Coaltech

SOILS IN THE MINING ENVIRONMENT

A guide to their properties, use and conservation

Compiled by Garry Paterson

ACKNOWLEDGEMENTS

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- **Compiled by Garry Paterson**

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GLOSSARY OF TERMS

Cover soil	Inclusive term within the mining environment for the soil portion that is replaced for rehabilitation
Horizon	Distinct layer in the soil, such as topsoil horizon, subsoil horizon etc.
Mine Rehabilitation	A process to repair and restore landscapes damaged by mining, aiming to return the land to its pre-mining condition or better, fulfilling legal and ethical obligations.
Peds	Naturally occurring structural units within a horizon, ranging in size.
Permeability	Measurement of how easy it is for water to flow through a substance, such as soil
Porosity	Measurement of the space between particles in a soil or rock medium
Slickensides	Shiny pressure faces in swelling clay soils caused by friction within the profile.
Soil profile	Vertical sequence of horizons extending downward from the soil surface
Soil texture	The relative arrangement of sand, silt and clay soil fractions
Soil weathering	The process whereby soil components can be altered and/or leached out of the profile. May be physical or chemical weathering
Spoil	Non-soil material that is replaced in the mine excavation prior to placement of cover soil
Subsoil	soil science term for the soil layer/s occurring below the topsoil
Topsoil	soil science term for the soil layer occurring at the surface

LIST OF FIGURES

1. INTRODUCTION

Soil is a vital natural resource for humankind. Apart from the obvious uses in the agricultural field, soil also provides building materials (e.g. mortar and plaster sand, glass), as well as food and fibre, both directly and indirectly. Soil is the growth medium for grass and plants that sustain wildlife, as well as for trees that provide wood, paper, furniture and many more. It is thus imperative that the soil resource of a country be appreciated, conserved and properly (and sustainably) utilised.

In South Africa, there is a great variety of soils that occur, ranging from sandy dunes in the Kgalagadi, to erodible duplex clay soils in the south-eastern parts, shallow rocky soils in mountain areas, and most importantly, the deep, productive agricultural soils that cover much of the eastern Highveld plateau, as well as other areas. Archbishop Tutu coined the phrase “The Rainbow Nation” to describe South Africa, but we can just as well refer to a “Rainbow nation of soils” (see Figure 3 for an idea of the variety of soils that exist).

The Eastern Highveld of Mpumalanga is a very important agricultural area, with highly productive soils that produce around 30% of South Africa’s maize (van den Berg et al. 2008). Ironically, however, this area is underlain by economically important coal reserves that, apart from export and other uses, are also used to generate the majority of electricity required for the country. Unfortunately, the open cast extraction method that is used has a serious deteriorating impact on soil properties, even if good rehabilitation procedures are applied. In many cases, however, the lack of good rehabilitation practices results in the loss of millions of tons of high-quality soils. Certain impacts by mining, such as the complete disturbance of the very important soil horizon sequence, is largely unavoidable. Mining cannot be halted, however, and it is therefore crucial that all other potential mitigation measures are applied as precisely as possible to ensure that the pre-mining productive ability of soils is retained as far as possible.

It should however be understood that rehabilitation starts with proper stripping and stockpiling of soil types and does not simply commence with backfilling of stored topsoil. Rehabilitation of soils and their agricultural ability is not very complicated. It requires only certain basic principles that need to be executed throughout the entire mining process, which subsequently requires continuing management.

Management of the rehabilitation process and implementation of control measures are key issues that will unavoidably determine the standard of rehabilitation.

This handbook is aimed at everyone within the coal mining sector who has an interest in the soil or who works (directly or indirectly) with soil-related aspects on a coal mine, or who would simply like to know more about the whole spectrum of soils. It is not intended to be a highly scientific, detailed book on soil science, but rather a (hopefully) easy-to-understand summary of the main aspects of the soil, ranging from the main soil-forming factors, the classification and evaluation of different soils, to the handling of soils during the rehabilitation process in order to restore the soil to the highest possible post-mining land capability. It is also not intended to be a handbook on rehabilitation or operational mine tasks (which may in any case vary from site to site), but rather the aim is to provide the soil science principles and other relevant aspects that support or influence such actions.

Topics that are covered include:

- ***Introduction and background*** - what is soil and how is it formed?
- ***Basic soil properties and definitions*** - such as texture, structure, effective rooting depth and more.
- ***Soil identification and basic classification*** - why do we classify soil and what does it mean?
- ***Pre-mining soil survey*** - what is involved and why is it necessary?
- ***Land capability*** - what systems are used in South Africa and for the mines?
- ***Rehabilitation planning*** - what aspects are important?
- ***Stripping*** - how to strip the soils properly for maximum environmental post-mining benefit?
- ***Stockpiling*** - how to optimally store the stripped soil types?
- ***Rehabilitation*** - how to do it properly and sustainably and to avoid potentially costly mistakes.
- ***Post-rehabilitation*** – monitoring, surveys and soil evaluation
- ***Soil health and Fertility*** - what is a “fertile” soil and how to achieve this in the rehabilitation environment?
- ***Conclusion*** - summary of the most important soil-related aspects.

- ***References*** - a list of published sources that give more details about various aspects of soils and their properties. This is both for reference and for further reading, if desired.

The format of the handbook was designed to follow the general soil handling cycle on a coal mine, as shown in (***Figure 1***).

The handbook also contains a number of relevant and insightful photographs, diagrams, tables, graphs etc., that should be helpful in understanding the topics covered.

Soil handling cycle

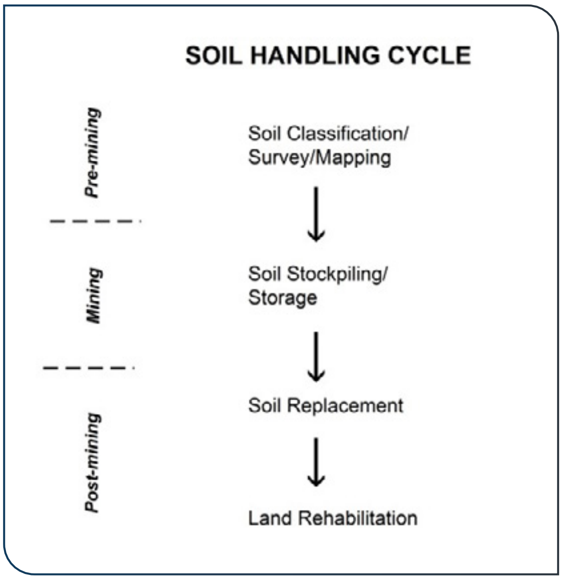

Figure 1

1.1 BACKGROUND

The author has spent over 40 years involved with the description, classification, mapping and interpretation of soils, for a variety of purposes and at a variety of scales. Among these have been a range of pre-mining surveys, where, according to legislation, a detailed soil survey is required before any new mining operation (or extension of an existing one) can take place. At a later stage, he became involved with the processes involving the soil resource when mining commences. This involves the stripping and storage ("stockpiling") of the natural soil horizons that comprise the cover soil and the later replacement of that stored soil as part of the final rehabilitation of the landscape. Much of this work has been documented in various Coaltech Research Projects, including ***Project 8.2.6 on stockpiling*** (Paterson, Adeleke, Mushia, Mkula & Mashigo, 2016), ***Project 9.2.2 on soil microbiology*** (Adeleke & Ezeokoli, 2020) and ***Project 8.4.5 on ground penetrating radar*** (Paterson, van Schoor & Kgarume, 2020).

During these projects, it became clear that there was, amongst mining practitioners, at various levels and in many areas, a lack of basic knowledge and insight about soils in general. This lack of knowledge unfortunately also often extended to the environmental officer (or equivalent) on the mine, so that there is not sufficient appreciation of the need to look after the soil resource, as far as possible, during the coal mining process. At the Coaltech Ideation Session in 2024, discussions with various delegates, including Dr Phil Tanner, led to the formulation of the project to compile this handbook.

1.2 MPUMALANGA

The soils of the eastern Highveld in Mpumalanga are generally highly suited to arable agriculture (crop farming), and produce on average 24% of South Africa's maize, 24% of the grain sorghum, 23% of the dry beans and 51% of the soya beans (van den Berg *et al.,* 2008). This is due to the fact that there are significant areas of arable soils, as shown by the fact that, for example, the Emalahleni Local Municipality (Witbank/Ogies/Kriel) has almost 30% of its area under cultivation and the Steve Tshwete Local Municipality (Middelburg/Arnot/Hendrina) 36% (Geoterraimage, 2005).

The situation is perfectly illustrated (***Figure 2***) in maps from Simpson, Badenhorst, Jewitt, Berchner & Davies (2019), where the green areas in the map on the left, which represent the best cultivation areas, are compared with the purple areas (mining rights) and red areas (prospecting rights) in the map on the right. It can clearly be seen how much high quality agricultural soil has been, and probably will be disturbed due to coal mining. Much of the coal producing areas (the black outlined area on the map on the left) is underlain by good soils (the green areas on the map), while the map on the right shows the threats posed to these soils by mining, both current activities (in purple) and possible/probable future expansion (in red).

Soils and mining in Mpumalanga

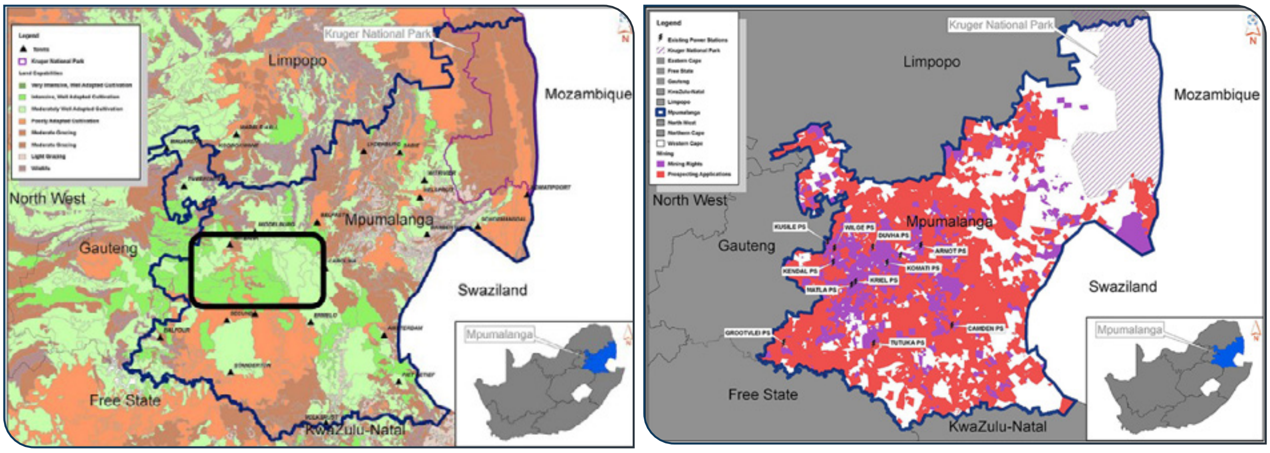

Figure 2

1.2 MPUMALANGA (continued)

Rethman (2006) estimated that some 40 000 ha had been disturbed by coal mining and that this was around half of the potential area. It is most probable that the area has significantly increased in the meantime, possibly to even double the original figure. If one accepts that there are also extensive areas adjacent to the actual disturbed land that also suffer negative impacts (e.g. vehicle traffic, dust, surface and subsurface runoff), then the situation regarding impacts on the soil resource is clearly significant.

In addition, while there are many thousands of hectares where mining currently takes place, and where the soil (for better or worse) is actively being managed, there are also significant areas where previous mining has been abandoned ("legacy sites") and where there is either no current owner of the land or no responsible party, so that soil conditions there are often very poor, with either no rehabilitation or rehabilitation to a very low standard..

2. BASIC SOIL PROPERTIES AND DEFINITIONS

The first question to be asked is "What is soil?" There are many definitions, and some depend on the context of the definer (e.g. agricultural vs non-agricultural etc.), but a simplified definition that best fits the coal mining environment would be something like:

"Soil is the biologically active, porous medium that has developed at the uppermost layer of Earth's crust to allow plants to grow"

The important concept here is that the layer is ***biologically active***, involving billions of micro-organisms, as distinct from any underlying hard or weathered rock material, which could not support plant life. This is especially important in the opencast coal mining process, where it is vital to separate the overlying soils from the underlying weathered rock and other non-soil material, especially in terms of later rehabilitation. This aspect is addressed more fully in Sections 7-9.

Soil composition varies greatly, but in its natural state, there are four main components:

- ***Mineral matter*** *(mainly derived from the underlying rock)*
- ***Organic matter*** *(small proportion, but vital for plant growth)*
- ***Air and pore spaces*** *(because plants need to breathe)*
- ***Water*** *(seasonally variable, but vital for root survival)*

The exact proportions of these components will vary, according to such aspects as the geological unit, land use and season. (***Figure 3***) gives a good idea of their relative proportions.

