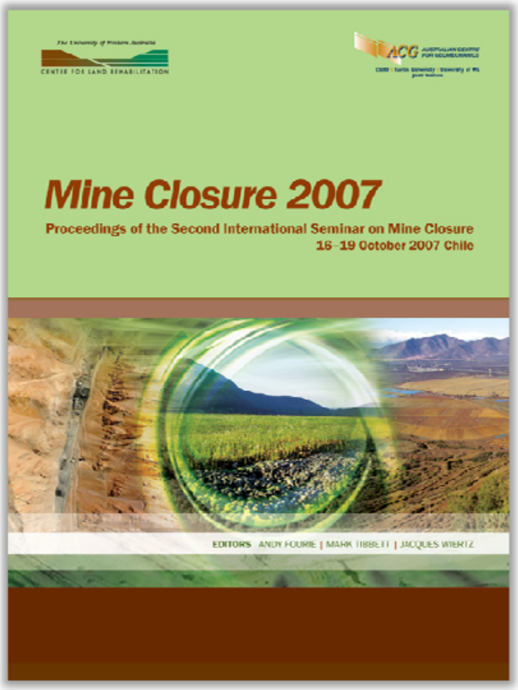
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Post-Mining Landforms — Engineering a Biological System

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Abstract

The construction of cover systems on decommissioned tailings storage facilities and waste rock dumps can represent one of the largest cost components of a mine closure project. There have been great advances in the understanding of the hydrology of cover systems in recent years, but some uncertainties in long-term performance remain. This paper describes some of the changes in engineering characteristics, particularly hydraulic characteristics, which may occur over time, and some of the causes of these changes. It is suggested that covers designed to act as barrier systems are most susceptible to these effects which are a result of pedogenic activity. Finally, it is argued that a new approach to cover design is necessary, which is informed by input from a range of relevant disciplines in order that further improvements in the performance and affordability of appropriate covers are achieved.

1 Introduction

Virtually without exception, the closure of tailings storage facilities (TSFs) and waste rock dumps (WRDs) require the construction of some form of cover system. In the past, many covers have been relatively rudimentary, consisting of only a growing medium on top of the tailings. However, in recent times there has been a move to more and more elaborate covers, sometimes consisting of a number of layers of different materials, each with particular properties and functions. Although the mining field (unlike the landfill industry) has not seen the widespread implementation of cover systems that include multiple layers of geosynthetic materials, there are increasingly cover systems being designed and constructed that are in excess of a metre thick, excluding the growing medium, resulting in very high construction costs.

The primary function of a cover system is protection of the environment, particularly groundwater and the soil subsurface below a waste storage facility. Although other factors are also important, such as providing a stable growing medium and, in some cases, regulating oxygen ingress to the stored waste, prevention of contamination of water resources is likely to always be a major consideration. It may be that we have become obsessed with the prevention of any moisture infiltration into the stored waste, without considering why this is an absolute requirement. For example, Blight (2006) argued for the concept of an `infiltrate-stabilise-evapotranspire' landfill cover, where some (small) amount of drainage into the retained waste could be allowed during periods of excessive precipitation, as long as this only happened rarely. Having said this, it is obviously necessary to ensure that groundwater resources are protected and this remains a primary objective of any cover system.

In setting out to achieve the objective of minimising infiltration, the initial approach was one followed by the landfill and hazardous waste industry, namely the construction of cover systems that were intended to be hydraulic barriers, consisting of (usually) multiple layers of compacted clay. In the mining industry there has been a move away from this approach as a unique solution, realising that climatic conditions often rendered these compacted clay based covers ineffective. The deficiencies of this approach were particularly evident in arid and semi-arid climates, although there are numerous examples of landfill covers in more temperate zones that have experienced similar problems. Despite these observed failures, many in the landfill industry have continued to advocate `hydraulic barrier' type solutions and many jurisdictions internationally still require them. The pragmatic approach of the mining industry has focussed on performance aspects, rather than the obsessive prescriptive approach of requiring the same cover system in all climates and geomorphological settings.

