MODELING OF PREDICTED PERFORMANCE OF THE DESULPHURIZED TAILINGS COVER AT THE DETOUR LAKE MINE

by

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ABSTRACT

The problem of Acid Rock Drainage (ARD) remains a critical environmental issue associated with mining in Canada, as well as globally. Some untreated mine tailings can produce acids that percolate into ground water resources endangering aquatic environments and communities. Responsible mining practice requirements fuel the quest to understand, control and prevent ARD to assure sustainable mining.

ARD results from sulphide mineral oxidation and still poses a significant challenge to all stakeholders in mining operations. Numerical modeling is powerful when utilized to enable performance evaluation of covers and enhances the ability to predict parameters that are responsible for ARD generation. The Verification of numerical models is critical to substantiating accuracy and it contributes to the model development process. The model assists in evaluating the measures in place to control ARD by predicting the parameters that are considered critical to understanding ARD.

This research intends to verify the VADOSE/W model currently used in the industry to predict the performance of soil covers and its abilities to predict parameters that are critical to ARD generation and management in mine tailings. The hypothesis is whether the VADOSE/W model is able to predict the same published results as the finite difference model. The finite difference model simulation results used to verify the VADOSE/W model were previously verified through comparisons to a closed form solution, POLLUTE solution, and measured oxygen profiles from a column

experiment. It is important to note that the VADOSE/W is widely used in mining industry and research as well has never been adequately tested.

Agreement between both results would contribute to verification of the VADOSE/W model. It would also ascertain practicality and functionality thus minimizing costs associated with trial and error methods as well as improving implementation time and knowledge constraints with regard to ARD control and prevention.

Findings indicate agreement between the results of the VADOSE/W model (precipitation, evaporation, saturated water content, run off, infiltration, oxygen diffusion) and published results computed by the finite difference model. This point to the successful potential abilities of the VADOSE/W model, to predict critical parameters in preventing and controlling ARD.

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"Trust in the Lord with all your heart and lean not on your own understanding; and in all your ways acknowledge Him and He shall direct your path" (Proverbs 3:5-6).

DEDICATION

This work is dedicated to my mother Edith B.I., who values education. Mother wrote my name as “Micheal” [sic] and I have never felt like correcting the spelling.

Chapter 1: INTRODUCTION

1.1 Background

Model development goes through several stages including laboratory experimental testing, validation, calibration, and comparisons with field measurements. Verification must be independent from developers to increase credibility, and validation by third parties is meant to fully authenticate claims and performance of a model.

Several models have been designed to predict parameters that are considered critical for the understanding of what really causes mineral oxidation and how to prevent it sustainably. The VADOSE/W model has been through experimental testing and is at the independent verification level. Verification is needed to increase credibility, ascertain accuracy and applicability for industry use in predictions of factors such as oxygen diffusion, saturated water content, precipitation, infiltration, evaporation and run off. Most numerical models designed to predict ARD work without full scale are long term spanning several decades of field study, Wilson, (2008). These are used to verify and validate numerical models. It is therefore not unusual that models are verified using well known solutions, and this is the primary focus of this research is to verify the VADOSE/W model.

Many researchers have focused on reducing or preventing ARD production, hence mitigating its impact on the environment over the past two or three decades, and the general agreement is that oxidation of sulphide minerals is dependent on the

availability of sulphide minerals, water, and microbes such as bacteria making it imperative to study oxygen concentration and its movement in tailings. This gives an idea of how much oxidation takes place assuming that the presence of oxygen concentration is the most important factor, which is true for moist conditions. The VADOSE/W model Geo-slope (2004) among others has been developed to predict several parameters critical to ARD formation as well as to evaluate tailings cover performance; therefore verification of VADOSE/W is relevant to determine its accuracy in measuring relevant ARD causing parameters.

Mining processes produce waste consisting of waste rock and tailings piles that are normally disposed on site. Subsequent contact with precipitation in form of rainfall or snow causes percolation and drainage through the waste materials, reacting with sulphide minerals, which in the presence of oxygen and water produce sulphuric acid. This low pH effluent is known as Acid Rock Drainage (ARD).

Relevant research to prevent or reduce ARD must therefore account for oxidation prevention either by limiting oxygen or water availability. This can be achieved through the utilization of soil covers that maintain a saturated layer on top of the dump eventually limiting oxygen diffusion. So making models that are able to predict oxygen diffusion is relevant in understanding and controlling ARD.

A substantial body of research suggests that covers have a potential for long-term ARD reduction and prevention. Numerical modeling presents a convenient solution

to evaluate the performance of covers in order to understand their ability to control ARD by limiting the percolation of water and oxygen to underlying sulphidic layers.

After a series of comparisons and testing, a variety of experimental, theoretical and field data models have been developed to estimate the parameters that control the movement of the oxygen and water in tailing profiles. Oxygen diffusion through unsaturated pore spaces (air filled porosity) is important due to the low solubility of oxygen in water (saturated pore spaces); therefore the diffusion rates in the water are known to be several orders of magnitude less than in the air filled porosity. Oxygen diffusion research is an extensive focus of researchers in this area and the VADOSE/W model is based on oxygen equations developed over the years making it relevant to understanding ARD management.

This study also aims to make an assessment of the relative effects of climate and water table levels on the oxygen concentration data predicted at a desulphurized tailings cover at Detour Lake Mine with a finite difference model developed by Dobchuk (2002).This model was verified with in-situ field measurements and is therefore considered accurate.

Under similar conditions the VADOSE/W model is utilized to predict oxygen concentrations data, total evaporation, run off, potential evaporation, infiltration and surface flux for comparison to test, and compare verify the VADOSE/W model with the FD model described above. Model performance is scrutinized under different

scenarios for effects of weather and water depth on oxygen concentrations predicted in the desulphurized tailings.