Soil composition

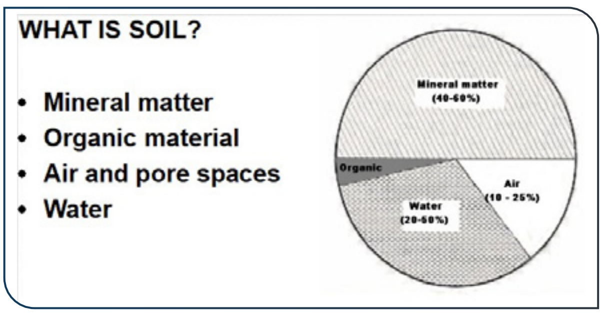

Figure 3

2. BASIC SOIL PROPERTIES AND DEFINITIONS

2.1 THE SOIL PROFILE

Under natural conditions, if one digs a hole vertically downward from the surface, to expose the soil below, the vertical sequence of the various layers (known as "horizons"), all the way down to the underlying parent material, is known as the **soil profile**. It can be deep, with many horizons, or shallow, where only a thin topsoil horizon covers solid or weathered rock.

In (***Figure 4***), a schematic profile can be seen with a topsoil at the surface over a subsurface horizon ("subsoil"), grading gradually downward into weathering material, and eventually into hard rock. The names given are the possible types of each horizon, and they are discussed more fully in Section 3.1.

The depth of the profile can vary greatly, from a few centimetres to may metres, but every soil profile has at least two horizons (Section 3.1).

The concept of the soil profile

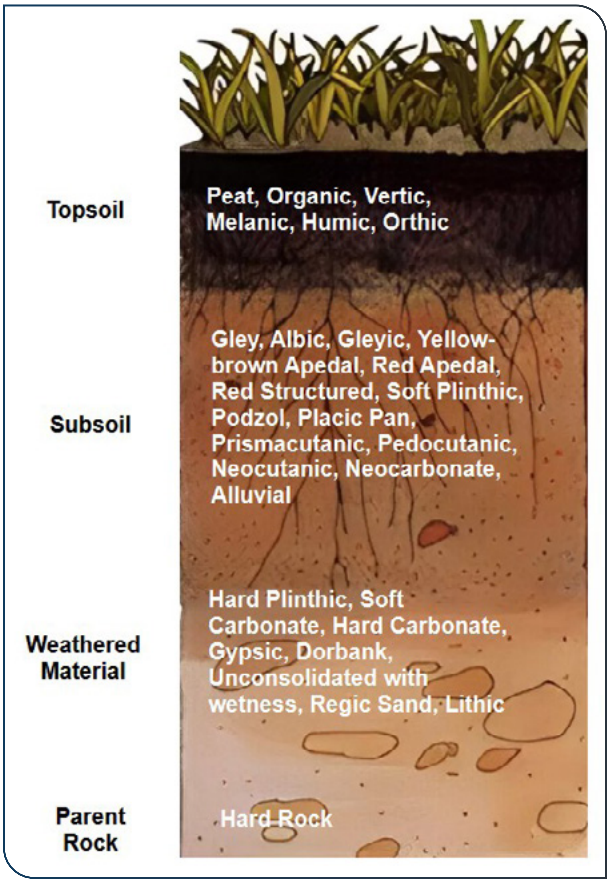

Figure 4

Actual examples of such soil profiles are shown in the photos below (***Figure 5***), and the variation in colour, structure, parent material, thickness of horizons, stoniness, degree of wetness etc. can clearly be seen (the tapes in many of the photos are for relative depth comparison).

Examples of soil profiles from across South Africa

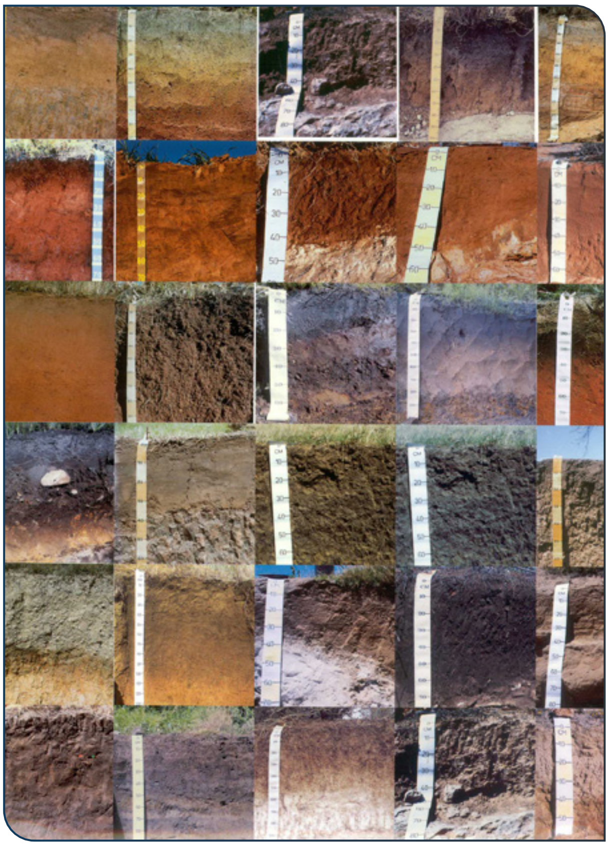

Figure 5

2.2 SOIL-FORMING FACTORS

There are a number of important factors that lead to the formation of the soil, five in total. These are:

- ***Parent Material*** (rocks)
- ***Climate*** (rain, heat, frost)
- ***Topography*** (slopes)
- ***Organisms*** (plants, animals)
- ***Time***

It is important to note that all of these factors operate over a long period of time ("***geological time***"), and that while it takes a long time (even as long as several centuries) for a soil to form, it can be destroyed within a very short period.

2.2 SOIL-FORMING FACTORS

Natural soils and reconstructed mine soil profiles ("mine soils") have distinctly different morphological features. Natural soils are usually formed from homogeneous parent material, where soil development processes, acting over thousands of years, have modified these parent materials so that distinct horizons formed, where organic matter, clay and/or calcium carbonate accumulated. Mine soils are youthful soils, which developed from a heterogeneous mixture of soils and often include geological material. Stratification of contrasting cover soil and spoil material (term for crushed and replaced geological strata) are common in mine soils, having been created by the deposition of dissimilar layers of material.

If we look at the factors in more detail:

2.2.1. ***Parent Material*** - this is the most important factor, since a soil gets most of its characteristics from the weathering (physical and chemical) of the underlying rock. Thus, from ultra-basic materials (gabbro, basalt etc.), we get structured, often dark, clay soils, while coarse grained rocks, such as granite and gneiss, give rise to sandy and gravelly, usually acidic soils, mostly fairly shallow. In the coal mining environment, the underlying rocks are medium-textured sandstone and shale of the Vryheid Formation, so that the majority of the soils are reddish-brown to yellowish-brown, have no macrostructure, and fall within the sandy loam to sandy clay loam texture classes (Section 2.3.1).

2.2.2. ***Climate*** - the prevailing climate in which the soils form will have a significant effect on the type and intensity of the weathering processes that give rise to the eventual soil profile. If one looks at the varied spectrum across South Africa, there are hot, dry areas, such as the Northern Cape, where the lack of rainfall has led to restricted weathering, resulting in shallow soils on hard rock, and a low degree of chemical leaching, so that the soils are alkaline, with a relatively high calcium carbonate ("lime") content and high pH (often >8).

Then there are moist to wet, warmer environments, such as much of KwaZulu-Natal and areas such as the Limpopo Drakensberg, where abundant rainfall has led to deeper and more intense weathering, with deeper soils on softer underlying rock, and a lower pH due to more leaching, with values often <5.5.

Across the coal-bearing zone of the eastern Highveld of Mpumalanga, the climatic conditions lie somewhere between these two extremes, so that the soils are moderately leached and weathering is not so advanced. Here, the pH range of the soil is usually around 5 to 6.5 (a pH of 7 is considered fairly neutral). See also Section 2.3.2.1.

2.2.3. ***Topography*** - the prevailing terrain of the land surface will also have an effect on soil formation. Factors such as slope length and steepness, aspect (e.g. north- or south-facing slope etc.) and position in the landscape play a significant role in soil formation.

There are four main types of weathering that can be considered here:

- ***In situ*** - this is where the underlying rocks weather in place and soils develop from the rock, in the same position.
- **Colluvial** - here, the slope of the land plays a role, and soil and other particles can be detached and moved down the slope due to gravity, to be deposited elsewhere.
- **Alluvial** - where excessive surface water (e.g. flood events) can detach material and deposit it elsewhere. This usually happens in lower-lying landscapes, such as river valleys and floodplains.
- **Aeolian** - usually in drier areas, where the lack of vegetation can cause surface soil particles to be blown into the air and deposited elsewhere, often at a considerable distance.

2.2.4. ***Organisms*** - soil fauna and micro-organisms will also play a role in the decomposition process, especially in wetter environments and/or in wetter seasons. These organisms include protozoa, bacteria, nematodes, fungi, actinomycetes, earthworms, ants, termites and many more. The study of these processes is called ***microbiology*** and is a specialised field. It is important to general soil health that a good microbiological variety and quantity be maintained, so that the "natural" soil processes can continue.

2.3 SOIL PROPERTIES

All soils have a set of basic properties. These may be directly inherited from the parent material (mostly the underlying rock), or may have been changed by various processes over the life of the soil. These processes may be ***natural*** (weathering, leaching, drainage, waterlogging), may be ***event-driven*** (floods, landslides) or ***anthropogenic*** (agriculture, excavation).

The soil properties that exist as a result of these processes may be ***morphological*** (observable), ***physical*** (can be felt) or ***chemical*** (need to be tested/ analyzed).

A complete list and explanation of all relevant soil properties would be extensive and is beyond the scope of this handbook, but many textbooks and other sources are available, such as Weil and Brady (2017) and many others. Some of the most common and important soil properties are listed and defined below.

2.3.1 Morphological and physical properties

2.3.1.1 ***Soil texture*** - this refers to the relative occurrence of different-sized particles in the soil. The three main particle size classes are ***sand, silt and clay***. Sand (0.05-2.0 mm) is the coarsest class, silt (0-002-0.05 mm) the middle size and clay (<0.002 mm) is the finest (smallest). This is better understood if one thinks about sand in general (e.g. on the beach), where the large particles mean that there are large gaps ("pores") between them so that the water infiltrates quickly. At the other end of the scale, we have clay, where the very fine particles have very small pores that makes clay so useful for moulding and baking (e.g. pots and bricks). Most of the soils in South Africa have a texture that lies somewhere in between, with a varying combination of sand-, silt- and clay-size particles, and these soils generally fall into one of the "loamy" texture classes.

Soil texture classes

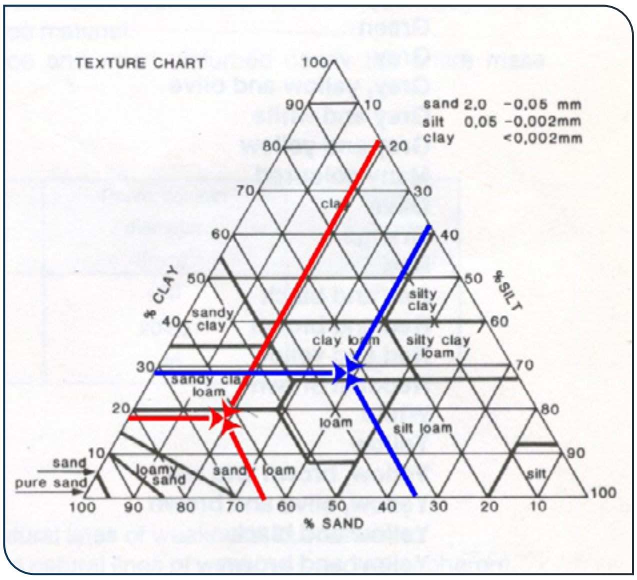

Figure 6

The soil texture chart (***Figure 6***) shows how the particle size classes vary between a minimum of 0% and maximum of 100%. If one class increases, the others will decrease accordingly, so that the overall total of the three sizes will always be 100%. The silt fraction in many South African soils is fairly consistent, usually somewhere between 5% and 20% of the soil, so that it is the clay fraction that is the main variable. Soils with a relatively low clay content (<10%) are classed as ***sand*** or ***loamy sand***, while medium clay content soils (15-35%) fall into the ***sandy loam*** or ***sandy clay loam*** classes. Soils with a high clay content (>35%) fall into the ***sandy clay*** or ***clay*** classes, while soils where the silt fraction exceeds more or less 40% (scarce), fall in one of the silt classes..