This pragmatic approach led to the rapid development of prototype trials and the assimilation of cover systems based on approaches that tried to utilise the cover system as a storage reservoir, rather than a barrier. The term `store and release', ET (evapo-transpirative) cover, and others has now become ubiquitous and there are many examples of the adoption of this approach in the mining industry. The philosophy of the approach is described in some detail elsewhere (Campbell, 2004), and will not be dealt with in any detail here. Suffice it to say the intention is to provide sufficient water storage capacity in the voids of the cover system to store rainfall during periods of prolonged or heavy rainfall, and then to release it via evapotranspiration during subsequent dry periods. The approach is particularly suited to areas where potential evaporation is in excess of precipitation, but through judicious choice of materials, it may be possible to make the system work in more temperate climates. The apparently simple elegance of this approach could lead to the mistaken belief that the issue of cover design is now a completely tractable problem. It is the intention of this paper to highlight gaps in our understanding of how covers evolve over time and how irrepressible natural processes can potentially change the composition and performance of cover systems. We believe it is only through an approach that is neither grounded only in the engineering paradigm, nor one that takes a purist ecological stance, but one that recognises the need for a complementary approach, that truly sustainable cover systems will be an achievable goal.

Before moving on to a discussion of some of the observed as well as potential factors affecting cover performance, it is also important to flag another important reason for constructing acceptable cover systems. The mining industry would naturally like to minimise any future liability in terms of environmental contamination and requires some certainty that current solutions are going to provide the required performance to make liability minimisation a reality. No one wants to spend vast amounts of money on cover trials, modelling and eventually cover construction, if the resulting recommendations remain vague. Of course, the field is an evolving one, and we learn something valuable from most new cover installation projects. However, we need to look at what other industries have tried (both successfully and unsuccessfully) and what potentially important factors have been overlooked to date and that in fact prove to be major factors in the long-term performance of cover systems.

2 Changes in material characteristics over time

While this paper cannot discuss all factors that contribute to the evolution of a cover system and its performance, a number of important aspects are dealt with, hopefully leading to an approach that will ultimately benefit from the expertise that exists across the engineering and science spectrum. It should also be noted that we do not discuss aspects of cover evolution related to erosion effects. That is an enormous topic in its own right, and has been dealt with to varying degrees by others. Our prime interest is in the potential generation of deep drainage, so although we do discuss conditions where infiltration is affected by changing surface conditions, we do not attempt to extend this to the resulting effects on surface erosion.

Extremely useful information on the evolution of hydraulic properties with time in large cover test plots is beginning to emerge from the ACAP (Alternative Cover Assessment Programme) in the United States. In this very large research project, large-scale lysimeters were constructed at fourteen sites across the U.S., with the full range of possible climatic zones being covered (Benson et al., 2001). The objective of the research programme was to compare the performance of conventional, barrier-type covers, with alternative covers that utilised some variation of the `store and release' concept. Construction took place between 1999 and 2002, and all covers were extensively instrumented in order to accurately quantify the water balance of each test plot. Details of the construction methods are given by Bolen et al. (2001).

Comparisons of the performance of the different covers in terms of the water balance have been presented in a number of forums (e.g. Albright et al., 2004) and will not be repeated here. Of relevance to the current discussion are the measurements made of in-situ properties some years after construction. During construction, samples of the cover soils were recovered by taking block samples to produce truly undisturbed samples. The procedure was repeated in 2002-2004, with most samples being recovered from the near surface (upper 30 cm), where most changes in properties were expected (Benson et al., 2007). Laboratory tests were carried out on the undisturbed specimens, with the tests of relevance to this discussion being saturated hydraulic conductivity tests (using 15 cm diameter specimens in flexible-wall permeameters) and soil-water characteristic curve (SWCC) determination using a combination of pressure plate extractors and chilled mirror hygrometers.

