is the surface area of the flow element and Δt (1 minute) and Δx_e (2 m) are the time and space increments. The discharge, Q, is governed by Manning's equation for broad sheet flow on a slope, s, where the hydraulic radius reduces to h, the depth of flow (Moore and Foster, 1990) as:

$$Q = \alpha A^{5/3}$$ **Equation 12**

where:

$$\alpha = \frac{1}{n} w^{-2/3} s^{1/2}$$

n is Manning's roughness co-efficient and w is the width of the segment (1.2m)

Each scenario was run for a slope of 0.5% and 5% for the 1:2 year, 1:10 year and 1:100 year daily rainfall events. A summary of the simulations is presented in Table 10.

The effects of the increase in slope are only marginal in each scenario. However, significant differences exist between cover materials, with the Estcourt soil being far more effective in shedding runoff than the Soil 1. The Soil 8 tested in the laboratory flume would be less effective in shedding runoff than the Soil 1.

Table 10: Summary of runoff response to rainfall on slopes of 0.5% and 5%

Soil type Slope (%)	1:2 year event		1:10 year event		1:100 year event	
	Rainfall (mm)	Runoff (mm)	Rainfall (mm)	Runoff (mm)	Rainfall (mm)	Runoff (mm)
Estcourt						
0.5%	96	85	190	180	400	380
5%	96	86	190	182	400	384
Soil 1						
0.5%	96	49	190	80	400	260
5%	96	51	190	83	400	262

9 DISCUSSION

Current rehabilitation practices favour soil covers being placed on coal discard dumps. This has been primarily to provide a substrate for vegetation establishment. Recent research has seen the industry move towards thicker soil covers (0.75m depth) designed to also limit ingress of oxygen to the capped coal discards, with vegetation stabilisation of the cover. A problem highlighted during the current assessment is the ongoing loss of soil off such covers, even where good vegetation covers are present. It is unsure whether the cover layer on many of the older rehabilitated coal discards dumps will fail in the years ahead as soil is lost to erosion.

Apart from water rapidly draining from the ash sample, the compaction results posed a problem. The sample did not follow a smooth parabolic-type curve to the maximum dry density. The curve showed a peak density at relatively low moisture, and then decreased. This was followed by a higher peak in density as the water content increased further. The second, higher peak is the correct combination of density and water content to use for design and modelling purposes (it is only this peak that is shown on the data sheet for estimation of the optimum water content and maximum dry density in Appendix 3). The same phenomenon observed while collecting the sample in the field, was also evident during the compaction test: the sample held the required moisture as it was loosely placed into the compaction mould, but the moisture was freed as soon as compaction of layers began. This could lead to problems when trying to place a compacted (even lightly compacted) ash layer as part of a cover.

Further, the ash sample was friable. This means that the particles break down during compaction. According to von der Hude et al. (1999b) and Kämpf et al. (2001) soils used in capillary barrier systems should have sufficient grain stability to ensure that loads applied during compaction do not significantly alter the particle size distribution. The same should be applied to store-and-release covers since the final cover would have different characteristics to those determined for "uncrushed" samples in the laboratory. Kämpf et al. (2001) even suggest the use of a "smashing test" (based on standard Proctor compaction tests) to eliminate soils that change particle size distribution under load. Kämpf et al. (2001) indicated, however, that grain stability was of greater concern in the capillary block layer than in the capillary layer, since with the finer soils loads would be distributed over a greater number of particles. It was, however, decided that the characteristics of the ash sample tested showed that it was unsuitable for use in either store-and-release or capillary barrier applications. This may not be the case for all power station ash and provided that a sample met the desired criteria, it may be suitable for use.

SWCC's are commonly fitted to suction-versus-water content data using either the van Genuchten model or the Fredlund and Xing (1994) model (Section 2.2.3). For Sample 1, both curves adequately fitted the data over the range of measured values (Figure 35). However, for Sample 8, the Fredlund and Xing (1994) gave a poor fit to the tests data (Figure 36). The parameters used for the best fit Fredlund and Xing (1994) curve were obtained using *SoilCover*. In using numerical models such as *SoilCover*, it must be noted that there are assumptions programmed into the model. These may or may not be the most suitable ones. Resulting values can therefore be compared, but should be used with caution.

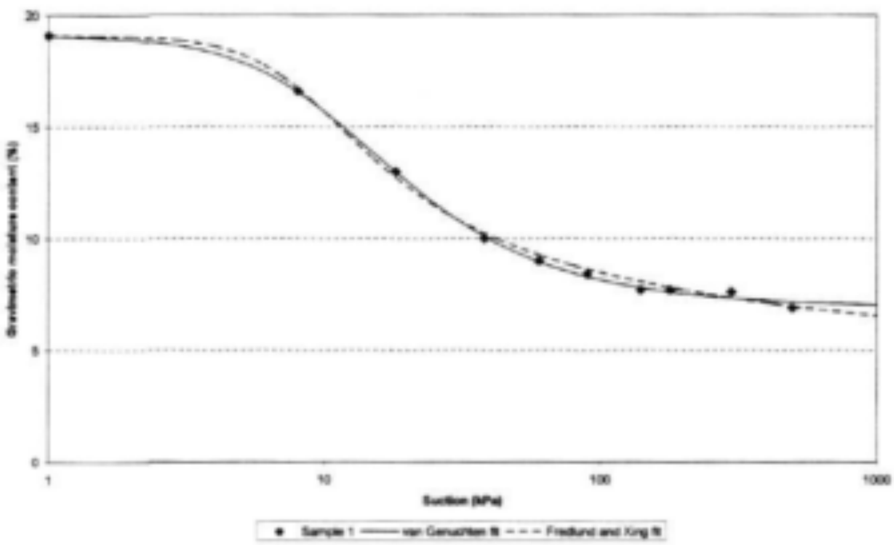


Figure 35: Best fit SWCCs for Sample 1 using van Genuchten (1980) and Fredlund and Xing (1994)