The diagram above (***Figure 6***) shows the soil textural triangle, whereby the texture class of a soil can be determined if one knows the relative proportion of the sand, silt and clay fraction within the soil.

The two examples on the chart give different texture classes.

The ***red*** lines show a soil with an approximate clay content of 17% (left axis), a sand content of 65% (bottom axis) and a silt content of 18%, so that the soil texture falls in the ***sandy clay loam*** class.

The ***blue*** lines show a soil with an approximate clay content of 28% (left axis), a sand content of 34% (bottom axis) and a silt content of 38%, so that the soil texture falls in the ***clay loam*** class.

2.3 SOIL PROPERTIES

2.3.1 *Morphological and physical properties (continued)*

The clay content/fraction can be reasonably well estimated in the field by an experienced pedologist (soil scientist) by wetting a ball of soil and assessing how cohesive and/or plastic it feels in the hand. By estimating the clay content, the associated texture class can be estimated fairly accurately.

Alternatively, many extension people use the "Jar Method", also known as the Jar Test or Mason Jar Test, which is a simple, visual method for estimating soil texture by observing how soil particles separate in water. By shaking soil and water in a jar and allowing it to settle, one can roughly determine the percentages of sand, silt, and clay in the soil (***Figure 7***).

Jar test for soil texture

Figure 7

However, for more accurate determinations (required for purposes such as soil fertiliser applications, irrigation scheduling, soil modelling etc.), the exact soil texture should rather be determined by submitting a sample to an appropriate laboratory.

2.3.1.2 ***Soil structure*** - often confused with soil texture, the structure of the soil refers to the relative size and characteristics of the actual peds, or "building blocks" of the soil (***Figure 8***). Soil structure is often influenced by texture, but other factors are at play. If a soil has mainly small, loose particles that crumble and do not stay together, the structure grade is referred to as ***structureless*** or ***weak***. If there is some cohesion between the particles, and some blocks/peds occur, then the structure grade is usually referred to as ***weak*** or ***moderate***. Where the intact, solid peds comprise most of the soil body with few crumbs, then the structure grade is classed as ***strong***.

Soil structure grades

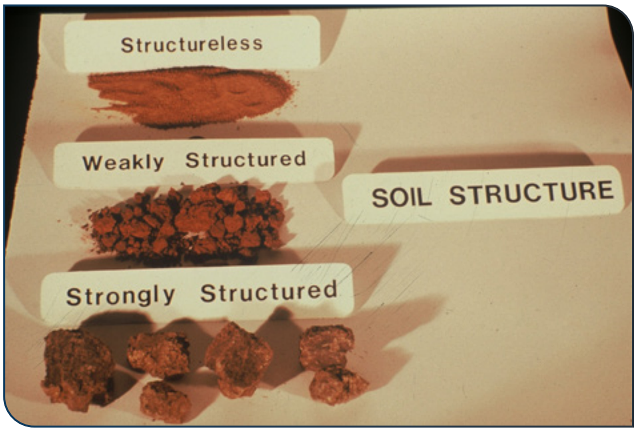

Figure 8

An increasing grade of structural development often makes a soil more difficult to cultivate. In the mining environment, soils with strong structure tend to compact severely which result in water logging problems during the rehabilitation phase. The soil structure units can be mostly rounded (***blocky***), vertical (***columnar***) or horizontal (***platy***).

2.3.1.3 ***Soil colour*** – when travelling through a landscape in South Africa, the variation in the colour of the soils is both obvious and significant. Such examples are the black turf soils in the Rustenburg or Standerton areas, the grey-brown soils of many mountainous areas and the reddish soils across much of the Highveld.

2.3 SOIL PROPERTIES

2.3.1.3 ***Soil colour*** – Colour is influenced by a variety of factors, including the mineral composition of the soil and the degree of leaching or saturation by water, which tells the observer a great deal about the soil. Red and yellow soils indicate freely-drained conditions dominated by iron, with the red soils being dominated by the mineral haematite and the yellow soils dominated by the mineral goethite. Black soils can be high in organic matter, or represent high clay content, depending on their location, while grey soils often indicate that there is impeded drainage, which often results in downward leaching and waterlogging. The range of colours is illustrated in (***Figure 9***) below.

Soil colour variation (left to right): red, yellow-brown, brown, grey, dark brown, black on olive.

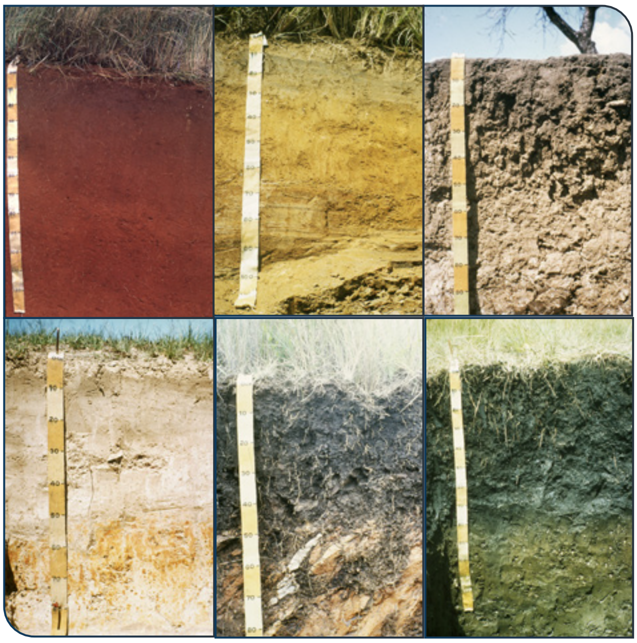

Figure 9

Colour can be very subjective. Thus, a system of accurately recording the soil colour by using Munsell soil colour charts (Munsell Colour, 2015) is used world-wide, to provide uniformity. In this system, three steps are followed, namely to identify the ***hue, value*** and ***chroma*** of the soil. The ***hue*** refers to the overall base colour scheme of the soil, such as reddish (R), yellowish (Y) or yellowish-red (YR). The ***chroma*** (horizontal axis) represents the intensity or contrast of the soil and the ***value*** (vertical axis) represents the lightness or darkness. This process helps to determine, among others, the degree of water saturation in the soil.

(***Figure 10***) shows the specific 10R page from the Munsell soil chart book and the example highlighted by the black box would be **10R5/4.**

Munsell soil colour book (10R page)

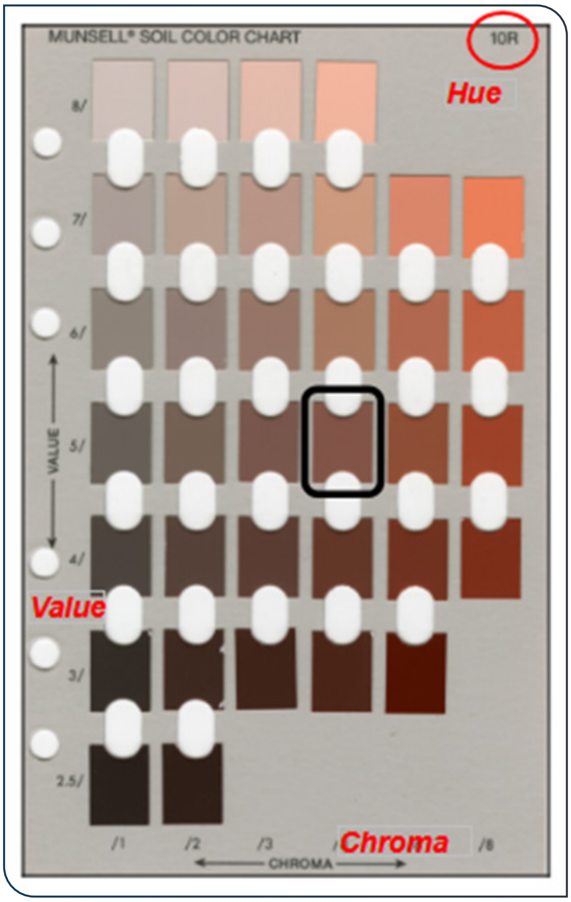

Figure 10

(The holes between the colour blocks are to allow a soil sample (usually a small clod) to be held behind the page for easier comparison)

It is also important to note whether the observed soil colour is in the moist or dry state, as soils become lighter as they dry out. If possible, obtain both the moist and dry colours for the best comparison.

2.3 SOIL PROPERTIES

2.3.1.4 ***Soil depth*** - this refers to the total vertical depth from the soil surface down to any non-soil layer. The concept of depth is usually further defined as ***effective*** soil depth, that is the depth to a layer that is permanently restrictive to water or plant root penetration. Such layers will include: hard or weathered rock; cemented materials such as ferricrete (iron), silcrete (silica), calcrete (calcium carbonate); heavy, often structured, clay layers; saturated zones such as a water table; abrupt changes in texture, structure or chemical conditions. In many cases, total soil depth and effective soil depth will be the same, but in some cases, such as deep, wet, clay soils, the total soil depth will be greater. An example of restricted soil depth in coal mine soils is where a compacted layer occurs (either close to the surface or deeper). This is often caused by heavy mechanical equipment during soil replacement and restricts water and/or root penetration. ***Effective soil depth cannot be greater than the total soil depth.***

The photo below (***Figure 11***) shows how suddenly the soil depth can change within a landscape (often due to underlying geology). To the left of the dashed line, a very shallow topsoil is underlain by weathering rock, while to the right, a much deeper red soil occurs.

This scenario is very common in road cuttings and other excavations across much of the country.

Soil depth variation

Figure 11

2.3.1.5 ***Water-holding capacity*** - one of the primary functions of soil is to store water that can be used by the plant. Water-holding capacity is directly related to soil texture, more specifically the fine particle sizes, namely the clay and silt fractions. Water is held in hygroscopic layers (water film) around each particle (sand, silt and clay), referred to as ***soil water***. When the amount of water in the soil becomes more than that can be accommodated in hygroscopic layers around the particles, then water starts moving into the pores between the particles, and it is at this stage that the a soil becomes saturated/waterlogged. The water replaces the air in the pores and the soil's condition becomes anaerobic. Plants will then start dying, primarily due to a shortage of oxygen than too much water.

This explains why coarse sandy textured soils cannot hold much water, because there are fewer particles that can hold water and larger pores in between that cannot hold water. Conversely, fine textured soils can hold much more water, because there are many particles that can hold hygroscopic water and the pores in-between are very small. Such clayey soils are mostly poorly aerated.

However, there needs to be a balance between water flowing too rapidly through the soil (usually caused by a sandy texture), causing plant roots to dry out, and water taking too long to infiltrate (usually in heavy clay soils), causing waterlogging in the profile and especially the root zone. Soil moisture is measured by inserting a sensor probe into the soil (***Figure 12***) to obtain continuous measurements via a data logger.

Soil depth variation

Figure 12

2.3.1.5 ***Water-holding capacity*** - At the start of the rainy season (around September in the summer rainfall zone of the Highveld), the soils are generally dry, with much of the water that fell in the previous rainy season having drained slowly downward or evaporated upward into the atmosphere.

As the rainfall starts to fill up the soil pores, the profile moisture content increases, mainly from surface water draining downward. If the rainfall is sufficient, the profile may reach a point where all the pores are full, so that no more water can infiltrate. This is called ***field capacity***, which is defined as the amount of water that the soil can retain after it has been saturated and allowed to drain to a stage where the drainage rate has become very small (usually around 2-3 days after rain or irrigation).

In contrast, if rainfall is inadequate (either due to a drought period or at the end of the season), there may be too little water available to keep the plants alive, so that they begin to wilt and eventually die. This is called the ***wilting point***, which is the water content at which plants can no longer obtain sufficient water to provide for their transpiration requirements.

Total available water is therefore the difference in the soil water content between field capacity and permanent wilting point (**Figure 13**, which illustrates these concepts).

In the coal mining environment, factors that affect water movement (infiltration) through the soil profile include the texture (as mentioned above) as well as any restrictive layer within the profile. This is especially significant if compaction occurs, either at the surface, within the profile or at the soil/spoil interface. If the water infiltration rate is impeded due to soil compaction, either excess water will flow on the surface (possibly leading to erosion), or certain subsurface layers may remain too dry for plants to establish or to survive.

2.3.1.6 ***Bulk density*** - this is a measure of how compacted a soil is. Compaction can occur when soil volumes are compressed by heavy mechanical equipment during stockpiling. Compaction also occurs during the soil replacement phase when topsoil is dumped and spread over the spoil surface using heavy mechanical equipment.

It is measured as the mass of soil within a measured volume (sampled using a core sampler - see photo), and is given in units of g cm^3. Under natural conditions, bulk density values of around 1.3 to 1.5 g cm^3 are common, but compacted soils, such as in soil stockpiles and even after rehabilitation, can approach 2.0 g cm^3. To measure bulk density, a core sampler is pressed into the soil until just below the surface (***Figure 14***), then the excess soil at the top and bottom is carefully trimmed, so that the ratio of the mass of soil to the known volume of the sample can be calculated.