The results showed a surprising change from initial, as-placed conditions. With one or two minor exceptions, the hydraulic conductivity increased over time, by as much as 10 000 times in one case. It was clear that the lower the initial, as-placed saturated hydraulic conductivity (ksat), the greater was the increase in this parameter over time. The majority of the soils that initially had ksat values of 10^{-7} cm/sec, ended up with values between 10^{-5} and 10^{-4} cm/sec. Clearly, covers designed as barrier systems were no longer behaving as barriers. An interesting observation was that virtually all specimens tested, irrespective of the soil texture or the prevailing climatic condition, ended up with ksat values of between 10^{-5} and 10^{-3} cm/sec, as can be seen from Figure 1, which is reproduced from Benson et al. (2007). It could be that any ksat value less than 10^{-5} cm/sec is unachievable in the long term and designs based on lower values may be overoptimistic and potentially unconservative. As store and release covers generally have saturated hydraulic conductivities higher than 10^{-5} cm/sec (e.g. Zhan et al., 2006), this particular problem does not arise with these covers.

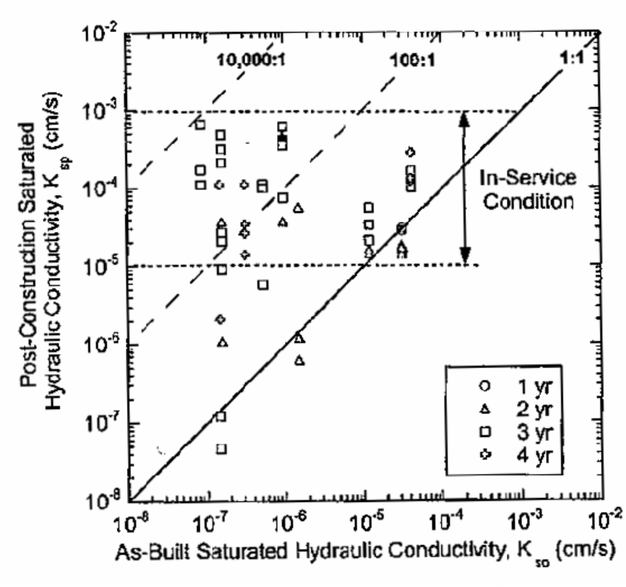

Figure 1 Postconstruction versus as-built saturated hydraulic conductivity for soils after 2 to 4 years, as measured in ACAP research programme in the USA (after Benson et al., 2007)

It was not only the saturated hydraulic conductivity that changed, but also the measured water retention characteristics. Two key parameters in characterising the SWCC are the α and n parameters, which are inversely related to the air entry suction and the slope of the SWCC curve respectively (Leong and Rahardjo, 1997). There was an increase in the α value of up to two orders of magnitude. As α is inversely proportional to air entry value, this indicates a very significant decrease in the air entry value, which corresponds to the formation of larger pores (Hillel, 1998). The saturated volumetric water content (equivalent to the porosity) also showed an almost universal increase, confirming the development of larger pores. There was also a very significant decrease in the parameter n, meaning that the slope of the SWCC became shallower. This reflects a broadening of the pore size distribution, which is consistent with the development of larger pores as evidenced by the increase in α.

So what does this all mean and what is the significance for owners of decommissioned TSF's and WRD's? The first obvious conclusion is that conditions that prevail at the end of construction of a cover system will not necessarily be representative of conditions after a few years of operation. In the data reported by Benson et al. (2007), there was virtually no site where conditions remained unchanged, including the alternative cover system sites (although the changes were less pronounced than for the barrier covers). Considering that changes in key parameters such as ksat were not trivial, but in some cases up to three orders of magnitude, the basis on which some designs have been made appear to be fundamentally flawed. However, the question then arises, how do we account for these potential changes? We cannot simply assume the worst case will always prevail, otherwise costs of cover construction will become even more prohibitive than is already the case. Before we can begin debating how to address this issue, we need to understand what some of the factors are that can cause changes in the properties of cover soils.

3 Factors contributing to changes in hydraulic properties of near-surface soils

3.1 Establishment and development of vegetation patches

In most of the numerical models used to evaluate the water balance of systems such as landfills or covered TSF's and WRD's, the effect of vegetation is accounted for through the inclusion of an evaporative term based on the assumed leaf-area index of the vegetation. The intention is that during the growing season, given sufficient precipitation, the vegetation type assumed in the model will grow (and develop greater leaf area) and thus transpire more. In these models, the implicit assumption is that the contribution of vegetation to evapotranspiration is uniform over the area of the facility being studied, i.e. the influence of the vegetation is `smeared' across the study zone.