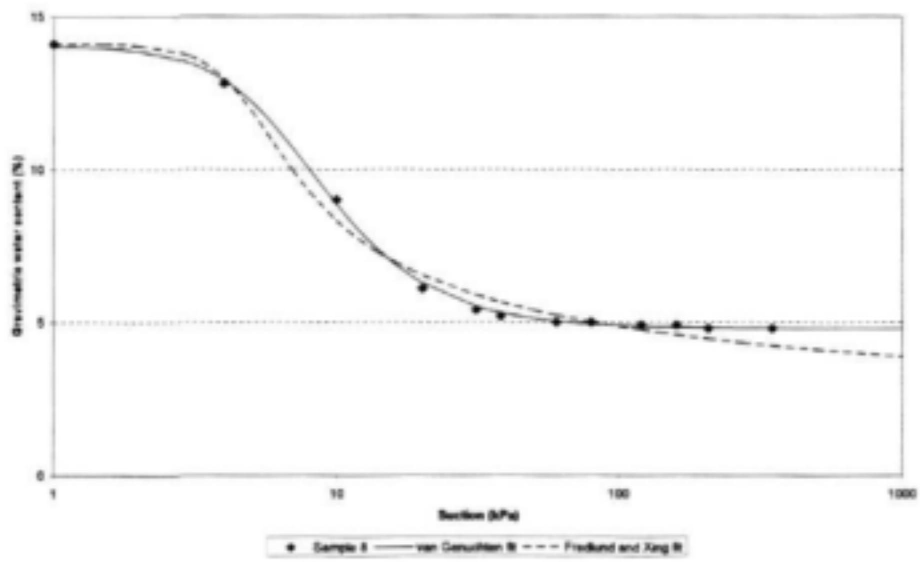


Figure 36: Best fit SWCCs for Sample 8 using van Genuchten (1980) and Fredlund and

Xing (1994)

Various soil cover scenarios were investigated to assess the influence of cover material and thickness, compaction effort and vegetation. Initially single year simulations were carried out to establish what the governing factors were.

Comparing the performance of the two soil types (Soil 1 and 8) with each other for a given cover thickness, compaction effort and vegetation, it was found that the throughflow through the Soil 1 cover was almost half of that of the Soil 8 cover. This could be attributed to the lower hydraulic and higher air entry value of Soil 1. These two properties govern the performance of the cover during both the wet and dry season. During the wet season the soil is able to retain the moisture up until a certain point due to the low permeability of the material. On the other hand, during the dry season the soil releases some of the moisture and negative pore pressures (suction) will build up at the ground surface. The soil is able to prevent air from entering the soil matrix until a suction of 10.4kPa is reached. Once this has happened air (and more importantly oxygen) will migrate through the soil cover to the discard. However, the probability of air and water entering the discard could be manipulated by selecting a soil with a favourable combination of hydraulic conductivity and water retention characteristics. Following the numerical simulations. Clearly, the combination of a low conductivity material with good water retention characteristics is the better hydraulic performer.

The influence of vegetation in limiting moisture ingress into the coal discard was investigated for a given soil type (e.g. Soil 1), cover thickness (1m) and compaction effort (90% of Standard Proctor). It can be noted that by comparing the best (excellent vegetation) and worst (no vegetation) with each other, the effectiveness of vegetation in limiting throughflow is limited (0.3% of MAP). The effectiveness of vegetation is slightly "improved" (0.7% of MAP) by the use of a thinner soil cover (0.5m). This "improvement" could be related to the performance of the soil cover. It is believed that the influence of vegetation on limiting ingress is not altered by the soil type but rather that its influence is more pronounced if the cover performance is less effective. Effectiveness in limiting ingress of water into the discard is improved by vegetation but it is the combined effect of the storage and subsequent release through both evaporation and evapo-transpiration that determines the performance of the cover. Additionally vegetation also reduces erosion and hence improves the stability and sustainability of the cover.

The influence of density as simulated using data for Soil 1 with no vegetation and 1m cover thickness, indicates that infiltration into the coal discard is the lowest for 85% compaction effort (1.1% of MAP) and increases to reach a maximum at 95% compaction effort (3.1% of MAP). It should be noted that moisture ingress of the 90% and 85% compaction effort is very close and it is difficult to select the better performer on this basis. Although the denser sample (95% compaction) has a slightly lower saturated hydraulic conductivity and higher air entry value than the sample at 85% compaction, the less dense layer limits throughflow to a greater extent. This was found at both cover thicknesses. This is explained by the larger voids ratio of the less dense soil which can store more moisture in voids within the soil structure than the denser soil. During periods of evaporation the moisture is released from storage in the less dense soil whereas it would already have passed into the underlying discard for the denser soil.

A capillary break below the cover compacted to 90% of standard proctor reduced infiltration by 50%.

For all the simulated cover configurations using data for soil Sample 1, the flow through the cover was below 3.1% of the precipitation for the year while that of Soil 8 was below 28.2%. The aim is to limit this value to below 5 % of the mean annual precipitation over the lifetime of the cover. Cover performance of Soil 1 was thus satisfactory was thus adopted for further simulation over a representative climatic period. On the other hand it is clear that soil 8 (hutton) was entirely unsatisfactory since its permeability was too high.

Additional simulations were carried out since it is not clear whether the year in question (2000) was a dry, average or wet year. The value of the scenario simulations is evident in the application to long term evaluations of cover performance. While a 90% Proctor standard compaction Soil 1 cover and a similar cover with a capillary break cover allow similar infiltration into the cover for one year of simulation, the cumulative discharge through the cover into the discard is lower for the capillary cover than the store and release cover on its own. The significance of the differences between the through flow between covers needs to be assessed in terms of construction costs prior to a final decision on selecting cover types.

The laboratory experiment illustrated the importance of *in-situ* measurements of hydraulic characteristics and particularly the consideration of any surface cracking that may occur in the cover. Surface cracks were observed during the drying phases of the experiment. These closed up rapidly during the event, but the infiltration/runoff mechanisms were clearly affected. This is illustrated in comparing the observed runoff volume with those simulated using laboratory derived hydraulic characteristics. The observed water balance in the laboratory flume was simulated adequately using the *HYDRUS2D* model. However, the hydraulic conductivity used in the simulation was 4×10^{-5}m/s whereas saturated hydraulic conductivities measured on small laboratory samples for the Hutton material at 90% proctor were 2 orders of magnitude lower than this. Indeed, the analytical evaluation of runoff processes using laboratory measured hydraulic conductivity values predicted high runoff rates (52% for and Avalon and 89% for an Estcourt). While the Hutton soil used in the flume had similar laboratory determined conductivity to the Estcourt soil, (2×10^{-7}m/s), the measured runoff was only 28% of the event. In the numerical modelling of various scenarios the runoff volumes were also high and should be viewed as illustrative of the different scenarios, since surface cracking and root induced preferential flows were not considered.