Soil water-holding capacity concepts

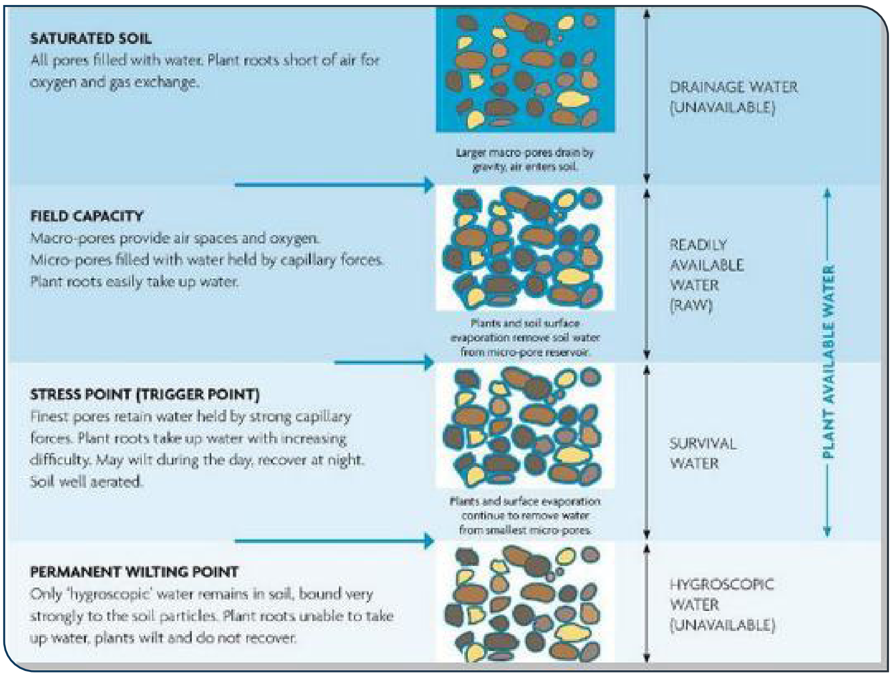

Figure 13

Bulk density sampling

Figure 14

2.3.1.6 ***Bulk density*** - The sliding weight forces the cylinder resting on the surface into the soil so that a sample can be collected.

The process of stripping the natural soil horizons, stockpiling and placement activities will typically result in higher bulk densities than those that occur in natural soil profiles. These higher densities often limit root penetration and development if the sequence of soil handling activities is not managed to minimise compaction, or if inappropriate equipment is used that results in unacceptable compaction.

2.3.2 CHEMICAL PROPERTIES

The chemistry of soil is extremely complicated, and a fuller assessment of all the soil chemical aspects can be found in specific textbooks, such as Strawn *et al.* (2019). Some of the more important and more relevant soil chemical properties are explained below.

2.3.2.1 ***Soil pH*** - this is a measurement of the relative acidity or alkalinity of a soil and is a function of both the underlying parent material, as well as the amount of rainfall received and leaching that a soil has undergone. pH ranges from 0 (pure acid) to 14 (extreme alkaline), but most natural soils vary from around 4.5 to 8.5, with a value of around 7 being neutral. One of the aspects in mining areas where pH is most strongly affected is **acid mine drainage**, whereby the iron sulphides unearthed by mining activity interact with water and air and oxidise. The process creates sulphuric acid, a highly corrosive acid capable of breaking down surrounding rocks, which can cause toxic metals to enter and eventually dissolve into the soil water, underlying materials and groundwater.

2.3.2.2 ***Organic Carbon*** - Soil organic matter (SOM) is the portion of organic residues in soil in various stages of decay. Despite being a small part of the soil matrix, the presence of SOM contributes significantly to soil health. Thanks to its chemical and physical properties, SOM retains large amounts of water and nutrients, which helps to maintain and increase soil biodiversity, improve water and nutrient availability, and reduce erosion and leaching. The main component of SOM is carbon, also known as **soil organic carbon** (SOC), which is measured as a percentage of the whole soil mass. This carbon constitutes the largest terrestrial carbon pool and makes soils integral to our planet's carbon cycling. On a global scale, the top 30 cm of soil contains more carbon than the atmosphere and vegetation combined.

2.3.2.3 ***Cations and CEC*** - The clay mineral and organic matter components of soil have negatively charged sites on their surfaces which adsorb and hold positively charged ions (**cations**) by electrostatic force. This electrical charge is critical to the supply of nutrients to plants because many nutrients exist as cations (e.g. magnesium, potassium and calcium). **Cation exchange capacity** (CEC) is a measure of the soil's ability to hold positively charged ions. It is a very important soil property influencing soil structure stability, nutrient availability, soil pH and the soil's reaction to fertilisers and other ameliorants.

As expressed in the South African Fertilizer Handbook (Fertasa, 2016), CEC is measured in centimols per kg of soil (cmolc kg^{-1}), and can vary between approximately 1.5 (infertile sandy soil) and about 80 (clay soil with high organic matter content). Most of our "good" soils have CEC values between 5 and 20 cmolc kg-1.

2.3.2.4 ***Functions of plant nutrient elements*** - plants require chemical elements in various quantities and in different forms, and are generally split into **macronutrients** and **micronutrients** (Fertasa, 2016), with the macronutrients being relatively more abundant, while the micronutrients, although occurring at lower levels, are equally critical for plant growth. The macro- and micronutrients and their important functions are described below and an indication of their chemical mobility is provided. The mobility status refers to the approximate ease with which each element can become available, either for plant uptake or to be lost through leaching.

Macronutrients

- ***Nitrogen*** (N) - important for photosynthesis, growth, reproduction, protein building, microbial activity. Mobile.
- ***Phosphorous*** (P) - especially important for cell division, root growth and development, flowering and ripening. Relatively immobile, but variable.
- ***Potassium*** (K) - important in transport of N, translocation of starch, stem strength, water regulation, enzyme activation, disease resistance. Mobile.
- ***Magnesium*** (Mg) - nucleus of chlorophyll molecule, required for photosynthesis, nutrient adsorption, stress tolerance. Mobile.

2.3.2.4 *Functions of plant nutrient elements*

Micronutrients

- ***Sulphur*** (S) - promotes chlorophyll formation, nitrogen uptake and root nodule formation. Immobile.
- ***Calcium*** (Ca) - promotes protein formation and cell growth. Important for cell wall strength, root development, enzyme activation, soil aggregation, pH regulation, toxicity mitigation. Not mobile.
- ***Manganese*** (Mn) - important for photosynthesis and oxidation-reduction reactions. Relatively immobile.
- ***Copper*** (Cu) - found mainly in seeds, important for respiration. Also Important in enzyme activation, protein and carbohydrate metabolism, chlorophyll production, disease resistance Immobile.
- ***Iron*** (Fe) - plays a role in oxidation-reduction reactions. Immobile.
- ***Boron*** (B) - important for biosynthesis of cell membranes, cell maturity and cation adsorption. Immobile.
- ***Molybdenum*** (Mo) - small quantities, but important in N reduction and root nodule development, as well as enzyme functionality, protein synthesis, seed development and stress tolerance. Mobile.
- ***Zinc*** (Zn) - promotes chlorophyll formation and growth hormones. Relatively immobile.

3. SOIL IDENTIFICATION AND BASIC CLASSIFICATION

As can be seen from the properties listed in the previous section, soil is a complex and infinitely variable medium. When we deal with this variety of soils occurring across the landscape, we need to simplify and group the most important properties, so that we can classify them, for a variety of purposes.

Classification of entities in the natural world is a long-established fact, whether formal or informal. The most informal type of classification might be whether a specific day is "cold" or "warm", or whether a vegetation type is "trees" or "grass". In most classification systems, there are various levels, usually with increasing detail, and soils are no exception.

So why do we classify soils? The reasons include:

- The process places soil within a fixed, defined system.
- It uses standard parameters and methodology.
- It facilitates consistent knowledge transfer between scientists and other users.
- It allows uniform input into other systems (e.g. databases).

Soil classification in South Africa began with a range of soil surveys in the 1920's and 1930's, mainly to assess the suitability of soils for irrigation downstream of the large dams that were constructed at that time. The classification focused on basic soil texture classes and pH values, especially to identify saline, or "brak" areas that would be problematic if irrigated. After the first broad national classification system (van der Merwe, 1940), a series of large surveys, mainly in what was then Natal, (Beater, 1959 & 1962; van der Eyk *et al.,* 1969), provided a range of information about how soils were distributed in often predictable and repeating patterns across the landscape.

With the impetus provided by the commencement of the national Land Type Survey (Land Type Survey Staff, 1972-2002) at 1:250 000 scale, a working group was set up to look at the whole question of soil classification and the first edition of the South African Classification system (the well known "red book") was published (MacVicar *et al.,* 1977). The soils occurring were allocated to one of 41 soil forms, each with a unique combination of topsoil and subsoil horizon/s. As more information was obtained across the country, mainly from the fieldwork carried out during the land type survey, a second, expanded edition (the "blue book") was published (Soil Classification Working Group, 1991), which now contained 73 soil forms. The final step was the appearance of the third edition (Soil Classification Working Group, 2018), which contained 135 soil forms and includes a separate section on anthropogenic ("man-made") soils, which is of special relevance to the mining industry.

(1977 edition on the left, 1991 edition on the right, 2018 (current) edition in the middle)

Various editions of the SA Soil Classification system

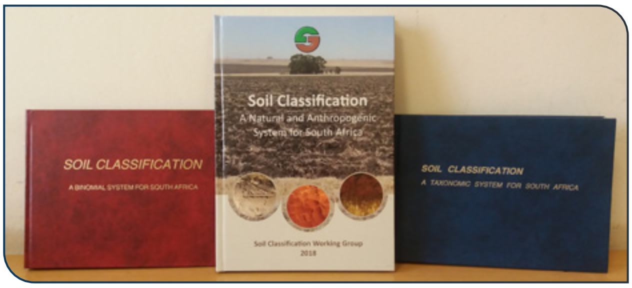

Figure 15

3.1 THE SOUTH AFRICAN SOIL CLASSIFICATION SYSTEM

This section is not intended to provide a detailed, in-depth study of the current system. That is supplied in the book itself, for those who are interested (Soil Classification Working Group, 2018). But some general background and principles are given below.

Two main soil classification systems are widely used world-wide, namely the American Soil Taxonomy (Soil Survey Staff, 1999) and the World Reference Base, formerly FAO system (IUSS Working Group WRB, 2022). Both systems have a wide range of acceptance in different regions. However, after studying both of these systems, the original authors of the first edition (MacVicar *et al.*, 1977) decided that the South African system would be developed from the start to be, as far as possible, a morphological system, so that most of the most important properties can be identified in the field, without the need for detailed supporting chemical analysis, as is the case with both of the systems mentioned above.

The current South African system (Soil Classification Working Group, 2018) is structured as follows:

- **Group** - this is the highest level and separates soils into either ***natural*** (including most normal agricultural soils) or ***anthropogenic*** (where the influence of human activity has significantly changed the soil).
- **Soil Form** - The soil form is defined by a vertical sequence of diagnostic horizons, moving downward from the surface, to a depth of 1.5 m. Each form has a name and abbreviation, e.g. Hutton (Hu), Arcadia (Ar) etc.
- **Soil Family** - The soil family is differentiated *within the soil form* by soil properties reflecting characteristics of that form, whilst having a narrower range of variation than permitted within the definition of diagnostic horizons. Examples would be Hu1120, Hu2320 etc.
- **Soil Series and Qualifiers** - these are not formally defined in the system, but are left to the user to include where necessary. Examples might include shallow and deep phases of an otherwise identical soil family, where such distinction would be important for agricultural potential. In many cases, these will equate to mapping units during a soil survey.

The following table, taken from the classification system, provides a summary of the critical concepts for the defined diagnostic horizons.

HORIZON	CRITICAL CONCEPT/S FOR IDENTIFICATION
Topsoils	
Peat	Very high organic carbon; dark; wet.
Organic	High organic carbon; dark; wet.
Vertic	Moderate to strong, coarse blocky structure; dark; slickensides; cracks.
Melanic	Moderate to strong, blocky structure; dark; slickensides absent.
Humic	Dark; carbon-rich; apedal to weak structure; freely-drained.
Orthic	None of the above; may be dark, chromic or bleached.
Subsoils	
Gley	Grey colours (blue-grey in sands); luvic character; apedal to weak structure; little mottling; often wet.
Albic	Grey colours; apedal to weak structure; few mottles (<10%).
Gleyic	Grey colours; moderate to strong structure; gley colour variation on ped exteriors.
Yellow-brown Apedal	Uniform yellow and brown colouring; apedal to weak structure; non-calcareous.
Red Apedal	Uniform red colouring; apedal to weak structure; non-calcareous.
Red Structured	Uniform red colouring; moderate to strong structure; red cutans.