The tailings cover design is based on the assumption of consuming the remaining sulphide minerals in the desulphurized tailings. This kind of scenario presents the best opportunity to verify the model mainly to determine the effectiveness of the cover in reducing oxygen diffusion by maintaining a high degree of saturated water content as well as creating capillary barrier effects that are known to reduce oxygen diffusion into the underlying tailings.

Numerical Modeling is one of the ways used by engineers to solve tailings management issues. Mining engineers continue to strive to understand and avoid such catastrophes, and the social-economic costs associated with them as well as the environmental effects of dam failure through developing state of the art science and technology. A tailings cover is one such development in this area that is being utilized to mitigate the effects of the environmental pollution in case of such catastrophes, Wilson (2008).

Tailing management however has been one of the key challenges to the mining industry and several mechanisms have been suggested and utilized to solve the challenges associated with the tailings management. Tailing covers are one of the well-known effective techniques to avoid contact of tailings with air especially reactive tailings. It is therefore incumbent upon the mining industry and researchers to ensure that the public trust is maintained by living up to the challenge through

maintaining proper tailings disposal that is acceptable for the public, Government, non-governmental organizations and the affected communities around mining sites. Wilson (2008) indicates that generally covers systems have been shown to be the most successful tailings management.

The mining industry and engineers have shown commitment to ensuring that the mechanisms that are put in place are according to the expected design and safety criteria, which is key to the continual permitting of any mining proposal and operations. However, the mechanisms in place to deal with tailings face a number of design challenges, which engineers constantly measure in the field to ascertain performance of design. It is not possible to have constant permeability of disposed tailings and tailings do not have the same properties as soil, they can be acidic, Well (2008). This may be due to reagents added during metal extraction or natural occurring acid producing tailings in the presence of water and oxygen.

Most tailings management systems rely on numerical modeling. The VADOSE/W model is one of the models currently used in the mining industry making it necessary to verify the model to independently ascertain its abilities to predict parameters that are critical for ARD occurrence. Wilson, (2008) indicates that we rely on numerical models due to a lack of a framework and proven practice for a long period of time. Model abilities to predict future effects on a cover by various parameters make verification for accuracy relevant in the industry.

1.2 Research objective

The objective of this research was to verify VADOSE/W model by comparing climate and water table level, relative effects on oxygen concentration, data predicted for desulphurized tailings cover at Detour Lake Mine tailings using the finite difference model developed by Dobchuk (2002).

Numerical modeling of different simplified cover simulations aimed at predicting oxygen diffusion through the cover to the sulphidic tailings throughout the modeling period were used to compare the predicted oxygen diffusion and consumption of the Detour Lake tailings cover using the VADOSE/W model to ascertain whether the results agree or otherwise with the already published predictions.

1.3 Scope of the research

The aim of utilizing the published results generated by another model was to enable relevant and reasonable comparison of model results arrived at using a different model to verify the accuracy of predictions by the two models and to ascertain agreement or disagreement of results through answering questions, such as: What are desulphurized covers and can they help in predicting and preventing ARD? Is the VADOSE/W model capable of accurate predictions and measurements of parameters indicating ARD? Is the model consistent with current theory? What contributions to ARD understanding does the model further and why is there need to verify the model?

The verification process involved predicting the oxygen diffusion and therefore the oxygen a lone was the focus of this thesis. The oxygen concentration profiles were compared with the oxygen diffusion profile predicted by VADOSE/W model.

1.4 Thesis structure

The thesis is structured in seven chapters. The first chapter focuses on introduction, the scope of the research study, objectives, and structure of the thesis structure. Chapter two covers literature reviews of previous research at the Detour Lake Mine. Chapter three focuses on the theory of unsaturated flow of water and oxygen equations. Chapter four involves the verification of the VADOSE/W model. Chapter five is the application of VADOSE/W. Chapter six presents results discussion and analysis and finally chapter seven highlights conclusions.

Chapter 2: LITERATURE REVIEW

A substantial body of research suggests that ARD is one of the most important environmental issues facing the mining industry today. Wheeland & Feasby, (1991, Blowes and Jambor, (1990) point out that ARD occurs when sulphide minerals oxidize in the presence of oxygen and water to produce sulphric acid fueled by abundant sulphide minerals in the earth's crust. Sustainability conscious mining firms, international organizations, governments, educational research institutions and other stake holders are taking a range of initiatives to study, control and combat ARD.

Research by Aubertin *et al*., (2000); Timms and Bennett, (2000); Mbonimpa *et al*., (2003); Martin *et al*., (2006) and Aubertin *et al*., (2006) sought to address the problem through the utilization of soil covers which are currently being studied because of their ability to reduce and or prevent water from infiltrating into the lower layers of the waste dump material thereby the reducing ARD occurrence. While much still needs to be addressed in regard to covers, the design life of covers can be up to hundreds of years; construction experience of these covers is about a decade, Wilson *et al*, (2003),but their contribution in regard to ARD containment is commendable and currently under further study.

Yanful *et al*, (2003) point out atmospheric conditions like evaporation affect the saturation of cover soils. In the study, Yanful *et al*, (2003) modeled the flow through a

single clayey till cover using coupled liquid flow, vapor diffusion and heat transfer using soil cover. This cover layer was intended to control the diffusion of oxygen through the cover consisting of coarse sand, and fine sand with clayey till as an infiltration barrier. The study compared the results obtained by this model, which were compared with the experiment, and reasonable agreement was achieved.