In their detailed examination of what are termed 'vegetation patches', Ludwig et al. (2005), showed that, particularly for arid and semi-arid climates, the establishment of vegetation patches produced very non-uniform infiltration and water balance reactions, which were nothing like the processes assumed in currently available numerical models. They describe the trigger-transfer-reserve-pulse (TTRP) framework, which describes how precipitation is apportioned between vegetation patches and the ground between the established vegetation, which is termed interpatches. Their conceptual model is based on a variety of patchy semiarid vegetation types from Australia, Europe and North America and they show that vegetation patches can vary from small clumps of grasses, covering an area of no more than 0.5 to 2 m^2, to large groves of mulga trees (an Australian species Acacia aneura) that may cover an area of up to 1000 m^2. The relevance of their conceptual model is thus not restricted to only sparsely vegetated semi-arid or arid climates, but given the large proportion of the world's mining areas that are in climates of this type, the usefulness of the model becomes clear.

The field experiments by Ludwig et al. (2005) showed conclusively that for their sites, vegetation patches retained and infiltrated more water than the inter-patches, and had greater pulses of plant growth and hence biomass production (which in turn further improved infiltration capacity) than open inter-patch areas. Clearly the vegetation patches cannot expand indefinitely, as their expansion is restricted by the availability of precipitation in the climatic areas studied. The results of a study such as this may be considered to be intuitively obvious, as vegetation would be expected to intercept and retard overland flow, thus enhancing infiltration. However, there is more to it than just interception and retardation, as discussed in following sections. What is important to ask is, if this scenario is so obvious, why are the majority of planting schemes on covered waste sites based on a uniform planting arrangement, where the distance between individual plants is constant. Should we not rather be trying to accelerate the establishment of vegetation clumps or bands, and arrange initial planting in such a way as to initiate these developments? The dynamics of vegetation-driven spatial heterogeneity and its function in structured overland flow interception is surely worth greater consideration (Puigdefabregas, 2005).

3.2 Biological activity and its impact on soil properties

The fact that near-cover soils are not sterile environments, but contain a myriad of living organisms, is an accepted reality (Tibbett, 2006). This does not always appear to be taken into account when designing cover systems. For example, extensively instrumented trial cover plots are being routinely constructed on many mine sites. However, most of these are only monitored for two or three years, the results compared with numerical models, the models tweaked to provide better agreement with the cover trial results, and the monitoring terminated. However, given that biological activity can take some time to become fully established, and often goes through a series of successional phases, one has to question the sense of such relatively short-term monitoring programmes. Only once vegetation has become fully established, facilitating optimal conditions for various other organisms to establish, can the cover system be regarded as approaching a steady state. This issue is particularly relevant to barrier cover systems that rely on maintaining a low hydraulic conductivity as their key performance criterion.

Accepting that biological activity in near-surface soils is inevitable, how significantly can this activity change the hydraulic characteristics of the soil? Just a few examples are quoted here. Roth et al. (2003) (as reported in Ludwig et al., 2005) showed that mean infiltration rates within an enclosure with highly friable and biologically active soils, rich in earthworm castings and nests of ants and termites, exceeded 75 mm/hour, whereas adjacent open areas where cattle were grazed and there was no sign of biological crustal layers, the infiltration rate was only 13 mm/hour. There is invariably a huge number of fauna present in near-surface soils. According to Mitchell and Santamarina (2005), there are typically about 109 to 1012 organisms in a kilogram of soil near the ground surface. The greater number of these organisms are from the microbiota but the great biomass may be from the macrobiota.

The larger the soil macrofauna, the greater the physical interaction with soil. A few groups of invertebrates have a dominant impact, namely ants, termites and earthworms (Lee and Foster, 1991), with the latter having the most dominant impact, Pierret et al. (2007). It seems that earthworms are particularly important in altering the physical structure of the soil, although there are contradictory effects. As discussed by Lee and Foster (1991), burrowing earthworms disrupt the structure of soil, producing macropores that can then become preferential flowpaths for water infiltrating from the surface, thus potentially increasing the effective hydraulic conductivity. However, the production of casts by earthworms can act to reduce conductivity, e.g. Chauvel et al. (1999) note that in a tropical environment, earthworms can produce more than 100 t per hectare per year of casts, resulting in a dramatic decrease in the soil's porosity.