HORIZON	CRITICAL CONCEPT/S FOR IDENTIFICATION
Subsoils	
Soft Plinthic	Accumulation of vesicular Fe/Mn mottles (>10%); grey colours in or below horizon; apedal to weak structure.
Hard Plinthic	Accumulation of vesicular Fe/Mn mottles; cemented.
Podzol	Enriched with iron and organic matter; commonly dark; occurs in specific areas, such as the southern Cape
Placic Pan	Thin, wavy; hardened; dark; occurs in association with podzols in specific areas, such as the southern Cape
Prismacutanic	Structured; vertical prisms; abrupt transition; absence of gleying.
Pedocutanic	Structured (moderate to strong); blocky; absence of gleying.
Neocutanic	Apedal to weak structure; colour variegation; not gleyed; non-calcareous.
Neocarbonate	Calcareous (though soil material dominates horizon); apedal to weak structure; colour variegation; absence of gleying.
Soft Carbonate	Calcareous (carbonate material dominates horizon, often powdery or nodular); absence of gleying; colour variegation.
Hard Carbonate	Cemented, calcareous layer; usually hard to very hard; little soil present; occurs in semi-arid to arid areas.
Gypsic	Powdery or crystalline gypsum accumulation; may be cemented; occurs in arid areas.
Dorbank	Cemented, siliceous layer; usually hard to very hard; little soil present; occurs in arid areas.
Alluvial	Unconsolidated; apedal to weak structure; usually has fine stratifications; may contain wetness; often in low-lying areas.
Unconsolidated with wetness	Unconsolidated; apedal to weak structure; irregular texture variations; gleyed.
Regic Sand	Recent aeolian deposit; sandy; little or no structure; usually grey to red colours; dunes may occur.
Lithic	Dominantly weathering rock material; some soil will be present.
Hard Rock	Rock material; no soil; may be fractured or solid.

3.1 THE SOUTH AFRICAN SOIL CLASSIFICATION SYSTEM

Soil profile examples

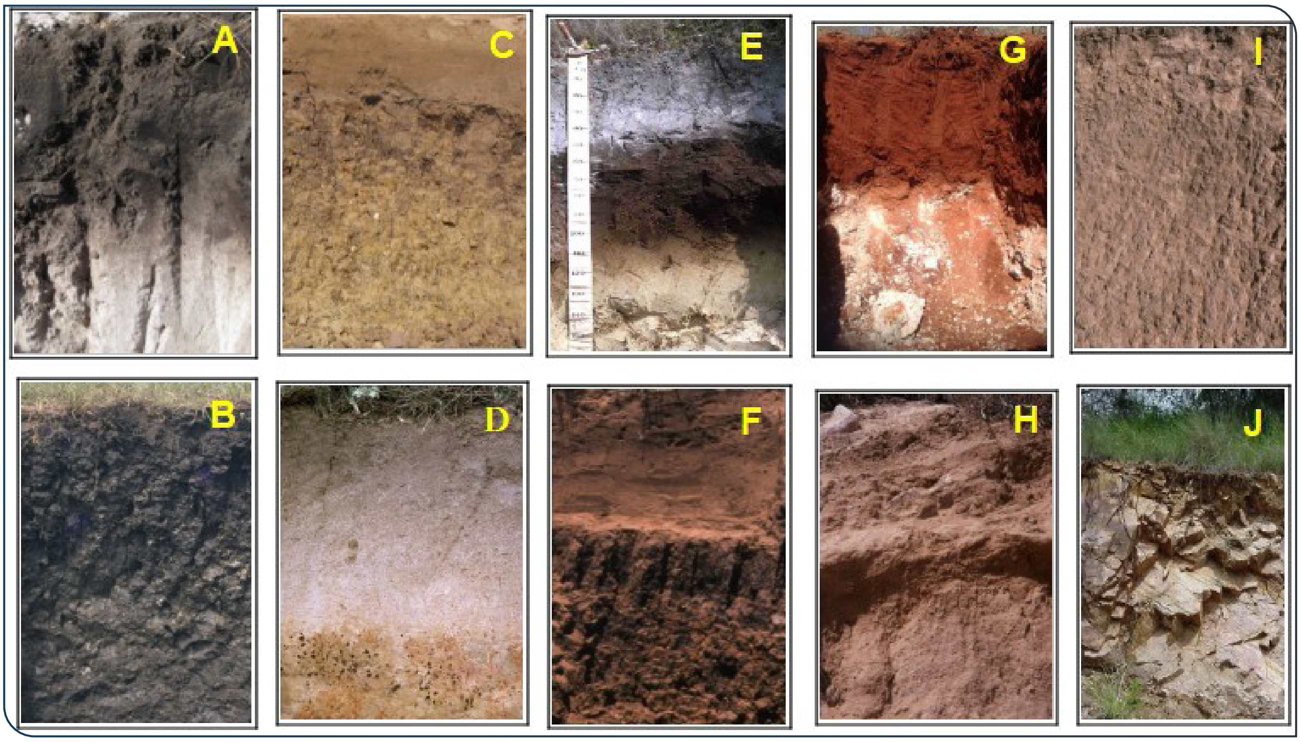

Figure 16

From 2018 edition:

A - Organic topsoil on sand;

B - dark, structured clay;

C - gleyed soil;

D - bleached soil on plinthite;

E – podzol;

F - duplex soil;

G - red apedal on calcrete;

H - cemented dorbank;

I - young alluvial soil;

J - shallow lithosol.

3.2 WETLAND SOILS

Wetland soils, or "Hydric soils" are defined as soils that develop under conditions of frequent and prolonged saturation, flooding, or ponding, leading to anaerobic (oxygen-depleted) conditions. In most landscapes, including those disturbed by mining, soils in certain positions, mostly the lower-lying parts, are subject to the periodic or virtually continuous saturation by water. Wetland soils play an important role in regulating and conserving the environment and should therefore be recognised, delineated and conserved as far as possible. Wetlands purify water naturally by acting as a filtration system, removing pollutants and improving water quality. They do this through a combination of physical, chemical, and biological processes involving their unique vegetation, soils, and micro-organisms.

Wetlands are generally divided into one of three types:

- **Permanent** – in such zones, virtually continuous saturation occurs. These soils are a solid grey colour with very few mottles and are usually easy to identify. The water table is high throughout the year, leading to anaerobic (oxygen-poor) conditions.
- **Seasonal** - these zones are usually only saturated during the wetter season of the year. The subsurface horizons are usually grey, but often have red, black or orange mottles, and are usually straightforward to identify. The water table rises in summer and falls in winter, with alternating reducing/oxidising ("redox") conditions.
- **Temporary** – these zones are subject to the least amount of saturation, but when it occurs, it can be intense. The soils are usually not grey (often brown to red), with few mottles, but there may be a wetter horizon in the lower soil profile. These soils are more difficult to identify visually by means of vegetation or terrain unit and require careful study, usually via auger observations.

This arrangement is shown in (***Figure 17***) below.

Wetland soil transect from dry to wet soils

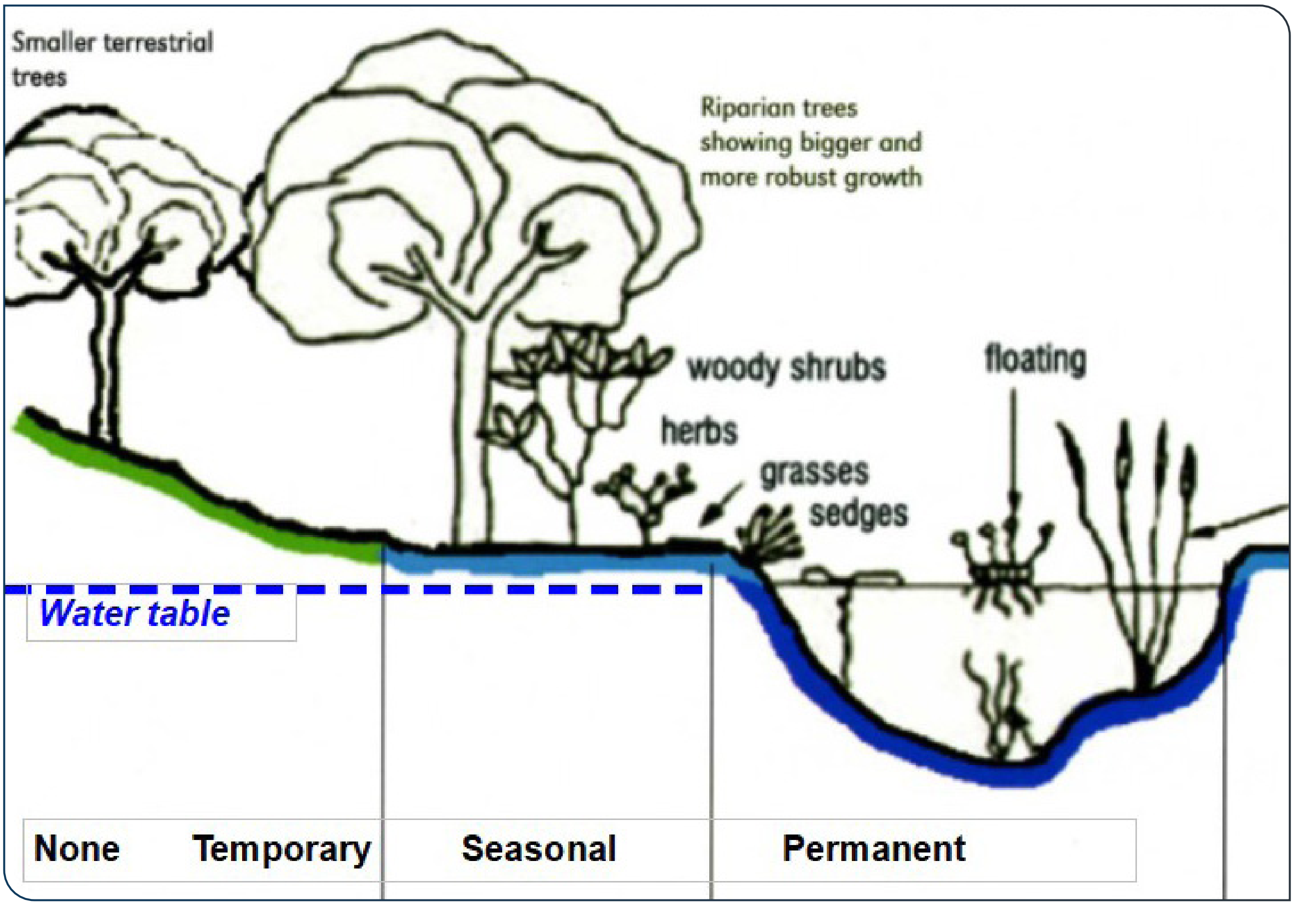

Figure 17

3.3 HIGHVELD CATENA

A catena is a sequence of soils in the landscape, generally down a slope, where the prevailing soil forming factors give rise to relatively predictable and known soil conditions. The general catena/ soil pattern on the Highveld is shown in (***Figure 18***) below.

During soil surveys (see Section 4), the presence of the catena often makes it easier to identify the soil patterns across the landscape, as well as to understand the specific local topography. On the upper slopes, shallow lithosols often predominate, while going down the slope, the soils become deeper, first red, then yellow-brown, and a subsurface mottled plinthite horizon often appears. In the lower parts, mostly grey soils occur, while close to the stream beds, heavy gleyed clay soils are usually found.