Oxygen diffusion is of particular interest to acid–generating mine tailings because it reacts with sulphide minerals in the presence of water to produce acid. Tailing dump covers are designed to control water and oxygen diffusion to underlying tailing layers. Dobchuk (2002) explored the effectiveness of using a desulphurized tailings cover at the Detour Lake Mining in reducing oxygen diffusion into the underlying sulphidic layers and the verification of VADOSE/W findings are based on her published results.

Bussière *et al*, (2003) investigated low sulphide covers with a capillary barrier to control acid mine drainage, and one of the challenges was that the material used to construct these types of covers was not readily available on mine sites. It was therefore imperative to use low sulphide tailings, which were available on site at Detour Lake Mine to construct the cover. The low sulphide tailings however, are not usually readily available to be utilized for this purpose without any difficulties. To create the allowable properties in terms of sulphide content a second flotation was used to desulphurize the tailings.

The experiment focused on a column with one of the slightly reactive layers with the ability to maintain high saturation, reducing the leachate to nearly neutral, which

confirmed Aachib *et al*, (2002). The aim of study was to limit the diffusion of the oxygen into the underlying tailings by maintaining saturation in the cover layers thereby significantly reducing the ability of oxygen reaching the reactive tailings.

This was to be achieved on the assumption that the diffusion of oxygen in a saturated environment is significantly low to prevent contact with the tailings several meters in the reactive tailings. Aachib *et al*, (2002) measured and predicted the diffusion of oxygen in unsaturated media, their study highlights that the flux of oxygen depends on effective diffusion, which decreases in value with decrease in oxygen flux. Effective diffusion takes into account both the diffusion of oxygen in unsaturated and saturated soil since oxygen moves in gaseous form and water phases.

In unsaturated soils, saturation is close to zero. Oxygen diffusion occurs in air filled pores and as the oxygen flux diffuses to saturated sections of the system, diffusion is reduced as oxygen fluxes through the partially air and water filled pores. The diffusion coefficient in this case is known as effective diffusion through both saturated and unsaturated media to account for both. Oxygen diffusion in media with low saturation occurs through partially filled air-filled pores because of lower diffusion coefficient in water than in air. This Aachib *et al*, (2004) research agrees with the understanding that well performing covers are highly saturated therefore the need to put into account diffusion through both saturated and unsaturated diffusion coefficient for diffusion in air and water phases, Aachib *et al*, (2002).

The Cover at Detour Lake Mine needs to maintain a minimum of an 85% degree of saturation to reduce oxygen diffusion into the lower layers and was also intended to determine the performance of the desulphurized tailings cover into sulphidic tailings. In addition, a model was created that could predict oxygen diffusion and consumption at the mine.

Clearly, several measures and techniques such as, mesocosms, oxygen measurements, the use of buffering methods, water covers, soil covers among others have been put in place to monitor environmental effects by previous researchers but numerical Modeling presents impressive approaches to reduce ARD impacts by predicting the flow of gases, water, and contaminants through waste dump. After a series of comparisons and testing of different experimental, theoretical and field data, models have been developed to estimate the parameters that control the movement of the oxygen and water in the tailing profiles – critical elements in understanding ARD.

Dobchuk (2002) created a model that could predict oxygen diffusion and consumption for the tailings at Detour Lake Mine without measuring the in situ oxygen concentration. This research utilizes results by Dobchuk (2002) to verify VADOSE/W model through inputting the Detour Lake Mine climatic data, volumetric specific function, volumetric water content, hydraulic conductivity functions of tailings, water content profile or function, vegetation, plant moisture limiting function and root depth function. The VADOSE/W model output is also verified using results of actual evaporation, potential evaporation, infiltration, runoff and cover oxygen diffusion of published data of a single

layer desulphurized tailings at Detour Lake Mine. However, this data was not included in this thesis because the focus was mainly on oxygen diffusion and the thesis aimed at using published data.

Model verification is relevant because it boosts model accuracy, practical usability, as well as providing a cost effective way of determining whether the model design is working as intended when applied to soil covers. The constant evolution in numerical modeling, the need for industry relevance, and possible design errors call for model verification to ensure accuracy. Evaluating desulphurized tailings covers using measured field data to verify models increases credibility and applicability.

Cover construction requires a great deal of material investigation, material selection, preparation including; tailing desulphurization, kinetic rate tests, diffusion rates, conductivity rates, uniform thickness, compaction to achieve effectiveness over large areas in order to reduce the overall cost of the cover. The use of low sulphur tailing as cover has gained popularity from the fact that the tailings are locally available on the mine site, Dobchuk (2002).

Knowledge about oxygen diffusion into tailings is important since oxygen is known to be transported through air and water - common reactants and critical in ARD formation. Oxygen diffusion through unsaturated pore spaces (air filled porosity) is the most important because of the low solubility of oxygen in water (saturated pore spaces),

therefore the diffusion rates in the water is several orders in magnitude less than the in air filled porosity.

Dobchuk (2002) focuses on the design of a desulphurized tailings cover at Detour Lake Mine to reduce ARD by decimating the oxidation of sulphide mineral oxidation. More about the processes that controlled the sulphide mineral oxidation are discussed in detail in the literature review of factors that affect the rate of sulphide mineral oxidation, the dominant factor being oxygen concentration. This led to the conclusion that, oxygen diffusion controls the availability of oxygen concentration in porous media. Research aimed at predicting the oxygen diffusion rate was developed. Oxygen diffusion rates were then predicted based on saturation profiles and porosity.