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Additional simulations were carried out since it is not clear whether the year in question (2000) was a dry, average or wet year. The value of the scenario simulations is evident in the application to long term evaluations of cover performance. While a 90% Proctor standard compaction Soil 1 cover and a similar cover with a capillary break cover allow similar infiltration into the cover, the ultimate discharge through the cover into the discard is lower for the capillary cover than the standard cover. The significance of the differences between the through flow discharge between covers needs to be assessed in terms of construction costs and the impact on the discard prior to a final decision on selecting cover types.

The laboratory flume experiment illustrated the importance of *in-situ* measurements of hydraulic characteristics and particularly the consideration of any surface cracking that may occur in the cover. Surface cracks were observed during the drying phases of the experiment. These closed up rapidly during the event, but the infiltration/runoff mechanisms were clearly affected. This is illustrated in comparing the observed runoff volume with those simulated using laboratory derived hydraulic characteristics. The observed water balance in the laboratory flume was simulated adequately using the *HYDRUS2D* model. However, the hydraulic conductivity used in the simulation was $4x10^{-5}$m/s whereas saturated hydraulic conductivities measured on small laboratory samples for the Hutton material at 90% proctor were 2 orders of magnitude lower than this. Indeed, the analytical evaluation of runoff processes using laboratory measured hydraulic conductivity values predicted high runoff rates (52% for and Avalon material and 89% for an Estcourt). While the Hutton material used in the large flume sample had similar laboratory determined conductivity to the Estcourt material, ($2x10^{-7}$m/s), the measured runoff was only 28% of the event. In the numerical modelling of various scenarios the runoff volumes were also high and should be viewed as illustrative of the different scenarios, since surface cracking and plant induced preferential flows were not considered.

The simulation of various scenarios illustrates the dependence of the water balance on the combination of hydraulic conductivity and soil water retention characteristics of the materials. It is clear that the best cover in limiting ingress of water into the discard was the soil with the lowest hydraulic conductivity even though the porosity of the better performer was higher than the worst. Clearly, the combination of a low conductivity with large voids ratio (good water retention characteristics) is the better performer.

Limited to a given soil type, however, the simulations illustrate the importance of finding the correct combination of water retention characteristic and hydraulic conductivity. A soil which is too densely packed may not have the necessary pore structure to act as an effective store and release cover event though the hydraulic conductivity of the more densely packed soil may be lower than a less densely packed cover of the same material.

Effectiveness in limiting ingress of water into the discard is improved by vegetation. The vegetation can not however function on its own. It is important to provide a cover of sufficient depth to allow for the storage and subsequent uptake of water by the vegetation over time.

The value of the scenario simulations is evident in the application to long term evaluations of cover performance. The more effective covers release water into the discard at a relatively uniform annual rate, whereas the poor performers release significantly larger volumes into the discard during the high rainfall years.

10 CONCLUSIONS

Soils from the Mpumalanga region were investigated for potential use in store-and-release covers and store-and-release covers with capillary barriers. The soils were selected based on material selection criteria given in the literature. Initial laboratory test results were used to reduce the number of potentially suitable soil types sampled from eleven to five. An ash sample was also included. Further laboratory testing indicated that Soils 1 and 8 would be suitable for a store-and release cover, based on their characteristics. Further testing and screening showed that only Soil 1 (Avalon) was suitable.

Although ash was considered during the initial laboratory analysis, because of its abundance in Mpumalanga and its alkalinity, the sample displayed features that could cause problems in covers. Moisture drained rapidly from the sample when disturbed and particles were friable, breaking down during the compaction tests. Although the initial indications are that ash was not suitable its favourable permeability and volumetric stability suggest that further testing to confirm the conclusions of this research could be warranted.

The conclusions from the field assessment of the existing dumps were:

- Most of the rehabilitated coal discard dumps assessed during the study exhibited erosion indicating that the cover of these rehabilitated dumps is becoming progressively thinner with time. In certain instances effective cover depth over large portions of a dump was found to be less than 0.2m.
- Salinisation of soil covers was also found to be occurring, although the incidence of salinisation appeared to be confined to localised seepage points on most dumps.
- Insufficient data is available to ascertain whether dump cover soils are being salinised through capillary rise from underlying saline discards. It is however likely that where potentially AMD material are situated close to the underside of the topsoil, oxidation will take place resulting in high salinity and acidity (oxidation products) emerging on the surface of the topsoil. It is suggested that this action is driven by diffusion. In addition to capiliary action.
- The geochemistry of the subsurface horizons could also impact on salinisation. Where Fe^{2+} , for example, dominates geochemical transformations and reactions occur that could be toxic to vegetation and result in dieback. Fe^{2+} in the soft plinthite and in the underlying gray glayed semi-saturated horizon are commonly found in Avalon, Pinedene, Bainsvlei and other soil forms.

The conclusions from the Kilbarchan trials were:

- The outflow through the Kilbarchan cells is a function of cover thickness and composition.
- The outflow results of sloped cells remained inconclusive.
- Uncovered and single layered cover cells displayed high oxygen concentrations while the oxygen concentrations in the cells with composite covers were low.
- Acid breakthrough occurred in all of the uncovered cells due to high oxygen ingress. Decrease in sulphate concentrations in the outflow in composite cells indicates sustained low O_2 ingress.

The following can be concluded from the results of the numerical simulations of cover scenarios:

- A valuable set of scenario simulations has been presented which illustrates the importance of selecting a soil with the correct combination of water retention and hydraulic conductivity characteristics.
- Of the two cover soil types studied; the better performer was the one with the lower hydraulic conductivity. This is supported by the intuitive conclusion that infiltration is proportional to permeability.
- Given a specific soil, the matching of water retention characteristic with the conductivity at different packing densities is important as it may not always be the lowest conductivity option, which is the optimum performer for that material. For a given permeability a soil with a higher void ratio is thus expected to perform better than one with a lower void ratio.
- The performance of covers can generally be improved by increasing the depth of the cover layer.
- The introduction of a viable vegetation cover can improve the performance of poor cover materials significantly. A minimum depth of cover will however always be required in order to store the excess water until it can be removed by evapo-transpiration.

The conclusions from the numerical simulations over a long climatic period were:

- The performance of the 0.5m cover compacted to 90% of Standard Proctor, was unaffected by the inclusion of a capillary barrier.
- The density of the cover however, significantly influences the performance of the cover.

Conclusions that can be drawn from the laboratory flume experiment include:

- Surface cracking of large samples reduces runoff and increases the amount of water infiltrating into the soil cover.
- The effects of a change in slope from 1:50 (runoff 25%) to 1:5 (runoff 28%) did not affect the runoff volume significantly.
- The soil water dynamics can be adequately simulated provided the hydraulic characteristics of the material match those of the *in-situ* material.
- Large sample monitoring yields valuable insight into the mechanisms of cover performance and modifications necessary to simulate these with soil physics models.