It is not only earthworms that have the capacity to dramatically alter the flow characteristics of a soil cover. At the Ranger uranium mine in the Northern Territory of Australia, the soil cover performed according to the design specifications for nearly a decade, after which the percolation rate increased substantially and remained at higher levels for the remaining duration of the study reported by Taylor et al. (2003). These same authors describe an extensive field study of the cover 18 years after construction, which showed extensive termite activity had resulted in a major alteration of the cover porosity and enabled flow to channel along macropores thus formed. They reported an increase in hydraulic conductivity of up to several orders of magnitude and attributed this to a combination of factors, including galleries formed by termites and ants, root growth and the development of shrinkage cracks in the near-surface soil. Once again, in retrospect it can be seen that the inclusion of a barrier layer could not be relied on to perform in perpetuity as designed.

The carbon fixed by the developing plant community supplies the input of energy (carbon) from the vegetation into the developing soils. This is in the form of both aboveground litter fall and belowground root death as well as the carbon that commonly flows out of “leaky” roots (Stevenson and Cole (1999). This carbon supply is critical to power the developing biological systems in the covers. Soil carbon (soil organic matter) is known to develop rapidly during the first few years of soil formation from observations made outside of the mining industry (Stevenson and Cole, 1999). These sources of carbon can have a large effect on the hydrological properties of cover material as the vegetation and soil biology evolve. As necrotic roots decompose they will leave “biopores” in the soil providing preferential flow pathways, although these effects will tend to be concentrated in near-surface soils. Leaf litter that falls on the soil surface may also strongly affect infiltration rates. In the case of developing soils at a Bauxite mine in the Northern Territories of Australia, the infiltration rate of post-mining rehabilitated soils increased several fold over 25 years (Figure 2). In this particular example the initial infiltration rate was already higher than would be found on most mine waste deposit cover systems, but the trend that it illustrates is important. Observations such as these must lead to questions about how, and to what extent, biological processes affect hydrological (and other) properties of cover materials over time frames we can easily measure.

When designing a cover system for a TSF or a WRD, how does one take account of these effects? One approach could simply be, we cannot, and it does not really matter. Given the magnitude of the changes that can potentially occur, this is clearly not a sound approach. A possible engineering solution might be to try to ensure that earthworms, for example, cannot flourish, perhaps through some extreme measure such as pre-treating the soil with a biocide (which is clearly not environmentally acceptable) or compacting the soil to a density so that earthworms have extreme difficulty in burrowing. This latter approach is also doomed, since as discussed later, compaction beyond certain critical densities renders the soil impenetrable to roots. Once again, the pragmatic and sensible approach seems to be to recognise the inevitability of changes due to fauna activity and to design to accommodate it. Some of the more recently implemented store and release cover systems inherently recognise this issue and rely on water storage efficiency (and possible changes to this property) rather than relying on barrier properties (Zhan et al., 2006).

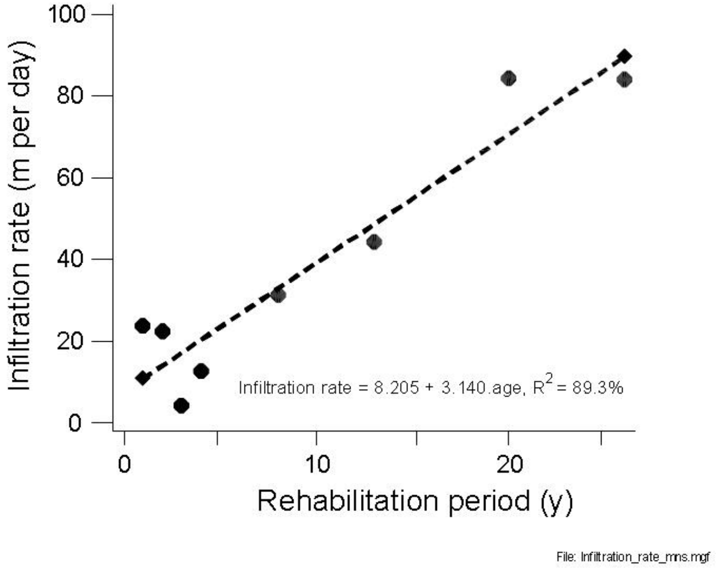

Figure 2 Temporal change in infiltration rate in rehabilitated bauxite mine soils. After Spain et al. (2006)