Aachib *et al*, (1994), Bussière *et al*, (1997b), Benzaazoua and Bussière, (1997a), Aachib *et al*, (2002), Elberling *et al*, (2005) among other researchers over the years have directly or indirectly investigated the low sulphur tailing cover potential and one of the significant areas of research has been the variations of diffusion coefficients and reaction rates based on ever changing water content of a cover system due to weather events. Dobchuk (2002) highlights that most of the models assumed constant tailings properties with respect to time. Using VADOSE/W model, all indications are that changes in weather scenarios affected the processes used by the model to predict the evaporation rates, runoff, infiltration, actual transpiration and potential evaporation and is independent of the calculation of oxygen diffusion rates particularly in saturated soil.

The VADOSE/W predictions were compared with published results, which showed good agreement as was hypothesized. The predicted results that were generated by the finite difference model, confirmed by the closed form solution, POLLUTE solution and validated by the oxygen column experiment, indicating a reasonable match based on assumption of saturation controlled oxygen diffusion. The oxygen diffusion profiles that were computed based on results by soil cover model saturation profiles were in agreement with the oxygen diffusion profiles generated by the VADOSE/W model. Based on these results the VADOSE/W model was verified.

2.1 Acid rock production

ARD is a result of sulphide mineral oxidation if not properly treated eventually ends up contaminating the environment including water resources and ecosystems. This has been a significant challenge to mining industries for many years and several researchers focused on reducing or preventing its production. Efforts to mitigate the impact of ARD on the environment have been progressing for more than two decades. Oxidation of sulphide minerals is dependent on the availability of sulphide minerals, water, and microbes such as bacteria. Therefore, it's imperative to study oxygen concentration and movement in tailings, giving an idea on how much oxidation, takes place, assuming the presence of oxygen concentration, is the most important factor.

Kabwe (2007) highlights that previous research showed that the availability of oxygen is a factor that determines the rate of oxidation. The factors that affect the rate of oxidation allow researchers to effectively understand oxygen concentration through the tailings.

Several factors that affect the sulphide mineral oxidation have been investigated by other researches, which would be a good starting point to understand the rate of sulphide mineral oxidation, relevant in understanding and preventing ARD occurrences.

Dobchuk (2002) considered factors that affect the rate of sulphide oxidation and they included near pH factors that affect the pyrite mineral oxidation, which are mineral surface area, oxygen concentration and temperature. In addition to the above factors, the effect of oxidation as a result of bacteria was found to be less effective at near neutral pH, Nicholson *et al* (1988). Dobchuk further quotes Nicholson *et al* (1989) in an investigation on the effect temperature of reaction rate, which was found to vary with temperature using the Arrhenius equation. The conclusion of the pyrite oxidation investigation suggested that under saturated conditions, the oxygen concentration was the most significant factor.

Dobchuk also points out that the research carried out by Elberling *et al* (1994a), agrees with the previous research that oxygen availability controlled the rate of acid production making these findings relevant to understanding and designing soil covers that can control ARD. It was also determined that the rates of oxidation initially are predominantly under kinetic oxidation control and that after the abundance period ends, diffusion takes over the rate of oxidation. The research concluded that, overall, diffusion controlled the rate of oxidation in sulphidic tailings. Previous research carried out to determine among other measurements oxygen concentration and diffusion through the soil showed that the oxygen movement was a result of both advection and diffusion.

If in unsaturated porous media, oxygen movement is controlled by diffusion as argued by Collin, (1987), Mbonimpa *et al* (2001), then oxygen movement essentially being affected by its consumption Aubertin *et al*, (2000), Dobchuk (2002), is probable as that could reduce the amount of oxygen reaching the underlying reactive tailing Mbonimpa *et al* (2003).

It is worth noting that one of the reasons why most of the tailings are covered by water is to prevent oxygen movement since the diffusion of oxygen in water is significantly slower than diffusion in air as highlighted. As oxygen diffuses through the cover to the reactive layers below the cover, its amount is significantly decreased and can be determined using the oxidation rate. To determine the amount of oxygen consumed, the consumption rate coefficient K_r is introduced in the oxygen equations discussed in chapter three of this thesis. In the case that the tailings are not reactive; the kinetic consumption rate coefficient K_r then tends to zero.

The factors that affect the sulphide oxidation rates are not only limited to the availability of oxygen although availability of oxygen is a predominant factor, other factors like the amount of sulphide mineral present in the host rock and surface area play a part in controlling the reaction rates, Janzen *et al*, (2003), and Ouellet *et al*, (2006).

Oxidation rates especially under saturated conditions, is a phenomenon that is not straight forward because of the ability especially for the fine-grained material to retain more moisture thereby significantly reducing the oxidation rate, Molson *et al*, (2008).

Demers *et al*, (2008) performed an investigation at Doyon Mine Quebec, Canada using the desulphurized tailing cover material to prevent ARD. The investigation was detailed in nature involving laboratory columns to fully evaluate the effectiveness of a single layered cover made out of the desulphurized tailings. The investigation further evaluated the influence of residual sulphur content, water table and cover thickness on the performance with respect to the quality of percolating water after repeated leaching. The results of this investigation involving a desulphurized cover were able to control the release of zinc and copper in the leachate by a significant percentage of more than 87% and 98 % respectively. The investigated desulphurized cover also exhibited the ability to significantly reduce oxygen flux under steady conditions by up to 96% at the end of the investigation indicating the abilities that successfully modeled covers have in controlling ARD occurrence.

The use of desulphurized tailings to construct a tailings cover approach encourages further research and application because of the ability to reduce the volume of tailings to be disposed. The acid concentrate later undergoes desulphurization by floatation before leaving the plant.

Demers *et al*, (2008) cite Benzaazoua *et al*, (2000) indicated that froth flotation is one of the most efficient method to desulphurize tailings. In this case, a sulphide concentrate is used to make in paste backfill technology and the desulphurized tailings would be used as the cover thereby reducing the cost of sourcing another material which has to be brought to the site.