11 RECOMMENDATIONS

11.1 General recommendations

The following general recommendations follow from the conclusions of this research project:

- Volumetrically stable soils with permeability of less than 1×10^{-8} m/sec should be used for covers, The following criteria should be adopted for selection of soils for covers::
- Clay fraction <10%
- Non plastic
- Linear shrinkage <1%
- Coefficient of uniformity <10
- The selection of soils for covers should be done in advance of rehabilitation planning and should be based on baseline studies that provide the geotechnical parameters required for design of the covers. Laboratory testing to confirm that the candidate soils are volumetrically stable and will have the required permeability should be undertaken..
- Cover designs should be substantiated by throughflow modeling based on laboratory determined parameters and should be verified by field trials before full scale implementation
- Field trials should not be done without first demonstrating that the trial configurations are potentially viable on the basis of the throughflow modeling.
- Effects of erosion, surface cracking and vegetation on the runoff and infiltration should be taken into account in the design of future covers. Soils for covers should be selected on the basis of a thorough investigation and on criteria selected to serve the objective of minimisation of infiltration, erosion prevention and support of vegetation. A multidisciplinary team having the necessary range of skills and experience should therefore be involved in the design.
- The effect of salinisation should be considered in the design and where vegetation is to play an important role on the water balance and stabilization should be resolved in the design of the cover.
- The use of rock armouring (approximately 40% rock and 60% topsoil) should be investigated as a means of further stabilising covers. (The practice of using rock armouring is receiving considerable research attention in other sectors of the South African mining industry for stabilisation of mine residue slopes).

11.2 Recommendations for future work

The following recommendations are offered to guide further research and investigations flowing from this project:

- Field trials of promising alternative cover configurations using the soil types satisfying the criteria set out in the general recommendations above should be carried out in the Mpumalanga region
- Field trials should investigate the following:
- Influence of compaction
- salinisation of the soil cover
- influence of capillary breaks
- armouring of slopes to control erosion
- natural (possibly compacted) or geosynthetic barriers below store and release covers
- The performance of existing soil covers on existing dumps should be investigated in more detail to assess the progress of erosion, the extent of salinisation and throughflow and to correlate this with the soil types used, the slope angle, the slope geometry and time. In this regard existing soil covers should be instrumented and monitored over time in order to assess the progression and rate of erosion and salinisation and to correlate this with soil type, slope and geometry.
- Laboratory scale experiments and simulations should be conducted to investigate different soil types, layering configurations and slopes, interface mechanisms between materials of different hydraulic characteristics and layer configurations with different boundary conditions and the effects of preferential flow in the water balance by induced cracking or preferential pathways into the medium. The should be done in order to identify further promising opportunities to further reduce infiltration and oxygen ingress into rehabilitated coal discard.
- Further scenarios should be investigated by simulation to illustrate the effects of soil water retention and hydraulic conductivity combinations. The optimum compaction effort for a cover configuration and the associated voids ratio pore space arrangement should thus be established. This should be done by incorporating a capillary break as this proved to be the best cover design for limiting moisture ingress into the coal discard.

12 REFERENCES

Aachib, M., Mbonimpa, M and Aubertin, M. (in prep) Measurement and prediction of the oxygen diffusion coefficient in partly saturated media, with application to soil covers, cited Mbonimpa et al (2003).

Akindunni, F.F., Gillham, R.W. and Nicholson, R.V. (1991) Numerical simulations to investigate moisture-retention characteristics in the design of oxygen-limiting covers for reactive mine tailings, *Canadian Geotechnical Journal*, 28, 446-451.

Albrecht, B.A. and Benson, C.H. (2001) Effect of desiccation of compacted natural clays, *Geotechnical and Geoenvironmental Engineering ASCE,* 127 (1) 67-75.

Albrecht B.A. and Benson, C.H. (2002) Predicting airflow rates in the coarse layer of passive dry barriers, *Geotechnical and Geoenvironmental Engineering ASCE,* 128 (4) 338-346.

Albright, W.H., Benson, C.H., Gee, G.W., Abichou, T., Roesler, A.C. and Rock, S.A. (2003) Examining the alternatives, *Civil Engineering ASCE*, May, 73 (5), 70-75.

Albright, W.H., Benson, C.H., Gee, G.W., Roesler, A.C., Abichou, T., Apiwantragoon, P., Lyles, B.F. and Rock, S.A. (2004) Field water balance of landfill final covers, *Journal of Environmental Quality*, 33, 2317-2332.

Aubertin, M., Chapius, R.P., Aachib, M., Bussière, B., Ricard, J.F. and Tremblay, L. (1995) Evaluation en laboratoire de barières sèches construites à partir de rèsidus miners, Rapport final pour Energie, Mines et Resources Canada, cited Doye and Duchesne (2003) and Yanful et al (2003).

Aubertin, M. and Mbonimpa, M. (2001) Diffusion of oxygen through pulp and paper residue: Discussion, *Canadian Geotechnical Journal*, 38, 658-660.

Aubertin, M., Mbonimpa, M., Bussière, B. and Chapius, R.P. (2003) A model to predict the water retention curve from basic geotechnical properties, *Canadian Geotechnical Journal*, 40, 1104-1122.

Barbour, S.L. (1998) Nineteenth Canadian Geotechnical Colloquium: The soils-water characteristic curve: a historical perspective, *Canadian Geotechnical Journal*, 35, 873-894.

Blotz, L.R., Benson, C.H., Boutwell, G.P. (1998) Estimating optimum water content and maximum dry unit weight for compacted clays, *Journal of Geotechnical and Geoenvironmental Engineering ASCE,* 124 (9) 907- 912.

Baker, R.S. and Hillel, D. (1990) Laboratory tests of a theory of fingering during infiltration into layered soils, *Soil Science Society of America Journal*, 54, 20-30, cited Morris and Stormont (1998).

Bower, H. (1966) Rapid field measurement of air entry value and hydraulic conductivity of soil as significant parameters in flow system analysis, *Water Resources Research*, 2 (4) 729-738, cited Smesrud and Selker (2001).

Brauns, J., Schneider, H. and Gottheil, K. (2000) Wasserverlust und Schrumpfen bei mineralischen Dichtungen aus geotechnischer sicht, *Geotechnik*, 23 (1) 36-47.