Typical Highveld soil catena sequence

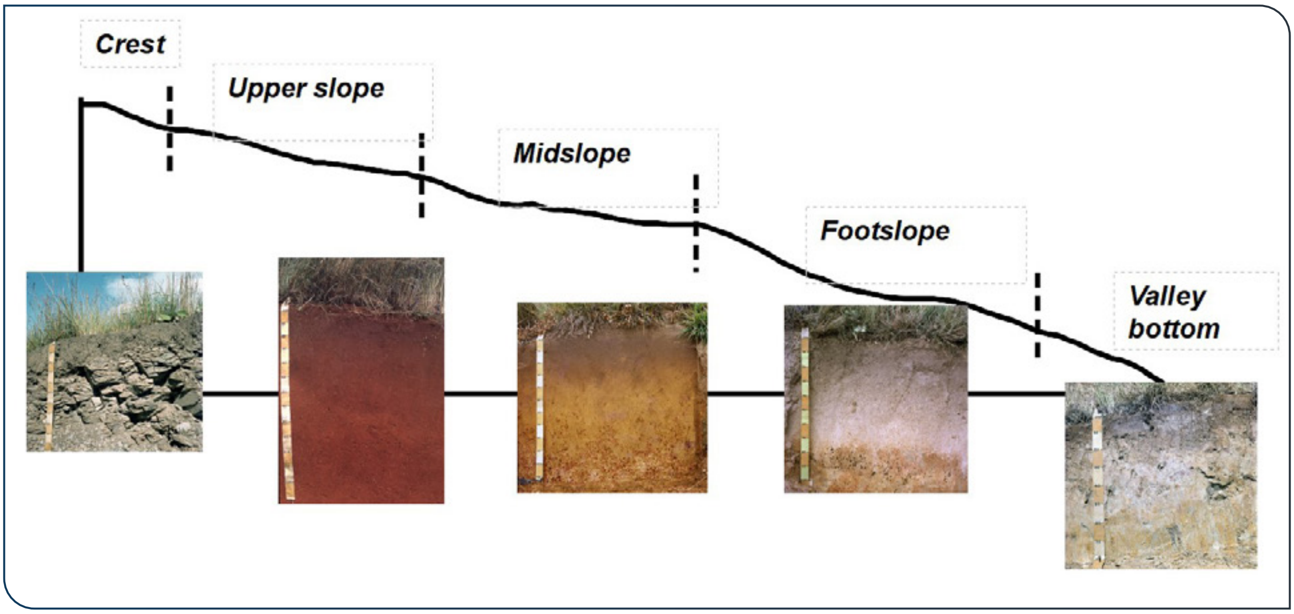

Figure 18

4. PRE-MINING SOIL SURVEY

Within the mining environment, as quoted in the latest land rehabilitation guidelines (LARSSa/ Coaltech/MinCoSA, 2018), there is collaborative governance between the Department of Mineral Resources and Energy (DMRE) and the Department of Forestry, Fisheries and the Environment (DFFE). This is to provide aligned legislation so that environmental impacts from mining and other projects would be minimised and effectively managed.

The National Environmental Management Act, No. 107 of 1998 (NEMA), and its associated regulations is endorsed by DFFE. It stipulates the approach to conducting mining and other environmental impact assessments (EIAs) and is the primary piece of legislation for managing environmental impacts. In addition, the Conservation of Agricultural Resources Act, Act 43 of 1983 (CARA), requires a soil survey to be done as part of any application for a change of land use (which obviously includes mining).

Within the EIA process, before any new mining development, or extension to an existing mine, can take place, a pre-mining soil survey must be carried out to supply baseline soil data on the area/s to be disturbed. A ***soil survey*** is a process whereby the soils occurring within a specific area are described, identified and classified. From this, a soil map can be produced, which shows the distribution of these soils across the various parts of the landscape within the survey area. This soil map can then be interpreted for a variety of purposes, including land capability, expected crop yield, erosion hazard and very importantly, be used to develop a soil stripping plan.

IMPORTANT: according to legislation, namely the Natural Scientific Professions Act (Act No. 27 of 2003), the South African Council for Natural Scientific Professions (SACNASP) is mandated to register scientists (including consultants) in various categories and fields of practice, one of which is soil science. Therefore, all soil surveys and associated actions, ***must be carried out and/or signed off by a soil specialist registered with SACNASP*** in the field of soil science.

In South Africa, as in other parts of the world, a soil survey is a fairly straightforward process, but one where the desired results may not always be of a uniformly high standard. In order to address this issue, among other objectives, a Field Book, with the main emphasis on soil classification, was published (le Roux *et al.,* 2013). This has since been since superceded by a more up-to-date publication (Verster *et al.,* 2022), which also looks at the wider aspects of surveying and mapping.

4.1 THE SOIL CHARACTERISATION PROCESS

The extent of the proposed footprint for a development (such as an opencast mine) will be provided by the developer/client. The aim is to determine the nature and extent of the higher potential agricultural soils as well as to assess the relative area and soil volume of high-quality soil material (A and B horizons) within each soil mapping unit. Usually, an observation density of 150 x 150 metres would be used. This density of auger observation points has been proven over the years to provide a sufficient amount of usable soil information considering factors of cost- and time-effectiveness.

The first stage is to establish an electronic study area boundary ("shape file"), using a Geographic Information System (GIS), such as ArcGIS, QGIS or an equivalent. Then, a grid of points at 150 x 150 m density is generated and transferred to a hand-held Global Positioning System (GPS) receiver, for the soil surveyor to be able to navigate accurately to each point in the field. In most cases, the soil observation is made using a hand-held soil auger, but occasionally, some or all the observations may be made by means of an excavated soil pit (bearing in mind the logistical constraints, as well as the extra time and expense involved).

(***Figure 19***) shows the equipment typically necessary to carry out a soil survey; soil auger/s, classification book, clipboard with recording forms, Munsell colour book, geological/soil hammer, 10% HCl, water, sampling bags.

Soil survey equipment

Figure 19

Classifying soils involves examination of the soils unique characteristics in order to understand the origin and processes that lead to the physical properties of that specific soil form. In order to achieve that aim, there is a series of steps that must be executed, *in this specific sequence*.

- **Description** - at every soil observation point, identify and describe all the relevant properties and characteristics of each soil horizon (layer), starting *from the surface downward*.
- **Classification** - match these properties to the diagnostic requirements of each soil horizon, then establish the prevailing soil horizon sequence. That sequence will correspond with one of the 135 unique soil forms accommodated in the soil classification system (Soil Classification Working Group, 2018), as summarised in Section 3 above.
- **Mapping** - once the soil form at each observation point has been classified, observation points with similar soils can be grouped into uniform mapping units, with a boundary being drawn between all the different map units.
- **Sampling** - if required by the nature of the assessment, soil samples (ideally a topsoil and subsoil sample) can now be collected for delivery to an accredited soil laboratory. It is important that the number and location of the sampling points are decided only ***after*** the mapping phase is completed, so that the surveyor can ensure that all the major map units are sampled, thus obtaining well-distributed representation.
- **Interpretation** - depending on the purpose of the survey, the mapping units can now be interpreted for specific purposes, such as agricultural potential.
- **Report** - a comprehensive report will be produced. This will include terms of reference, methodology, a soil map and associated legend, soil analytical results and interpretation thereof. Depending on the purpose of the assessment, other information such as an impact assessment based on the planned structures and/or activities should be compiled.

The soil maps below (***Figure 20***) show the mapping units that were identified as well as their distribution. The label within each mapping unit on the left-hand soil map indicates the size of the map unit, the average soil depth and the calculated soil volume. The right-hand map is a land capability map that was derived from the soil information on the soil map and groups soil forms in land capability classes such as; arable, grazing, wilderness and wetlands (see section 5).

4.1 THE SOIL CHARACTERISATION PROCESS

Basic soil map (left) and interpreted land capability map (right)

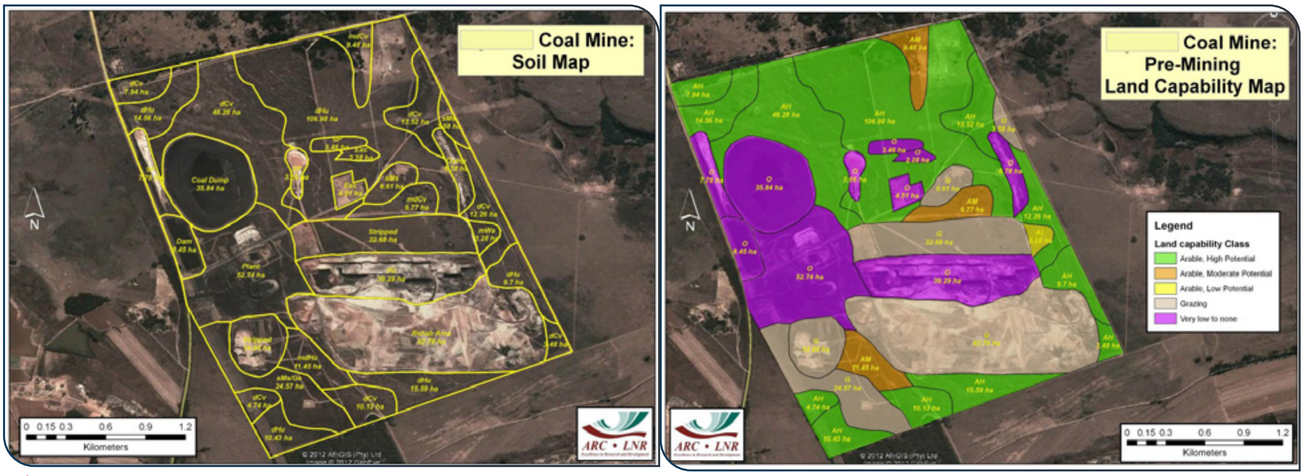

Figure 20

4.2 HYDROPEDOLOGY

An aspect of soil characterization and interpretation that has become increasingly prevalent in recent years is that of ***hydropedology***. This area of soil science refers to the specific properties of soils that influence water flow within the soil profile, and one of the principal components is to classify a soil into one of several hydrological soil groups. According to van Tol (2000), these are:

- **Recharge soils** - In these soils, vertical water flow into, through and out of the profile into the underlying bedrock is the dominant flow direction. These soils will then eventually 'recharge' groundwater aquifers or wetlands in valley bottoms. These soils do not have any morphological properties indicative of saturation (i.e. no mottles or grey colours).
- **Interflow soils** - Subsurface lateral (downslope) flow is the dominant flow direction in interflow soils. It can either occur 1) at the topsoil/subsoil horizon interface, where a temporary build-up of water may occur, often resulting in the development of a bleached E horizon, or 2) where freely drained soils overlie relatively impermeable bedrock which promotes lateral flow on the soil/bedrock interface.
- **Responsive soils** - These soils 'respond' quickly to rain events and are responsible for overland flow generation during typical rain events. Soils with morphological indications of long periods of saturation are close to saturation during most of the rain season and any additional precipitation on these soils will typically flow overland due to saturation excess.

By having knowledge of these properties, aspects such as hillslope and catchment management become easier, and soil water movement and storage in different parts of the landscape can be assessed, modelled and predicted. This is especially important in water management from a mine excavation.

5. LAND CAPABILITY

Land capability is defined as "the ability of a specific area of land to support various uses, such as agriculture or construction, without causing long-term harm to the environment". This concept helps guide sustainable land use by categorising land based on its physical and chemical properties, such as soil type, slope and climate. Understanding land capability ensures responsible land management practices to optimise productivity while maintaining ecological balance.

The relevance of this to the mining environment is the ability to determine the long-term land capability of any area prior to any mining development, so that the relative areas of different land capability classes can be established, both for application and later rehabilitation purposes. The original land capability system was developed by the United States Department of Agriculture (USDA) in the 1960's (Klingebiel & Montgomery, 1961) and used eight classes, from Class I to Class VIII. The first four (Class I to Class IV) covered land that was considered to be suitable for arable cultivation, while classes V to VIII were non-arable. This system was slightly adjusted for South Africa and adapted by a joint ARC/NDA project (Schoeman *et al.*, 2002). More recently, the Department of Agriculture in South Africa has produced a fifteen-class system for land capability (DAFF, 2018), but this has not been widely distributed nor the methodology made available, so it is generally not yet used.

Subsequent to the adoption of the eight-class system in South Africa, in the "Guidelines for the rehabilitation of mined land" (Chamber of Mines/Coaltech, 2007), it is proposed that four classes of pre-mining land capability and agricultural potential be recognised, namely: **Arable, Grazing, Wilderness** and **Wetland,** as introduced by de Villiers in 1981. The full definitions are given in the document referenced above, but in essence, they are:

- **Arable land** has deep (>75 cm), structureless, permeable soils
- **Grazing land** has shallow (<75 cm) soils
- **Wilderness land** is too steep and/or rocky/stony for any type of agriculture
- **Wetland** has gleyed, usually grey, clayey soils, and may be permanently or seasonally wet

In addition, to properly account for all the soil variation that usually occurs, it is useful to separate the "Arable" class into "high", which accommodates deeper (usually >1.2 m) soils that are highly productive, and "low to moderate", which accommodates soil that is slightly shallower, or where there is a depth or other variation, but which can still be cultivated in most cases. For an example, see the right-hand map in (***Figure 20***) above.

Arable soils will include most of the deep, freely-drained, red and yellow soils across the Highveld, while ***grazing soils*** will be somewhat shallower, or have a restricting, structured clay horizon, or other horizons that restrict root development. ***Wilderness soils*** will be extremely stony, so that crop production, pasture and even livestock grazing, is impractical. ***Wetland soils*** represent those parts of the landscape that are affected by water saturation, either for most of the year or during the rainy season. Photos of examples of these soils are shown on the right in (***Figure 21***).