2.2 Oxygen transport in unsaturated soil

Several studies have been made on gas movement through engineering structures like covers with the view to understanding how acid seepage is produced in reactive tailings. The oxidation of minerals especially sulphide minerals in mine tailings is a major concern among mining stakeholders including the public and mining industry because of their ability to cause environmental problems when not properly mitigated or where they are exposed, causing ARD.

It is worth emphasizing that creation of conditions which limit oxygen availability to reactive tailings can control ARD occurrence. Several ways and means have been developed over the years to prevent tailing from producing ARD which include a water cover, soil cover, separation of reactive tailings, neutralization treatment, and co-mix tailings. Covers whether wet or dry are especially designed to act as oxygen or water barriers, so the movement of oxygen is an important aspect in studies about ARD prevention techniques in unsaturated soil.

Oxygen movement in unsaturated soil takes place through diffusion and advection through the pore spaces. Processes that affect oxygen movement in porous media are highlighted in work done by Dobchuk (2002). Oxygen diffusion in porous media can be affected by barometer pumping, wind and thermal gradient/volume displacements during infiltration. Dobchuk (2002) also cites Kimball and Lemon (1971) in an investigation of wind effect on soil gas exchange. The investigation also concluded that

diffusion is the dominant factor in soil gas transport for fine-grained soils and Penman (1940a)'s investigation of soil respiration was verified by Dobchuk's findings.

Dobchuk (2002) further cites Penman (1940a & 1940b) who investigated the relationship between the diffusion rate and air-filled porosity. The research concluded that the rate of gaseous diffusion through porous media depended on air-filled porosity and was not a function of grain-size or aggregation. The research made an assumption in regard to heterogeneity. Research by Flegg (1953), and Dobchuk (2002) concluded that Penman's experiments were limited in range of particle sizes and the study found that aggregate sizes ranging from 2mm to 12.5-25mm in diameter had no effect on the diffusion rate. Dobchuk (2002) also highlights Flegg's proportionality constant findings of 0.6 varying from Penman's value of 0.66. Dobchuk further quotes Currie (1960a, 1960b & 1960c) based on two shape factors, confirming Penman's findings. Currie concedes that the diffusion coefficient was more complicated and not only relied on internal geometry and porosity of the soil but also up to five shape factors.

Dobchuk, (2002) argues that the research was more complicated and that the preceding research focused on a physical model moving away from the empirical descriptions of diffusion. Milling and Shearer (1971)'s research calculated the diffusion coefficient for both aggregated and non-aggregated media, defining porosity as a function of total porosity. Later on a study by Troeh *at al* (1982) concluded that since it was not easy to estimate tortuosity of the soil, empirical estimations combining two empirical equations predicted diffusion through the soil. The estimations of diffusion porosity were a perfect

fit estimated by the modified equations when compared to published data than the relations before Dobchuk (2002).

Reardon and Moddle (1985) researched the gas diffusion through uranium tailings. Using Troeh *et al's* (1982) equation, the experimental data was verified. Assuming that the rate of oxygen consumption by sulphide oxidation was insignificant, the rate of diffusion of carbon dioxide could be used for oxygen, Dobchuk (2002).

Collin and Rasmuson (1988) investigated oxygen diffusion through a highly saturated mine tailings cover found that the empirical equations were not sufficient for estimating diffusion in materials with high water content. This lead Dobchuk (2002) to the conclusion that, Millington and Shearer (1971)'s diffusion estimation was more reasonable and therefore was adopted to include diffusion in water phase. Collin and Rasmuson (1988), investigation concluded that the diffusion coefficient values that estimated both high and low contents were a match for sandy materials when compared to experimental values.

Part of the investigation done at Doyon mine Quebec, Canada, Demers *et al*, (2008) investigated the desulphurized tailing cover material to prevent ARD as mentioned earlier in this chapter and it showed that the cover significantly reduced oxygen flux under steady conditions by up to 96%. In fact, the laboratory investigation that was carried out confirmed that the use of desulphurized tailings as a cover material in one-layer systems, when combined with water elevation prevented ARD. The test results

from the water quality experimental columns according to Demers *et al,* (2008), performed better than the columns without the cover. The sulphate concentration levels in the leachate from columns with a cover were more stable when compared to control columns. However, the monolayer desulphurized columns with lower water table S_r levels were significantly lower which is an indication of easily oxygen diffusion and therefore were susceptible to ARD. These findings are relevant in successfully understanding and measuring oxygen diffusion, its role in the occurrence of ARD and how models can be used to accurately predict and eradicate it among tailings covers.

2.3 Previous research on low sulphur tailings covers

Tailing covers are designed to limit oxygen movement to underlying layers that are often reactive. To determine the performance of a cover, oxygen rates have to be measured. Dobchuk (2002) quotes Elberling *et al* (1994a) research that points out that the consumption method is the best between the two alternative methods, sulphide release and oxygen gradient method, which are used to estimate the oxidation rates in the tailings at various saturations. This is because of its ability to allow the research to use repeated sampling, used at different saturations and is non-destructive method. These two findings are vital for the design of low sulphur tailings covers.

Investigations of low sulphur covers have been executed by Reardon and Moddle (1985), with the aim being ability to come up with the cover for the Uranium tailings using peat and desulphurized tailings. In this cover, peat was used as an oxygen

consuming material that would prevent oxygen movement to the underlying tailings for 1000 years. This was to be achieved through designing a surface layer that would be maintained at high saturation to deter oxygen movement to the underlying peat layers Dobchuk, (2002). The researchers, Reardon and Moddle (1985) measured the diffusion coefficient at various water contents. The diffusion coefficient could not fit the criteria of 1000 years, regardless of the layer thickness. Dobchuk (2002) concluded that, adequate compaction to reduce the total porosity would reduce the diffusion of oxygen through the layer.