Brooks, R.H. and Corey, A.T. (1964) Hydraulic properties of porous media, *Hydro. Paper No. 3*, Civil Engineering Department, Colorado State University, Fort Collins, Colo.

Burger, C.A. and Shackelford, C.D. (2001a) Evaluating dual porosity of pelletized diatomaceous earth using bi-modal soil-water characteristic curve functions, *Canadian Geotechnical Journal*, 38, 53-66.

Burger, C.A. and Shackelford, C.D. (2001b) Soil-water characteristic curves and dual porosity of sand-diatomaceous earth mixtures, *Journal of Geotechnical and Geoenvironmental Engineering* ASCE, 127 (9) 790-800.

Cabral, A., Racine, I., Burnotte, F. and Lefebvre, G. (2000) Diffusion of oxygen through a pulp and paper residue barrier, *Canadian Geotechnical Journal*, 37, 201-217.

Cassel, D.K. and Nielsen, D.R. (1986) Field capacity and available water capacity, *Methods of Soil Analysis, Part 1: Physical and Mineralogical methods*, Agronomy Monograph 9, 2nd edition, Soil Science Society of America, Madison, Wisconsin, cited Morris and Stormont (1998).

Chaplot, V. and Le Bissonnais, Y. (2000). Field measurements of interrill erosion under different slopes and plot sizes. *Earth Surface Processes and Landforms*, 25 145-153 cited Janeau et al (2003).

Childs, E.C. and Collis-George, G.N. (1950) The permeability of porous materials, *Proceedings of the Royal Society of London, Series A*, 201, 392-405, cited Fredlund et al (1994)

Cravotta III, C.A. and Trahan M.K. (1999) Limestone drains to increase pH and remove dissolved metals from acidic mine drainage, *Applied Geochemistry*, 14, 581-606.

Choo, L.P. and Yanful, E.K. (2000) Water flow through cover soils using modelling and experimental methods, *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, 126 (4) 324-334.

Chiu, T.F. and Shackelford, C.D. (1998) Unsaturated hydraulic conductivity of compacted sand-kaolin mixtures, *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, 124 (2) 160-169.

Corey, A.T. (1957) Measurement of water and air permeability in unsaturated soil, *Soil Science Society of America Proceedings*, 21 (1) 7-10, cited Mbonimba et al (2003).

Corey, A.T. (1977) *Mechanics of Heterogeneous Fluids in Porous Media.* Water Resources Publications, Fort Collins, Colorado, USA.

Cosby, B.J., Hornberger, G.M., Clapp, R.B. and Ginn, T.R. (1984) A statistical exploration of the relationships o soil moisture characteristics to the physical properties of soils, *Water Resources Research*, 20 (6) 682-690.

Craig, R.F. (1997) Soil Mechanics, 6^{th} ed, E & FN Spon, London.

Croney, D. and Coleman, J.D. (1961) Pore pressure and suction in soils, Proc: Conference on Pore Pressure and Suction in Soils, Butterworths, London, cited Fredlund and Xing (1994) and Leong and Rahardjo (1997).

Daniel, D.E. (1994) Surface barriers: problems, solutions, and future needs, in Gee G.W. and Wing, N.R. (eds) Proc: 33 Hanford Symposium on health and the environment, Battelle Press, Columbus, Ohio, 441-487, cited Morris and Stormont (1997).

Daniel, D.E. and Benson, C.H. (1990) Water content-density criteria for compacted soil liners, *Journal of Geotechnical Engineering ASCE*, 116 (12) 1811-1830.

Daniel, D.E., Koerner, R.M., Bonaparte, R., Landreth, R.E., Carson, D.A. and Scranton, H.B. (1998) Slope stability of geosynthetic clay liner test plots, *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, 124 (7) 628-637.

Daniel, D.E. and Wu, Y.K. (1993) Compacted clay liners and covers for arid sites, *Journal of Geotechnical Engineering ASCE*, 119 (2) 223-237.

Department of Mineral and Energy Affairs (1998) cited Vermaak et al. (2002)

Department of the Environment: Australia (1998) Best practice environmental management in mining: Landform design for rehabilitation, Environment Australia, ACT.

Doye, I. and Duchesne, J. (2003) Neutralisation of acid mine drainage with alkaline industrial residues: laboratory investigation using batch-leaching tests, *Applied Geochemistry*, 18, 1197-1213.

Dubrovsky, N.M., Cherry, J.A., Reardon, E.J. and Vivyurka, A.J. (1985a) Geochemical evolution of inactive pyritic tailings in the Elliot Lake uranium district, *Canadian Geotechnical Journal*, 22, 110-128, cited Nicholson et al (1989).

Dubrovsky, N., Morin, K., Cherry, J. and Smyth, D. (1984) Uranium tailings acidification and subsurface contaminant migration in a sand aquifer, *Water Pollution Control Research Journal of Canada*, 19 (2), 55-89, cited Kim and Benson (2004).

Dwyer, S.F. (1998) Alternative landfill covers pass the test, *Civil Engineering ASCE*, Sept, 68 (9),50-52.

Dwyer, S.F., Starkey, S., Goodyear, D. and Smit, N. (2001) Finding a better cover, *Civil Engineering ASCE*, 71 (1) 58-63.

Esterhuizen, J.J.B., Filz, G.M., Duncan, J.M. (2001) Constitutive behaviour of geosynthetic interfaces, *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, 127 (10) 834-840.

Feenstra, S., Blair, R.D., Cherry, J.A., Chakravatti, J.L. and LaRocque, E. (1981) Hydrochemical investigations of the two inactive tailings areas in the Elliot Lake uranium disctrict, Ontario, Canada, *Proc: 4th Symposium on Uranium Mill tailings management*, Geotechnical Engineering Programme, Civil Engineering Department, Colorado State University, Fort Collins, CO, cited Nicholson et al (1989).

Fortin S., Lamontagne, A., Poulin, R. and Tassè, N. (2000) The basic use of additives to tailings in layered co-mingling to improve AMD control, *Proc: Environmental Issues and Management of Waste in Energy and Mineral Production*, Calgary, Canada, 549-556, cited Doye and Duchesne (2003).

Fox, D.M., Bryan, R.B. and Price, A.G. (1997). The influence of slope angle on final infiltration rate for interrill conditions. *Geoderma*, 80 181-194.

Fredlund, D.G. and Rahardjo, H. (1993) Soil mechanics for unsaturated soils, John Wiley & Sons, New York.