The red soil profile (No. 1) is deep, well-drained and has a high arable potential. The next profile (No. 2) shows a soil profile with some restrictive structure and impeded internal drainage properties (gleying) that is more suitable for grazing purposes. The next profile (No. 3) is very shallow, overlying hard rock on a steep slope, which would typically qualify for the wilderness land capability category. Finally, while the right-hand profile (No. 4) shows a soil with subsurface gleying and a water table, typical of soils in the wetland land capability class.

Examples of soils from different pre-mining land capability classes

1. Arable

2. Grazing

3. Wilderness

4. Wetland

Figure 21

6. REHABILITATION PLANNING

The pre-mining soil survey, with its various interpretations, provides vital information for the planning of the soil handling activities throughout the operational phase until rehabilitation commences. Along with information supplied on the actual distribution of soil types, it is important that the soil surveyor supplies information on ***available soil volumes*** for each mapping unit. This is obtained by multiplying the area (ha) by the average soil depth of the unit, to give a good estimate of the amount of ***useable soil*** (see definition of effective depth, Section 2.3.4). For example, if a soil unit covers 30 ha and the average soil depth of the unit is 80 cm, then the volume would be:

300 000 m^2 (30 ha) x 0.8 m = **240 000 m^3**, which is approximately **320 000 tons** of soil (assuming an average bulk density of 1.5 t ha^{-1}).

If volumes for all the map units are calculated in this way, the total volume can used to calculate variables such as number of vehicle loads, area required for soil storage etc. *It is important to remember that this refers to the useable, high quality soil which consists of the natural A and B horizons and excludes plinthic horizons. The stockpiled topsoil is often referred to as "cover soil" by mine personnel.*

Aspects where careful soil planning needs to take place include the following:

- **Extent of areas to be stripped** - The pre-mining soil survey will also include areas where stripping of topsoil will not be required. The soil volumes of all the mapping units can be calculated, but it is crucial to calculate the soil volume of the planned open pit and other footprints where soil stripping will definitely take place, because this is the cumulative volume that will be applicable to the rehabilitation process.
- **Infrastructure** - this includes a variety of buildings, processing plants, roads, pipelines, conveyors and many more. In many cases, it is not feasible to remove the cover soil for later use, but if the infrastructure covers a significant area, it would be extremely advantageous to remove the cover soil prior to construction and store it in a designated stockpile.
- **Dumps/Waste Facilities/Dams** - Most overburden dumps at all opencast coal mines are removed at the end of life and the original soils underneath can then be rehabilitated (ripped, fertilised and re-vegetated). It is better to *not strip the topsoil* prior to dumping the overburden material, because during the operational phase the stored topsoil is highly likely to be used for another purpose, resulting in a lack of topsoil to rehabilitate the excavated footprint. In many scenarios, however (including underground coal mines) the discard dumps remain for ever and need to be rehabilitated by means of a soil capping layer. Where such a facility will remain in place after closure, it is crucial that the topsoil underneath is first stripped and stockpiled for later rehabilitation.

If all of the above practices are followed, it will make a significant contribution towards a mine having adequate stocks of cover soil available for rehabilitation.

7. STRIPPING

The pre-mining soil survey is designed to provide all of the information required for the effective and efficient stripping of the natural soil horizons and should provide guidelines for the stockpiling process, as well as suggesting a suitable location. The soil surveyor will generally be slightly conservative in estimating soil effective depth per mapping unit. The stripping team should adhere to the provided stripping depth as accurately as possible to prevent "over-stripping", which would consequently include non-desirable subsoil materials being mixed with the high quality soil material.

The photo in (***Figure 22***) shows the boundary between the natural soil and the underlying weathered rock (solid black line). If stripped too deep, as shown by the dashed blue line, then low quality underlying material (generally less fertile and with a higher rock content) will be included in the soil stockpile, while under-stripping (shown by the dashed yellow line) will result in much high quality soil being left behind, potentially causing problems of cover soil at the rehabilitation stage. This would unavoidably result in a reduction in the post-mining effective soil depth and subsequently a further degradation from pre-mining to post-mining land capability.

7. STRIPPING

Information from various mines, as well as personal experience, would seem to indicate that instances of over-stripping and under-stripping are equally likely to occur, but if effective management of the process is in place, as well as correctly compiled specifications, then the prospects for correct soil stripping will be greatly improved.

Profile showing depth to underlying material

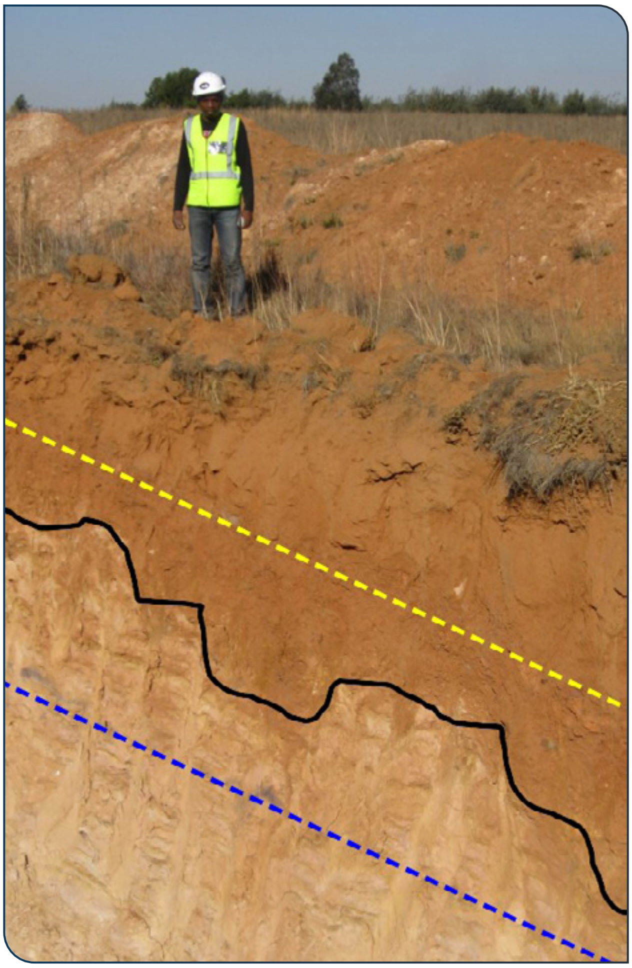

Figure 22

Best practice (maximum efficiency) would be for the soil being stripped to be immediately transported and placed in an already backfilled and prepared rehabilitation location ("live placement"). However, due to operational issues, this is usually not possible, so that the cover soil is stripped and stored elsewhere on a soil stockpile. It is often recommended that the "topsoil" (A horizon or upper 300 mm) be stripped first and stored separately, followed by the "subsoil" (B horizon or up to 1.2 m below the A horizon). However, this is generally impractical, for the following reasons:

- On the Highveld, there is often not a significant difference in texture and structure between the topsoil and subsoil, so to store them together does not have a massively detrimental effect.
- The action of stripping twice involves extra cost, and the high degree of accuracy required is usually not easily achievable.
- The subsequent replacement of the subsoil and levelling thereof followed by replacement and levelling of the topsoil would result in two separate phases of vehicular traffic, which would definitely imply higher costs, and higher soil compaction potential, often long-term.
- When dealing with horizons as thin as 250 mm, it is usually not possible to mechanically strip to this degree of accuracy.

There will always be a degree of uncertainty regarding the optimal stripping depth, due to the varying soil depth (clearly shown in (***Figure 22***) and the difficulty for large stripping machinery to strip at small depth tolerances. However, the amount of information contained in the pre-mining soil survey report will usually reflect a fairly accurate amount of useable soil that can be stripped.

In addition, it is crucial that the stripping depth is verified on a daily basis during the stripping action to ensure that little or no plinthic or other subsoil materials are stripped together with the high quality soil horizons. In this way, the soil stripping process can be carried out, and signed off, separately, before stripping of the underlying materials commences.

The Golden Rule: every cubic metre of good cover soil that can be stripped and stored is priceless!!

8. STOCKPILING

This is one of the most important phases of the soil handling time line on a coal mine, as the soil inevitably deteriorates during the storage process. The main effects of stockpiling are:

- **Physical disturbance** - the natural soil structure, layering (horizons), pore arrangement and internal drainage are broken down with the soil removal and will remain so for as long as the soil is stockpiled.
- **Compaction** - this will increase due to the disturbance during soil removal, as well as vehicle traffic on the surface of the soil stockpile.
- **Mixing of different soil types** - as described in Section 7, there is a strong likelihood that a significant mixture of soils will occur. Different soil types, colours and textures are dumped

together, which will produce variation in infiltration rates, water-holding capacity and fertility across the stockpile.

- **Fertility** - this is difficult to predict, and varies from mine to mine (Paterson *et al.*, 2016), but will often include: variation in pH due to mixing of soils; loss of organic carbon; loss of microbial diversity (soil health) and more.

Some photos below (***Figure 23***) illustrate these problems.

High, layered stockpile (top); compaction with surface erosion (bottom)

Figure 23

While none of the problems mentioned above can be completely avoided in the stockpiling process, a Coaltech report that specifically looked at soil stockpiling (Paterson *et al.*, 2016) was able to provide some quantification of the problems and some recommendations. A range of stockpiles (e.g. age, depth, soil type) across four mines was sampled and the soils compared with unmined, natural soils in the immediate vicinity.

Some of the findings are that, with stockpiling;

- ***average clay content*** increased by around 55% (mainly due to underlying clayey materials being mixed in with original soil horizons);
- ***average bulk density*** showed a small increase, but large variability, with values up to 1.98 g cm^3;
- ***average cation exchange capacity*** showed an approximate 10% increase (due to higher clay contents from mixing of soils);
- ***average soil pH*** showed a small decrease, but again large variability;
- ***average organic content*** showed a 47% decrease;
- ***Microbial variety*** showed a decrease, as many beneficial microbes go dormant in stored soil.

Some of the recommendations from the report, in order to improve the effectiveness of stockpiling, included:

- **Vehicle Traffic** – although it is accepted that vehicular transport is necessary for efficient transport and storage of soil, the detrimental effects of repeated surface compaction by vehicles has clearly been seen. No vehicles should be permitted to drive on a soil stockpile once the soil has initially been deposited.
- **Stockpile Height** – if it is accepted that no traffic should be permitted on a stockpiled area, this will automatically limit the height of the stockpile to that which can be deposited without further compression by tyres, tracks etc. The exact height will vary depending on the vehicle used, but should not generally exceed 3 metres maximum, so that a series of heaps (***Figure 24***) will be created ("end-tipping"), rather than a high, layered soil mass (***Figure 23*** top). In addition, excessively high stockpiles with steep side slopes will not be conducive to vegetation covering and will be susceptible to erosion. While available space may be a problem for some mines, it should be stressed that this is ***probably the most important recommendation in the stockpiling process.***
- **Stockpile Age** – soil response to stockpiling is difficult to predict, due to the variation in soil characteristics, as well as the physical stripping process. However, especially when coupled with any sort of compaction, the longer a soil is stored in a stockpile, the more potential problems will arise, and there will be significant effects, even if soil is moved and stored for a few weeks. Although no clear or fixed correlation could be obtained in this study between age of soil stockpile and soil deterioration, it would definitely be advantageous if no soil was stockpiled for longer than a period of 3-5 years.

Example of end-tipped soil stockpile, showing vegetation cover

Figure 24

Topsoil doesn't have a strict expiration date, but its quality can and will degrade over time depending on storage conditions. Key factors that influence its shelf life include soil moisture and aeration. However, excessive moisture can lead to compaction, nutrient loss, and microbial decline. It is therefore recommended that soil stripping and stockpiling is not done when the soil is excessively wet. It is also beneficial to ensure stockpiles are vegetated where possible and seeded with suitable species, especially if the lifespan of the stockpile will exceed 2-3 years.

8.1 BERMS

At most mines, there is a requirement for (mostly linear) berms to be constructed. The functions of these are varied, including delineation of haul roads and other access routes, security, visual screening and more. Where possible, non-soil material should be used for berm construction, as it is often difficult to reclaim and rehabilitate these materials, and often a significant number of berms are required. In addition, pollution from mine activities (coal dust, coal-rich water runoff from road wetting etc.) can have a very detrimental effect on soil materials used for that purpose.