Aachib *et al* (1994a), studied low sulphur tailings when used as a capillary barrier material in multilayer cover using two-cover scenarios; one single layer, and another multi-layered where low cover tailings were sandwiched between layers of sand. The analysis of the two covers concluded that both covers reduced oxygen diffusion rates Dobchuk, (2002).

Further research was carried out by Aachib *et al* (1994), Bussière *et al* (1997a), Bussière *et al* (199b), and Bussière *et al* (1998), to verify the previous conclusions. Column experiments were designed to investigate three different desulphurized tailings containing different percentages of sulphide mineral in a multi-Layer capillary barrier system and these were compared to the sulphidic tailings column, Dobchuk highlights these details and also points out that the conclusion of the researchers was that, to be able to use the desulphurized tailings cover, there would be need for adequate

neutralization in the desulphurized tailings to neutralize the remaining sulphide minerals Bussière *et al* (1997a).

Elliot *et al* (1997)'s research results of a pilot study aimed at evaluating the effectiveness of three organic materials and desulphurized tailings as potential for cover cited by Dobchuk, (2002) concluded that desulphurized tailings had potential as a tailings cover material as long as there was a way to reduce the cracks that had developed in the column during the experiment.

Research project at INCO Limited copper cliff tailings investigated the potential of desulphurized tailings. The outcome of the investigation using acid base accounting found that the desulphurized tailings had the required carbonate minerals to buffer the acid produced. It was concluded that the desulphurized tailings were relatively inert to oxidation and have a potential as a tailings cover material Dobchuk, (2002).

An investigated the potential of low-sulphur tailings as a potential for a cover material in Australia mine site in Tasmania and the conclusion of the preliminary investigation found out that the cover would remain highly saturated and maintain wetland grown on the cover which would treat the sulphur rich discharge Dobchuk, (2002).

Richard *et al* (1997) also carried out an extensive research design of low sulphur tailings' cover at Les Terrains Aurifères site in Quebec. The low sulphide capillary barrier cover was designed to maintain high saturation. After six months of observations,

the cover maintained the average saturation of 86% and reduced the oxygen diffusion rate to a factor of 75-1000 throughout some parts of the tailings, Dobchuk, (2002).

Bussière *et al*, 2003 investigated low suilphide tailings to prevent ARD. This investigation proposed covers that possess the capillary barrier effect (CCBE) as an effective way to control (ARD) especially in mine site where are other types or materials are not readily available.

The investigation showed that low sulphur covers designed to have the ability to limit gas diffusion by consuming some of the oxygen were effective at reducing contaminants in the leachate by 99%. Such low sulphur covers are designed to have a fine layer which has the ability to retain moisture placed on top of course grained which acts as a capillary break. The high moisture retention capabilities of the fine layer prevent oxygen diffusion (Collin, 1983, Yanful *et al* 1999, Bussière *et al*, 2003)

A more recent study by Demers *et al*, 2008 at Doyon mine investigated laboratory columns of desulphurized tailings covers. This study evaluated the effectiveness of a monolayer cover showed that the cover was able to control ARD and reduced the release of Zinc and copper by 87% and 98% respectively in the leachate as well as the oxygen diffusion under steady state conditions was also reduced by up to 96%.Previous research using a numerical modeling have shown that residue sulphide content in desulphurized tailings contribute to reducing of oxidation by consuming the oxygen that diffuses through the cover Mbonimpa *et al* (2003).

Research by Benzaazoua *et al,* 2008 at the same mine Doyon, Quebec, Canada utilized the desulphurized tailings and cement paste backfill technology (CPB) in the ratio of 30% of Portland cement and 70% blast furnace slag. This technology is still under research in the matters related to behavior of CPB underground in terms of stability and durability as it is known that sulphide minerals can still oxidize when included in the CPB. The study concluded that the concrete addition did not affect the geochemical behavior of CPB and desulphurization is feasible using froth flotation.

All in all, low sulphur tailings when utilized as covers have shown that they have a significant potential to reduce oxygen diffusion by consuming the remaining sulphide minerals as well as providing an alternative cover material in mine site that do not have the cover design material readily available.

2.4 Modeling of oxygen movement through tailings

Attempts have been made by researchers to model oxygen movement in the tailings and they have faced challenges which range from heterogeneity of the material, climate changes, changes in saturation, boundary conditions. To overcome such challenges assumptions have been made and other factors that significantly affect these processes have been tested both on the field and in the laboratory but few still remain. This is because those changes in climate that affect saturation of the material have been researched.

Most models therefore have assumptions that the changes in saturation are steady but the modeler has to take great care. For example it's assumed that dominant mechanism of oxygen movement through the cover is by diffusion and there rapid consumption of oxygen in the underlying tailings layers, Bussière *et al*, (2003).

Dobchuk (2002) cites Blowers and Jombor (1990), who approximated an analytical solution to predict concentration of oxygen diffusing through a porous media using shrinking-core model. The results of this modeling did not fit the data due to assumptions made that the diffusion coefficient and porosity were constant with depth and time. Aachib *et al* (1994) also attempted using an analytical solution to solve the diffusion through a non-reactive cover. The model assumed constant oxygen concentration at the top and bottom of the material profile.

Using the modified Millington and Shear method (Collin, 1987) diffusion coefficient was calculated. The assumptions made were constant saturation, porosity and diffusion coefficient with depth and time. According to Dobchuk (2002), the results were compared to different cover scenarios but were not calibrated to measured data.