Fredlund, D.G. and Xing, A. (1994) Equations for the soil-water characteristic curve, *Canadian Geotechnical Journal*, 31, 521-532.

Fredlund, D.G., Xing, A. and Huang, S. (1994) Predicting the permeability function for unsaturated soils using the soil-water characteristic curve, *Canadian Geotechnical Journal*, 31, 533-546.

Fredlund, M.D., Wilson G.W and Fredlund, D.G. (2002) Use of the grain-size distribution for estimation of the soil-water characteristic curve, *Canadian Geotechnical Journal*, 39, 1103-1117.

Gillham, R.W. (1984) The capillary fringe and its effect on water-table response, *Journal of Hydrology*, 67, 307-324, cited Nicholson et al (1989).

Giroud, J.P. (2000) Lessons learned from successes and failures associated with geosynthetics, *Proc: EuroGeo 2000*, Bologna, October 2000, 77-118.

Giroud, J.P. and Bonaparte, R. (1989) Leakage through liners constructed with geomembranes - Part II Composite liners, *Geotextiles and Geomembranes*, 8 (2) 71-111.

Gupta, S.C. and Larson, W.E. (1979) Estimating soil-water retention characteristics from particle-size distribution, organic matter present and bulk density, *Water Resources Research*, 15 (6) 1633-1635.

Hoins, H. (1999) Innovative systems for the surface sealing of landfills, *Proc: Sardinia 99, 7th International Waste Management and Landfill Symposium*, Cagliari, October 1999, Vol 3. 295-302.

Hsuan, Y.G. and Koerner, R.M. (1998) Antioxidant depletion lifetime in high density polyethylene geomembranes, *Journal of Geotechnical and Geoenvironmental Engineering ASCE,* 124 (6) 532-541.

Hupe, K., Unger, A., Heyer, K.U. and Stegmann, R. (2001) Alternative surface sealing systems for stabilized landfill bodies, *Proc: Sardinia 2001, 8th International Waste Management and Landfill Symposium*, Cagliari, October 2001, Vol 3. 295-302.

Janeau, J.L., Briquet, J.P., Planchon, O. and Valentin, C. (2003). Soil crusting and infiltration on steep slopes in northern Thailand. *European Journal of Soil Science*. 54 543-553.

Jo, H.Y., Katsumi, T. Benson, C.H., and Edil, T.B. (2001) Hydraulic conductivity and swelling of nonprehydrated GCLs permeated with single-species salt solutions, *Journal of Geotechnical and Geoenvironmental Engineering ASCE,* 127 (7) 557-567.

Kämpf, M., Holfelder, T. and Montenegro, H. (1999) Designing capillary barriers, *Proc: Sardinia 99, 7th International Waste Management and Landfill Symposium*, Cagliari, October 1999, Vol 3. 381-388.

Kämpf, M., Holfelder, T. and Montenegro, H. (2001) Material selection for capillary barriers, *Proc: Sardinia 2001, 8th International Waste Management and Landfill Symposium*, Cagliari, October 2001, Vol. 3. 325-334.

Khanzode, R.M., Vanapalli, S.K. and Fredlund, D.G (2002) Measurement of soil-water characteristic curves for fine-grained soils using a small-scale centrifuge, *Canadian Geotechnical Journal*, 39 (5) 1209-1217.

Khire, M.V., Benson C.H. and Bosscher, P.J. (1997) Water balance modelling of earthen final covers, *Geotechnical and Geoenvironmental Engineering ASCE,* 123 (8) 744-754.

Khire, M.V., Benson, C.H. and Bosscher, P.J., (2000) Capillary barriers: design variables and water balance, *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, 126 (8) 695-708.

Kim, H. and Benson, C.H. (2004) Contributions of advective and diffusive oxygen transport through multi-layer composite caps over mine waste, *Journal of Contaminant Hydrology*, 71, 193-218.

Koerner, R.M. (1994) Designing with geosynthetics, 4th edition. Prentice Hall, Englewood Cliff, New Jersey.

Koerner, R.M. and Soong, T.Y. (1998) Analysis and design of veneer cover soils, *Proc: 6th International conference on Geosynthetics*, Atlanta, Georgia, U.S.A. 1-23.

LaGatta, M.D., Boardman, B.T., Cooley, B.H. and Daniel, D.E. (1997) geosynthetic clay liners subjected to differential settlement, *Journal of Geotechnical and Geoenvironmental Engineering ASCE,* 123 (5) 402-410.

Lamontagne, A., Fortin, S., Poulin, R., Tassé, N. and Lefebvre, R. (2000) Layered co-mingling for the construction of waste rock piles as a method to mitigate acid mine drainage – laboratory investigations, *Proc: 5th International Conference on Acid Rock Drainage*, Denver, Colorado, May 2000, Vol 2, 901-910, cited Doye and Duchesne (2003).

Leong, E.C. and Rahardjo, H. (1997a) Review of soil-water characteristic curves equations, *Journal of Geotechnical and Geoenvironmental Engineering ASCE,* 123 (12) 1106-1117.

Leong, E.C. and Rahardjo, H. (1997b) Review of soil-water characteristic curves equations, *Journal of Geotechnical and Geoenvironmental Engineering ASCE,* 123 (12) 1118-1126.

Leroueil, S., Le Bihan, J.P. and Bouchard, R. (1992) Remarks on the design of clay liners used in lagoons as hydraulic barriers, *Canadian Geotechnical Journal*, 29, 512-515 cited Yanful et al. (1993a).

Lim, P.C., Barbor, S.L. and Fredlund, D.G. (1998) The influence of degree of saturation on the coefficient of aqueous diffusion, *Canadian Geotechnical Journal*, 35, 811-827.

Lorentz S., Thornton-Dibb S., Pretorius C. and Goba P. (2004) Hydrological systems modelling research programme: Hydrological processes, Phase ll Quantification of Hillslope, Riparian and Wetland processes. *WRC Report 1061 & 1086/1/04*. Water Research Commission, Pretoria, South Africa.

Mah, M.G.C., Douglas, L.A. and Ringrose-Voase, A.J. 1992. Effects of crust development and surface slope on erosion by rainfall. *Soil Science*. 154 37-43.

Maraqa, M.A., Wallace, R.B. and Voice, T.C. (1997) Effects of degree of water saturation on dispersivity and immobile water in sandy soil columns, *Journal of Contaminant Hydrology*, 25, 199-218.