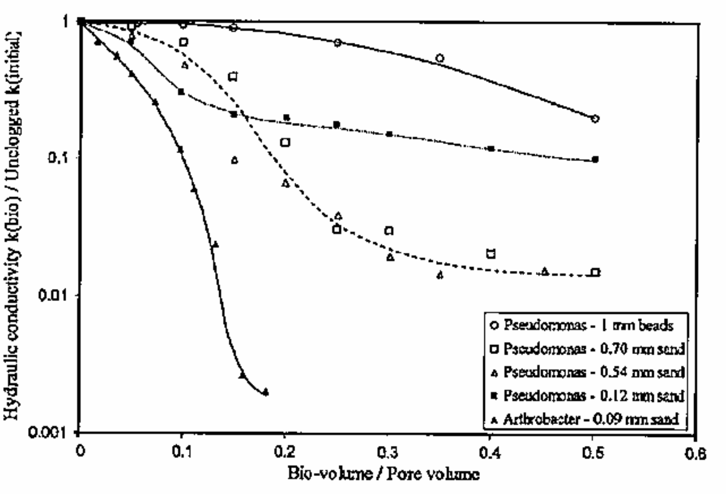

Figure 3 Evolution of the saturated hydraulic conductivity (normalised by the unclogged initial value) with respect to the bulk volume of biomass (normalised by the pore volume of the unclogged medium) after Baveye et al., 1998, as quoted by Mitchell and Santamarina, 2005)

It is not only the mesofauna, such as earthworms, that can alter the hydraulic characteristics of soils. Figure 3, which comes from the review by Baveye et al. (1998), shows the change in saturated hydraulic conductivity as a function of the biomass volume for a particular bacterium, Pseudomonas aeruginosa. As can be seen, there is a decrease of up to three orders of magnitude in the ksat of the finest sand tested. As discussed by Mitchell and Santamarina (2005), these changes are a result of multiple effects associated with the presence of bacteria, including bacteria attachment to soil particles, subsequent biomass accumulation, and the development of biofilms on mineral surfaces. The results of Baveye et al. (1998) are for saturated conditions. As long as moisture is not a limiting factor, biological activity will also occur in the unsaturated zone, and according to Horn and Meike (1995), the optimal conditions for anaerobic microbial activity is between 60% and 80% of full saturation.

There is another factor that adds to the complex interaction between bacteria and soil particles, and thus on global soil properties such as hydraulic conductivity. Bacterial cells in soils are often associated with a substance known as extracellular polymeric substances (EPS), which are usually attached to solid surfaces. This material is generally a complex mixture of macromolecules composed of polysaccharides, protein, lipid, DNA and vitamins (Sutherland, 2001). EPS generally constitutes a very minor component of soils by mass, e.g. Chenu (1995) suggested a value between 0.1% and 1.5% of the soil organic matter. Considering the almost miniscule amount of EPS that may be present in a soil, the potential effects are very significant. As an example, Or et al. (2007), presented results of experiments in which small amounts of an EPS analog (xanthan gum) were added to columns packed with glass beads, after which the hydraulic conductivity of the treated material was evaluated. They compared their results with similar data from the literature, in which sand columns were treated with xanthan gum. They found up to five orders of magnitude decrease in hydraulic conductivity with as little as 0.6% by dry mass addition of xanthan gum. As described by Or et al. (2007), EPS is capable of binding up to 20 g of water per gram of EPS, thus significantly increasing the water retention capacity of a soil containing even very small (<1% by dry mass) amounts of EPS. Changes of this type and magnitude will probably be very beneficial to store and release type covers.