9. REHABILITATION

In terms of the environment, the ultimate aim of the soil handling process is to recreate landscape conditions and re-establish post-mining productivity as close to the original as possible. While part of this process involves shaping the terrain, the major component involves the replacement of previously stripped and stockpiled soil. The following aspects play a critical role in the standard of rehabilitation that will be achieved: :

- ***Soil depth*** - it is desirable to have as much cover soil depth as possible, so that roots have the maximum possible space to develop. Although very much a generalisation, 750 mm can be seen as sufficient for arable production, while 300 mm will be suitable for pastures (or just possibly vegetables), if other soil variables are suitable. The pre-mining soil survey should guide rehabilitation in respect of areas to be returned to arable, grazing etc., and what depth of soil should be used in order to satisfactorily cover the **entire area** to be rehabilitation.
- ***Soil type*** - here, the aim is to use the previously suitable, non-plinthic soil material and to avoid mixing with less suitable materials, such as saprolite (weathered rock), plinthite and gleyed clay. Excessive soil mixing will result in frequent variation in the soil pattern, with patches of soil having a different land capability class.
- ***Compaction*** - the soil needs to be as loose as possible, so that roots and water can infiltrate without being impeded, either at the surface or deeper down the soil profile. Not only the cover soil, but also the underlying spoil needs to be taken into consideration, as excessive compaction of the soil can severely impede water infiltration. This can lead to increased surface runoff, which will subsequently cause soil erosion in places.
- ***Fertility*** - various soil chemical conditions for soil growth should be as favourable as possible for plant growth (see next Section).

The soil-spoil interface is a critical component in rehabilitation, as it provides a solid base for the rehabilitated soil profile to establish. The spoil surface should be uniformly but not excessively compacted before cover soil placement. In addition, it is important that the spoil surface is free-draining in terms of the overall landscape, so that areas of waterlogging, which manifest as "ponding", where downward drainage is limited, can occur on the soil surface. Such areas can be almost impossible to rectify.

One of the important aspects of rehabilitation is the cost involved. Rethman (2006) estimated that, of the total cost of rehabilitation, the grading or levelling of spoil, comprises some 70-75% of the total, the handling of rooting material (including stripping, transporting, storage, placement and loosening) some 18-20% of the total and seedbed amendment, seeding and monitoring the remaining 5-12%.

In the unfortunate event that there is no topsoil available for rehabilitation, research has been carried out into the effectiveness of creating an artificial growing medium from scratch (Human & Truter, 2021; Filho *et al.,* 2023). In this process, bulk ash-rich fine coal waste ("Fungcoal"), supported by microbial inoculation, can be re-purposed in to a fabricated soil that supports the growth of grasses typically used in mine rehabilitation. However, this should ***definitely be seen as a last resort***, as there are manpower and other costs, and the resulting material, while providing a growth medium, cannot be compared with the original soil that is generally used in rehabilitation.

Since the 1980s, statutory requirements for the granting of mining licenses in South Africa have become increasingly stringent. Environmental Impact Assessments and Environmental Management Plans have become integral parts of the mining license application process and must be budgeted and planned for. ***The definition of the degree to which land must be rehabilitated remains vague, however, and thus is open to interpretation***. The Mineral and Petroleum Resources Development Act of 2002 contains no definition of what is considered to be a 'natural' or 'pre-determined' state. Rehabilitation plans for open cast mines usually involve the replacement of (degraded) topsoil and a grass seed mix, which must then be maintained for only three to five years.

A high standard of rehabilitation is the responsibility of the mine, but the more precisely the soil-related rehabilitation procedures are executed, the smaller the liability will become. It further endorses sustainable development which is a principle most mines claim to strive towards.

10. POST-REHABILITATION

The Draft National Mine Closure Strategy of the DMRE requires mines to demonstrate that their rehabilitated areas can support profitable agricultural or other enterprises. In order to do this, they should be able to provide independent evidence of the quality of the rehabilitation. When carrying out such an assessment the success of the rehabilitation process, the accepted method is to carry out a point-based survey, usually on a 100 x 100 m grid, using a soil auger, to look at the most important soil characteristics, but especially the effective soil depth and any compaction issues (easy to detect when using an auger).

This process was time-consuming and could only supply point data, so that information on the soils between the points was generally lacking. A recent development is the use of Ground Penetrating Radar (GPR), which has the great advantage of enabling continuous transects to be studied, using various auger points only for reference and ground-truthing (***Figure 25***). A project carried out for Coaltech by CSIR and ARC (Paterson *et al*., 2020), indicated that using GPR, the relevant specialists could cover at least twice the area than traditional soil augering. It is important to note that GPR should be accompanied by selected soil sampling (such as for chemical conditions and bulk density), but that this can be substantially reduced due to the improved information from the GPR investigation.

GPR survey of rehabilitated area (top), with example of digital GPR cross-section (bottom)

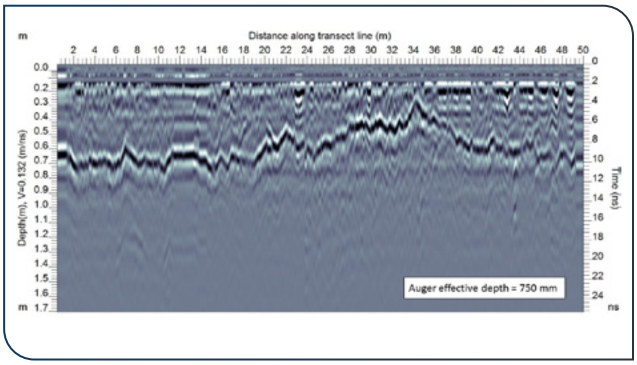

Figure 25

Post-rehabilitation monitoring is an often overlooked, but vital aspect of the rehabilitation phase. This is due to many factors, among them the unnatural soil chemical conditions that often cause excessive fertiliser uptake, the common practice of soil settling, which can lead to compaction, and the often patchy nature of plant growth, which may need augmentation.

Shown below are some examples of poor re-vegetation and other problems after rehabilitation.

Rehabilitation problems: A – patchy grass growth; B – waterlogging; C - crusting

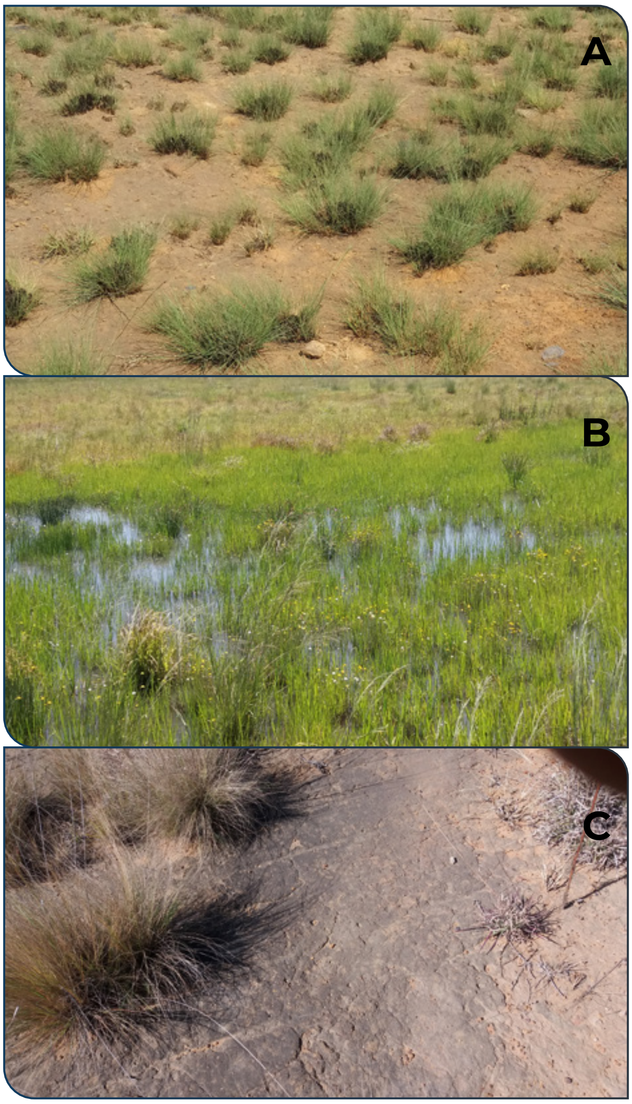

Figure 26

11. FERTILITY

Soil amelioration is a long-term investment into the foundation of rehabilitation success (Hattingh, 2019). It is the best (and often only) opportunity to positively affect the replaced soil and the importance of good soil amelioration can be measured in the vegetation's improved growth response, under prevailing climatic conditions (precipitation, temperature, etc.). When proper soil amelioration is carried out, good vegetation growth is stimulated and soils are stabilised more quickly by plant roots, resulting in better infiltration and reduced soil erosion.

In the rehabilitation process, replaced cover soils will ***always*** require some sort of physical (such as deep ripping) and chemical amelioration, and will often require biological amelioration as well. However, it is vital to ensure that ripping does not extend downwards into the spoil, as this will open pathways for excessive water infiltration into the spoil that should be prevented at all cost. Ripping too deep can also cause spoil material to be brought to the surface, including coarse spoil fragments that may cause mechanical obstacles.

"Live replacement" (where the stripped topsoil is immediately placed in another previously mined and prepared environment) will have considerable benefits in terms of soil quality, lack of deterioration, and reduced rehabilitation costs. However, this should not be done on inadequately prepared spoil surfaces, which may not be free-draining and can end up with subsequent problems. This can include poor post-mining surface drainage, high water infiltration into the spoil, rapid rising of the water table in the backfilled pit, and eventually decant and/or acid mine drainage. Such issues will lead to a perpetual expense, which can cost the mine many times more than what may have been saved through live placement.

Without deliberate topsoil management, the post-mining substrate is exposed at the surface, not the cover soil. Pedogenesis is slow, so the growing medium for plants remains hostile for a long time.

The most important soil chemical parameters were addressed in Section 2.4. From the pre-mining soil survey, there should be analytical data that indicates the "baseline" soil conditions, so it is important to collect and analyse comparable soil samples of the rehabilitated soil, so that optimum fertilisation can take place. Given the inevitable decline in soil condition, including fertility, during the stockpiling phase (Section 8), it is vital to try and restore these conditions as quickly as possible (Truter *et al.,* 2011; Hattingh, 2019). The more accurately this is done, the fewer additives (compost, fertiliser/s, lime etc.) will be required, both in the initial vegetation establishment phase and in later corrections.

The following actions can be used as a guide (Hattingh, 2019), but should be *supervised by a competent, SACNASP-registered agronomist and/or agricultural mechanisation specialist*:

- Following soil placement, apply lime and superphosphate fertiliser (as required) and rip all soils to the full depth of the replaced soil layer, if possible (but not deeper!!).

- Apply and incorporate, by discing, any additional chemical ameliorants required (N & K fertilisers), to condition soil for optimal plant growth.
- Till the soils to produce a seed-bed suitable for the plant species selected for seeding.
- Top dress with appropriate fertiliser, especially nitrogen, as growth proceeds.
- Undertake a post-placement soil fertility and compaction assessment (monitoring) to determine subsequent (following season) amelioration needs.

Following most types of soil disturbance, soil organic carbon is depleted, with rapid nitrogen mineralisation. Although there might be a short-term flush of plant-available nutrients, there follows extreme nutrient deficiency (e.g. of phosphorus, potassium and zinc) until the soil organic carbon, associated mineral nutrient pools, and normal soil functioning are restored. This can take a significant length of time, from years to decades.

Various fertility treatments and additives are available (***Figure 27)***, but these are both labour-intensive and expensive.

As previously intimated, if the **entire soil handling process**, from characterisation (survey), through removal (stripping), storage (stockpiling) and replacement (rehabilitation) is carried out sensibly and conscientiously, then there is a much better chance of a good end result, with benefits to the post-mining environment and favourable economic results for the mine.

Applying fertility ameliorants to rehabilitated areas

Figure 27

12. CONCLUSIONS

Any nation requires energy, and traditionally most of South Africa's energy has been produced as a result of coal-fired power generation. It is also inevitable that the coal-producing environment, and local ecosystems, will be impacted by this process, and the soil resource most of all.

South Africa will, for quite a number years, still rely on coal-fired power generation. Unfortunately, a significant amount of our coal reserves coincides with our highly productive agricultural soils on the eastern Highveld. This makes an ongoing impact by coal mining on our valuable national soil resource unavoidable. The only option we currently have is to apply the highest possible standard of rehabilitation in order to prevent degradation from the pre-mining to post-mining land capability as far as possible.

It is hoped that this handbook will provide useful guidelines to coal mine personnel and other interested parties related to the mining industry. It is the hope that the information provided proves to be valuable and that the handbook also serves as a reference to obtain more detailed knowledge, when necessary.

It is also strongly recommended that, in cases where clear and useful soil knowledge is required, suitable soil specialists are contacted. They are qualified and experienced and will provide first-hand, relevant solutions. Experience has shown over and over that negligent handling of the soil-related rehabilitation process and any cost-saving short cuts, will eventually resurface in adverse impacts, which are then costly to address and can in most cases be only partly mitigated, resulting in perpetuating costs and liabilities.

As in most areas of earth science, in the mining environment it is imperative to bear in mind the principle:

"Don't treat soil like dirt!"

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NOTES


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