Mbonimpa, M., Aubertin, M., Bussière, B. and Julien, M. (2000) Procèdures et interpretation des essays de diffusion et de consummation d'oxygène en laboratoire et in situ, *Proc: Volume des conférences et presentations du Colloque sur la recherche des methods innovatrices pour le contrôle du drainage minier acide, NEDEM 2000*, October, Sherbrooke, Qc, 17-22, cited Mbonimpa et al (2003).

Mbonimpa, M., Aubertin, M., Aachib, M. and Bussière, B. (2003) Diffusion and consumption of oxygen in unsaturated cover materials, *Canadian Geotechnical Journal*, 40 (5) 916-932.

Meerdink, J.S., Benson, C.H. and Khire, M.V. (1996) Unsaturated hydraulic conductivity of two compacted barrier soils, *Journal of Geotechnical Engineering ASCE,* 122 (7) 565-576.

Melchior, S. (1997) In-situ studies on the performance of landfill caps (compacted soil liners, geomembranes, geosynthetic clay liners, capillary barriers), in United States Department of the Environment, *Proc: International Technology Conference*, Report: CONF-9070208-Proc.

Mesri, G. and Olson, R.E. (1971) Mechanisms controlling the permeability of clays, *Clays and Minerals*, 19, 151-158, cited Jo et al. (2001).

Mihelcic, J.R. (1998) Fundamentals of environmental engineering, John Wiley & Sons, New York, cited Mbonimpa et al. (2003).

Miller, C.J., Yesiller, N., Yaldo, K. and Merayyan, S. (2002) Impact of soil type and compaction conditions on soils water characteristic, *Journal of Geotechnical and Geoenvironmental Engineering ASCE,* 128 (9) 733-742.

Minerals Council of Australia (1998) Mine rehabilitation handbook, 2nd edition, Minerals Council of Australia, Dickson, ACT.

Moore ID. and Foster GR. (1990) Hydraulics and Overland Flow. *in: Anderson MG. and Burt TP. (eds), Process Studies in Hillslope Hydrology.* John Wiley: 215-254.

Morel-Seytoux HJ. (1988) Recipe for simple but physically based modeling of the infiltration and local runoff processes. In: Morel-Seytoux HJ. and DeCoursey DG. (eds), Proc. 8th Annual AGU Front Range Branch Hydrology Days, Colorado State University, Fort Collins, CO: 226 – 247.

Morin, K., Cherry, J., Lim, T. and Vivyurka, A. (1982) Contaminant migration in a sand aquifer near an inactive tailings impoundment Elliot Lake, Ontario, *Canadian Geotechnical Journal*, 19, 49-62.

Morris, C.E. and Stormont, J.C. (1997) Capillary barriers and Subtitle D covers: estimating equivalency, *Journal of Environmental Engineering ASCE*, 123 (1) 3-10.

Mualem, Y. (1976) A new model for predicting the hydraulic conductivity of unsaturated porous media, Water Resources Research, 12 (3) 513-522.

Nicholson, R.V., Gillham, R.W., Cherry, J.A. and Reardon, E.J. (1989) Reduction of acid generation in mine tailings through the use of moisture-retaining cover layers as oxygen barriers, *Canadian Geotechnical Journal*, 26, 1-8.

Nyhan, J.W., Hakonson, T.E. and Drennon, B.J. (1990) A water balance study of two landfill cover designs for semi-arid regions, *Journal of Environmental Quality*, 19, 281-288.

Noël, M.M. and Rykaart, E.M. 2003. Comparative study of surface flux boundary models to design soil covers for mine waste facilities. *6th Int. Conf. on Acid Mine Drainage*. (ICARD) Cairns, QLD, Australia. 12-18 July 2003.

Park, J.K., Sakti, J.P. and Hoopes, J.A. (1996) Transport of organic compounds in thermoplastic geomembranes, I: Mathematical model, *Journal of Environmental Engineering ASCE*, 122 (9) 800-813.

Prapaharan, S., White, D.M. and Altschaeffl, A.G. (1991) Fabric of field- and laboratory-compacted clay, *Journal of Geotechnical Engineering ASCE*, 117 (12) 1934-1940.

Richards, B.G. (1965) Measurement of the free energy of soil moisture by the psychrometric technique using thermisters. In: Aitchison, G.D. (ed) Moisture equilibria and moisture changes in soils beneath covered areas, Butterworth and Co, Sydney, Australia, 39-46, cited Fredlund and Xing (1994)

Robinsky, E.I. (1979) Tailings disposal by the thickened discharge method for improved economy and environmental control, Proc: 2nd International Tailings Symposium, Miller Freeman, San Francisco, CA, 75-95

Rose, A.W., Phelps, L.B., Parizek, R.R. and Evans, D.R. (1995) Effectiveness of lime kiln flue dust in preventing acid mine drainage at the Kaufmann surface coal mine, Clearfield County, Pennsylvania, *Proc: National Meeting of the American Society for Surface Mining and Reclamation*, Gillette, Wyoming, June, 159-171, cited Doye and Duchesne (2003).

Ross (1990) The diversion capacity of capillary barriers, *Water Resources Research*, 26 (10) 2625-2629.

Rowe, R.K. (1999) Barrier Systems, Course notes: Short course, Kwa Maritane, South Africa, May 1999.

Rowe, R.K., Quigley, R.M. and Booker, J.R. (1997) Clayey barrier systems for waste disposal facilities, E & FN Spon, London.

Schaap, M.G. and Leij, F.J. (2000) Improved prediction of unsaturated hydraulic conductivity with the Mualem-van Genuchten model, *Soil Science Society of America Journal*, 64: 843-851.

Schulze, R.E., Maharaj, M., Lynch, S.D., Howe, B.J. and Melvil-Thomson, B. (1997) South African atlas of agrohydrology and climatology, *WRC Report Number TT82/96*, Water Research Commission, Pretoria.

Selker, J. (1997) Design of interface shape for protective capillary barriers, *Water Resources Research*, 33 (1) 259-260.

Simms, P.H. and Yanful, E.K. (2004) Estimation of soil-water characteristic curve of clayey till using measured pore-size distributions, *Journal of Geotechnical and Geoenvironmental Engineering ASCE,* 130 (8) 847-854.

Smesrud, J.K. and Selker, J.S. (2001) Effect of soil-particle size contrast on capillary barrier performance, *Journal of Geotechnical and Geoenvironmental Engineering ASCE,* 127 (10) 885-887.

Smyth, D.J.A. (1981) Hydrogeological and geochemical studies above the water table in an inactive uranium impoundment near Elliot Lake, Ontario, M.Sc. project, University of Waterloo, Waterloo, Ontario, cited Nicholson et al (1989).