The ability the model developed by Elberling *et al* (1994a)'s, to predict diffusion and consumption in reactive tailings based on first order reaction, oxygen diffuses only in gaseous phase, and with constant diffusion coefficient with depth and time. With the driving force for oxygen diffusion being oxygen consumption by sulphidic minerals and

not the water contents, fixed consumption concentration at two boundary conditions analytical solution was achieved.

The research further evaluated the effectiveness of desulphurized tailings Covers and an example of such research was done using tailings at Detour Lake Mine which included laboratory, field analysis and numerical simulations in the Dobchuk's (2002) thesis which evaluated the effectiveness of the desulphurized tailings at the mine. By maintaining a high level of saturation oxygen, the diffusion coefficient was reduced and the cover was also aimed at creating a sink for remaining sulphide minerals. To effectively evaluate the cover, field, laboratory and modeling analyses were employed. The aim of the field and laboratory analyses was to make qualitative conclusions and also to come up with a representative profile for modeling simulations. The simulations were aimed at predicting oxygen concentration profiles.

In addition, the numerical modeling was aimed at evaluating the accuracy of the theoretical equations in predicting diffusion and kinetic oxidation coefficients. The model also aimed at predicting the desulphurized tailings cover performance and to determine the relative effect of various weather, vegetation scenarios and water table depths. Saturation was found to be the primary variable factor that controlled that rate of oxygen diffusion. The calculation of oxygen concentration fluxes was based on the soil cover saturation profiles as input. The method of predicting transient oxygen diffusion and concentration through unsaturated tailings was based on Flick's law and first Order kinetic oxidation, Dobchuk (2002).

Elberling (2004) assumed that the sulphidic oxidation was generally negligible during winter because of low temperatures in the arctic region and investigated the role of oxygen and temperature on control pyrite oxidation. This investigation at Nanisivik Mine on Baffin Island, Canada evaluated oxygen concentrations and consumption rates examined the laboratory observations at lower temperatures ranging from -12 to 12°C at different oxygen concentrations.

It is well known generally that freezing temperatures will reduce or limit oxygen consumption by pyrite and thermal covers that maintain temperature at freezing point, hence suggested as alternative covers. Elberling, (2001, 2005) pointed out oxidizing bacteria to be active at temperatures as low as -4 ^{0}C in the same arctic mine investigated. The 2001 investigation and others studies concluded that the winter bacteria involvement in oxidation could account for more than 25% annually. The research by Elberling (2005), therefore focused not only on factors like low temperature and oxygen concentrations levels but also combined effects of both the low temperatures and low oxygen concentrations as well.

The laboratory findings of the 2004 investigation showed that oxygen consumption continued to occur at temperature as low as 11 ^{0}C. It was suggested that the decrease in oxygen consumption could be due to the freezing of tailings, which trap the oxygen in closed pockets that hinder oxygen movement that limits the oxygen availability for pyrite oxidation.

The results of this study revealed that both temperature and oxygen control pyrite oxidation and are both closely interrelated with each other at freezing temperatures. It was concluded that freezing temperature as pointed out earlier do not prevent ARD but limit the rate of acid generation-a step in the right direction for understanding ARD especially among cold regions.

2.5 Effective control of ARD in tailings

Pyrite production is controlled by the rate at which sulphide reduction as well as the presence of iron ions. The decommissioning of a mine's tailings requires extra care to treat the mining tailings and one of the ways to reduce acid generation is through the construction of oxygen limiting covers and low sulphur covers which are viable as a form of acid generating solutions. This is can be done through control of acid by controlling flow of water or oxygen diffusion as well as movement through the underlying layers. This is relevant to understanding the underlying principles and concepts of flow through the tailings making it relevant to understanding ARD.

The most prominent issue to note is that the water and oxygen through the cover is controlled by the degree of saturation which in turn controls the flow of water and oxygen through the covers layers is based on Fick's Law in case of oxygen flow and Darcy's law when it comes to the flow of fluids. Oxygen is a strong oxidizing agent and therefore has great affinity for electrons. It acts as an oxidant by oxidizing sulphide minerals in waste material Kabwe, (2007).

2.6 Flow through unsaturated material

The estimation and prediction of oxygen diffusion in low sulphur tailings is significant contribution in predicting the performance of desulphurized tailing covers to ensure proper management and control of ARD. This is because a cover is designed to maintain high saturation in order to get rid of oxygen, which could react with reactive tailings to produce ARD.

To predict and estimate oxygen diffusion various models have been developed by numerous researchers including: Reardon and Moddle (1985), (Elliot *et al* (1997), Hanton-Fong *et al* (1997), Ellerbroek *et al* (1997), Dobchuk, (2002), Richard *et al* (1997), Elberling *et al* (1994a), Bussière *et al* (1997a), Aubertin *et al*, (2002), Timms and Bennett, (2000), Mbonimpa *et al, (*2003); Martin *et al*., (2006) and Aubertin *et al*, (2006).

Numerical simulations of oxygen diffusion in low sulphur tailings have been developed to determine the movement of oxygen in porous media, which can indicate. This oxidation of the remaining sulphide in the low sulphur tailings, Dobchuk, (2002). Oxygen diffusion is important when evaluating the performance of these covers and has taken a center stage in the current research by Elberling *et al*., (2004), Yanful *et al* (2003), Aubertin *et al*., (2000, 2006), Mbonimpa *et al*., (2002, 2003, 2004), Martin *et al*, (2006), , Ouellet *et al*, (2006), Molson *et al*, (2008).