3.3 Potential hydraulic changes induced by vegetation itself.

In the fields of soil science and agriculture, the concepts of soil water repellency and the effect this may have on hydraulic characteristics is well-documented, eg Doerr et al. (2000). It is generally associated with coarse-textured, sandy soils and as shown by De Bano (1991) is most likely to develop in soils with less than 10% clay content. De Bano et al. (1970) proposed a mechanism in which heated hydrophobic organic substances in the ground litter and topsoil volatilise during burning and a proportion may travel downward into the soil, following a temperature gradient until they condense in a concentrated form, often forming a coating to the soil grains. This movement is easier in permeable, sandy soils. It is also interesting to note that the extreme heat generated at the ground surface tends to destroy these substances, with the consequence that water repellent soil may be concentrated at some (usually relatively shallow) depth below the surface (Doerr et al., 2000). This was clearly shown by Scott and van Wyk (1990) who found that under unburnt pine plantations water repellent soils were very infrequent, although they did occur at all depths. In areas where high fuel load fires had taken place, strongly repellent soils were developed below the surface to depths of up to 15 cm.

Changes to a soil which make it water repellent are also likely to alter other characteristics of the soil. Dekker and Ritsema (1994) found that an increase in the water repellency of a sandy soil decreased the water retention capacity of the soil, as would be expected. In tests on aeolian dune sands reported by Fourie et al. (2003), changes in field-saturated hydraulic conductivites were found to differ by over one order of magnitude due to the presence of hydrophobic soils.

3.4 Satisfying contrasting requirements: the issue of earthworks compaction

Construction of a cover system over a TSF or a WRD invariably requires the placement and spreading of a large volume of soil, and this is usually achieved using earthworks equipment, such as trucks, dozers, graders and perhaps sometimes even compaction equipment. Leaving aside specialised compaction equipment, the trafficking of heavy vehicles such as trucks and graders can result in relatively high degrees of compaction in many soils. In addition, to achieve specified values of in-situ hydraulic conductivity, it is necessary to compact soil layers to particular values of density. In terms of engineering specifications, these densities are measured with reference to standard laboratory data (which are used to determine the maximum achievable density) and field values are expressed as a percentage of this maximum. Achieving required values of hydraulic conductivity, as required in barrier systems, typically requires compaction to at least 90% (if not 95%) of the maximum achievable. Even if compaction densities are not being specifically targeted, the mere trafficking of heavy vehicles can easily result in 90% of maximum density being achieved in near-surface layers.

Data on the effect of soil density on the growth and viability of vegetation is relatively limited. Probably the most comprehensive data are those summarised by Goldsmith et al. (2001). They show results of what is termed, `growth limiting density' and the results are particularly useful as a range of soils with different textures are included, from well-graded sand to a clay material. Their results are unfortunately in terms of bulk density, which makes it harder to compare with typical engineering definitions of density (which are in terms of dry density), but nevertheless the data are a useful contribution to the debate. Based on the limited data available, it seems as though compaction to densities in excess of 85% of the maximum may be detrimental to vegetation growth. The problem is that this degree of compaction may be achieved relatively easily with much of the earthworks equipment currently used on many mine sites for cover construction. Although post-placement deep ripping of cover soils is one option to alleviate this problem, the disadvantage is that the structure of the placed cover is destroyed, and a relatively high hydraulic conductivity will result. This is not insurmountable, but the effects must be accounted for at the design stage.

4 Discussion

This paper has described some of the factors that can, and often do, contribute to changes in the performance of engineered cover systems. Some of the processes may be of little relevance in certain climatic zones, e.g. in arid and semi-arid climates the effects of macrofauna will be less important than discussed in this paper, and other effects such as the high suction gradients within the cover system and paucity of available moisture may be dominant considerations (Campbell, 2007). However, even in arid and semi-arid climates, other macrofauna may cause considerable changes to a cover system, e.g. Hakonson (1998) reported on the damage to landfill covers caused by gophers in the United States. An approach that does not recognise the potential changes that can occur within a cover system, and blindly utilises predictions from limited laboratory and field testing, or modelling, is probably doomed to failure. As shown in this paper, the effects are not minor, but can become dominant, potentially completely altering the hydraulic characteristics of a cover system within a relatively short time, of the order of a decade. The evolutionary changes are most detrimental to cover systems designed to act as a barrier to movement of water, as an increase in hydraulic conductivity may lead to failure of the cover system. In cover systems designed to act as temporary reservoirs, evolutionary effects are generally likely to be beneficial, e.g. slight increases in hydraulic conductivity and improvements in water-retention capacity produced through biological activity.