Soil Classification Working Group (1991) Soil classification: a taxonomic system for South Africa, *Memoirs on the Agricultural and Natural Resources of South Africa* No. 15, Directorate Agricultural Information, Pretoria.

Stark, T.D., Williamson, R.A. and Eid, H.T. (1996) HDPE geomembrane / geotextile interface shear strength, *Journal of Geotechnical Engineering ASCE,* 122 (3) 197-203.

Steenhuis, T.S., Parlange, J.Y. and Kung, K.J.S. (1991) Comment on "The diversion capacity of capillary barriers" by Benjamin Ross, *Water Resources Research*, 27 (8) 2155-2156.

Steinert, B., Melchior, S., Burger, K., Berger, K., Türk, M. and Mielich, G. (1997) Design of capillary barriers for capping of landfills and contaminated sites, in August, H., Holzlöhner, U. and Meggyes, T. (eds) Advanced landfill liners systems, Thomas Telford, London, 286-301.

Stormont, J.C. and Anderson, C.E. (1999) Capillary barrier effect from underlying coarser layer, *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, 154 (8) 641-648.

Stormont, J.C. and Morris, C.E. (1998) Method to estimate water storage capacity of capillary barriers, *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, 124 (4) 297-302.

Suter, G.W., Luxmoore, R.J. and Smith, E.D. (1993) Compacted soil barriers at abandoned landfill sites are likely to fail in the long term, *Journal of Environmental Quality*, 22 (2) 217-226, cited Morris and Stormont (1997).

Swanson, D.A., Barbour, S.L., Wilson, G.W. and O'Kane, M. (2003) Soil-atmosphere modelling of an engineered soil cover for acid generating mine waste in a humid, alpine climate, *Canadian Geotechnical Journal*, 40, 276-292.

Tami, D, Rahardjo, H, Leong, E.C. and Fredlund, D.G. (2004) Design and laboratory verification of a physical model of sloping capillary barrier, *Canadian Geotechnical Journal*, 41, 814-830.

Terzaghi, K. (1943) Theoretical soil mechanics, Wiley, New York.

Ursino, N. and Cossu, R. (2001)Combining local measurements:modelling and scaling theory of capillary barriers, *Proc: Sardinia 2001, Eighth International Waste Management and Landfill Symposium*, Cagliari, October 2001, Vol 3. 335-344.

Van Genuchten, M.T. (1980) A closed form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Science Society of America Journal*, 44: 892-898.

Vermaak, J.J.G., Wates, J.A., Bezuidenhout, N. and Kgwale, D. (2002) The evaluation of soil covers used in the rehabilitation of coal mines, WRC Report Number 1002/1/04, Water Research Commission, Pretoria.

Von der Hude, N., Katzenbach, R. and Neff, H.K (1999a) Kapillarsperren als Oberflächen-abdichtungssytem, *Geotechnik*, 22 (2) 143-152.

Von der Hude, N., Melchior S. and Möckel, S. (1999b) Construction of a capillary barrier in the cover of the Breinermoor landfill, *Proc: Sardinia 99, 7th International Waste Management and Landfill Symposium*, Cagliari, October 1999, Vol 3. 393-402.

Wagner, J.F. and Schnatmeyer, C. (2002) Test field study of different cover sealing systems for industrial dumps and polluted sites, *Applied Clay Science*, 21, 99-116.

Walter, M.T., Kim, J.S., Steenhius, T.S., Parlange, J.Y., Heilig, A., Braddock, R.D., Selker, J.S. and Boll, J. (2000) Funneled flow mechanism in a sloping layered soil: laboratory investigation, *Water Resources Research*, 36 (4) 841-849.

Weast, (1985) CRC Handbook of Chemistry and Physics, 66th ed, CRC Press, Boca Raton, FL, cited Choo and Yanful, 2000; Yanful et al, 2003.

Webb, S.W. (1997) Generalization of Ross' tilted capillary barrier diversion formula for different two-phase characteristic curves, *Water Resources Research*, 33 (8) 1855-1859.

Wohnlich, S. (1995) Kapillarsperren – Versuche und Modelberechnungen, Schriftenreihe Angewandte Geologie Karlsruhe, 15, Karlsruhe, cited Wagner and Schnatmeyer (2002).

Woyshner, M.R. and Yanful, E.K. (1995) Modelling and field measurements of water percolation through an experimental soil cover on mine tailings, *Canadian Geotechnical Journal*, 32, 601-609.

Yanful, E.K., Bell, A.V. and Woyshner, M.R. (1993a) Design of a composite soil cover for an experimental waste rock pile near Newcastle, New Brunswick, Canada, *Canadian Geotechnical Journal*, 30, 578-587.

Yanful, E.K. and Mousavi, S.M. (2003) Estimating falling rate evaporation from finite soil columns, *The Science of the Total Environment*, 313, 141 – 152.

Yanful, E.K., Mousavi, S.M. and Yang, M. (2003) Modelling and measurement of evaporation in moisture retaining soils, *Advances in Environmental Research*, 7, 783-801.

Yanful, E.K., Riley, M.D., Woyshner, M.R. and Duncan, J. (1993b) Construction and monitoring of a composite soil cover for an experimental waste rock pile near Newcastle, New Brunswick, Canada, *Canadian Geotechnical Journal*, 30, 588-599.

Yang, H., Rahardjo, H., Leong, E.C. and Fredlund, D.G. (2004a) A study of infiltration on three sand capillary barriers, *Canadian Geotechnical Journal*, 41, 629-643.

Yang, H., Rahardjo, H., Leong, E.C. and Fredlund, D.G. (2004b) Factors affecting drying and wetting soil-water characteristic curves of sandy soils, *Canadian Geotechnical Journal*, 41, 905-921.

Zhang, L.L., Fredlund, D.G., Zhang, L.M. and Tang, W.H. (2004) Numerical study of soil conditions under which matric suction can be maintained, *Canadian Geotechnical Journal*, 41, 569-582.

Zischak, R. (1997) Alternatives Oberflächenabdischtungsystem: Verstärkte mineralische Abdichtung mit untenliegender Kapillarsperre, *Schriftenreihe Angewandte Geologie Karlsruhe*, 47, Karlsruhe.

Zornberg, J.G., LaFountain, L. and Caldwell, J.A. (2003) Analysis and design of evapotranspirative cover for hazardous waste landfill, *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, 129 (6) 427-438.

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