An objective of this paper is to appeal for a change in thinking, away from the concept that steady state (or equilibrium) conditions can be predicted from a few years of monitoring, or that sophisticated numerical models hold the key to characterising long-term performance of a cover system, and towards an approach that understands and accommodates evolutionary changes. The difficulty with this suggestion is that we do not fully understand the evolutionary changes that can and will occur, particularly the issue of pedogenesis of cover systems. There is, however, a wealth of information available in literature such as that produced by the agricultural industry and this information should be mined for relevant findings, in order to build up a database of the potential magnitude of changes in engineering properties that can occur in a constructed cover system. This paper probably only represents the tip of the proverbial iceberg in this context, but does demonstrate the significant changes that may possibly occur.

It has not been possible in the space available to discuss in detail the impact of vegetation, particularly root development, on the infiltration rate of cover systems, although it has been mentioned in the context of Figure 2. Deeper rooting vegetation has the advantage that it can transpire moisture located at greater depths within a profile, but the disadvantage is that root senescence can result in significant macropore development, resulting in preferential flowpaths. Once again the designers of cover systems are confronted with the contradictory requirements of trying to maximise the engineering performance of the cover soil, while minimising negative impacts on the vegetation that must inevitably become established on the surface of the cover. Increasing attention is therefore being paid to the choice of suitable vegetation, with issues such as this in mind.

Many mining operations are approaching closure and clearly cannot wait decades for appropriate long-term field tests to be conducted before they finalise final cover designs. What is needed is a two-prong approach: firstly, longer term studies should be initiated as a matter of urgency, in order that the necessary answers become available at some finite future date. Secondly a short-term approach is necessary to try and address the remaining uncertainties. This cannot be achieved by a single-discipline approach, but requires input from a range of relevant disciplines. By adopting such an approach, the enormous improvements made in cover design in recent times (particularly the increasing preference for reservoir systems rather than barrier systems) can be consolidated. In addition, by recognising the inevitable evolutionary changes that may occur in a particular cover environment, and by taking advantage of these effects through judicious choice of materials and construction methods, the cost of future cover systems may actually be reduced.

5 Conclusions

The nature of cover systems dictate that they are influenced by natural, evolutionary processes. This is unlike many engineering earth structures, such as landfill liners, where conditions usually remain relatively stable (certainly in comparison with cover systems) for long periods of time. The structure and texture of the soil placed within a cover system evolves over time, a process that might be thought of as a form of pedogenesis. This evolution cannot be captured in short-term (less than three years) field studies in all but the most exceptional circumstances and will in many cases take a great deal longer. Wherever possible, existing field trials should be continued for as long as feasible in order to maximise the scientific return on the expense that has already been incurred.

Conditions within a cover system change with time and covers cannot be constructed in such a way that changes in engineering performance are prevented. Everyone involved in the design of cover systems now need to recognise the need to work with nature not against it or to ignore it. A risk based approach that accounts for the possible changes is required, but at this time we probably do not have sufficient knowledge available to make this a reality at anything but a few selected sites. Nevertheless, cover systems based on a `store and release' approach have been shown to be inherently less susceptible than barrier systems to such changes. In fact, it might be that the performance of these reservoir systems will improve with time, as pedogenic processes alter the cover properties in a beneficial way. More fundamental knowledge is needed before this optimism can be proven and realised.

As the process of mine decommissioning and closure becomes a more mature discipline, the industry is going to have to grapple with problems such as that described in this paper, which do not have readily available solutions and require the investment of resources to develop the necessary knowledge and disseminate it appropriately.

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