The prediction of oxygen diffusion and performance of desulphurized cover will be evaluated using VADOSE/W in agreement with Dobchuk's argument that oxygen diffusion is controlled by the percentage of saturation or water content. The diffusion of oxygen decreases with increase in water content in soil material pore spaces. The presence of oxygen in mine waste tailings reacts with the remaining sulphide minerals to produce ARD in the water filled pore spaces or unsaturated pore spaces and oxygen has the ability to dissolve in water in the pore space and the diffusion rate dependent on the air filled pore spaces Dobchuk, (2002).

It must be appreciated that previous research based on water content and changes in the weather scenarios assumed constant characteristics with time, Dobchuk (2002). The research evaluated whether the oxygen diffusion and consumption were affected by the weather conditions. The conclusion indicated that vegetation had little effect on the coarse over fine tailings regardless of water table and weather. Evapo-transpiration was not dependent on vegetation quality (Dobchuk (2002).

Demers *et al* (2007) investigated the performance of monolayer covers at Doyon tailings made of desulphurized tailings and this study involved laboratory columns to evaluate the influence of the residual sulphur content of the cover material, water table level and cover thickness on water quality after repeated leaching. Acid generating tailings would be desulphurized by floatation in order to be used as a cover material, Benzaazoua *et al* (1997, 2003), Dobchuk (2002). The assumption made in this investigation was that oxidation and neutralization mechanisms are constant with time.

More recently, Molson *et al* (2008) also investigated the drainage from mine tailing cells covered by capillary barriers. The tailings were simulated using MIN3P finite volume model for coupled ground water flow, oxygen diffusion and multi-component reactive transport. Based on the simulation results, it was concluded that the moisture-retaining layer remained almost saturated thereby limiting oxygen diffusion into the underlying reactive waste materials. It was also concluded that the thickness of the layer was not a factor of significance on the results. This is relevant to understanding ARD mainly because oxygen diffusion into reactive materials would fuel ARD occurrence.

In unsaturated or negative pore water pressure, coarse layers drain rapidly whereas fine layers retain the water content, Molson *et al* (2008). The assumption made in this investigation was that the columns are initially water saturated and oxygen free and for the first eight frozen months, the cell was assumed frozen at a temperature of 10ºC with no activity. The longitudinal dispersion was also assumed to be 0.5mm.

Assuming oxygen movement in porous media is mainly by diffusion; Kabwe (2007) summarized the diffusion models which include the Knudsen model that is influenced by the molecular weight, pore size and temperature of the gas. This is not affected by the presence of other gas molecules. The model also further assumes that during diffusion, these molecules collide with other gas molecules. The physical nature of the porous media is basically not put into account therefore the molecular diffusion depends on the weights and temperature of the gases. The last model assumes that the gas molecules collide with the each another and the porous media.

Dobchuk (2002) quotes the investigation by Scharer *et al* (1995) of kinetic oxidation using two models. The shrinking core radius model assumes that oxidation takes place after diffusing through a layer that is formed by the precipitate on the surface, which means that diffusion controls oxidation.

The second model (shrinking radius model) assumes that the particle shrinks as it oxidizes which means that the oxidation rate is under kinetic control. Scharer *et al* (1995) model is applicable to fine particles in an acidic environment and have been found to work well with large sulphidic particles.

The conclusion of this investigation was that if diffusion is assumed not to control oxidation then, the shrinking radius model which assumes kinetic control is applicable for grain size less that 1mm.If kinetics control the rate of oxidation, then this rate is still limited by the rate at which oxygen moves Dobchuk, (2002).

2.7 Effects of water content on diffusion

The critical parameters for ARD formation subject for study emphasize water; this is mainly due to the significant role water content plays in enabling oxygen diffusion since it affects the rate at which the oxygen diffuses through the tailings.

Yanful's (1994) investigation of a glacial till showed that the diffusion coefficient decreased with increase in water saturation that resulted in low diffusing of oxygen in water. Although this investigation did not involve low sulphur tailings the findings indicated the relationship between diffusion coefficient and water saturation. Further

research by Gosselin, *et al* (2009) investigated the effect of degree of saturation on oxygen reaction rate of sulphidic tailings.

Few models generally are known to calculate coefficient of oxygen reaction taking into account the effect of degree of saturation. The preliminary results from the study have indicated that degree of saturation affects the value of reaction rate of sulphidic tailings. The results also showed that effective oxygen reaction coefficients predicted are often over estimated, especially at low degrees of saturation values. This called for further research to verify numerical models.

An investigation using numerical simulations of pyrite oxidation in unsaturated waste rock piles indicated rates of sulphide oxidation throughout the pile by two orders of magnitude because of the small changes in moisture content and grain size. It was highlighted that in the fine-grained layers, the oxidation rates went up despite the relatively high moisture content. This might explain the role played by increased surface area, Molson *et al*, (2005).

The rate of oxygen diffusion varies throughout different layers of the tailings and water content plays a significant part at this rate since the rate of diffusion in water is significantly lower than the rate of diffusion in air, Fredlund and Rahardjo (1993), Collin and Rasmuson (1988), Mbonimpa *et al*, (2003), Molson *et al*, (2005), and Ouellet *et al*, *(*2006).

Research conducted on a mine stope filled with cemented paste backfill at the Laronde Mine, Quebec, Canada was set to discover the rate of oxygen consumption. The results of this investigation found a high rate of oxidation at the start of the investigation, but gradually decreased as the tests continued. The reduction in oxidation rate was related to the high degree of saturation that was exhibited by the material, Ouellet *et al*, (2006).

Demers *et al*'s, (2008) investigation of the use of desulphurized tailings mono-layer cover systems in laboratory columns discovered that the columns with higher water table levels performed better in terms reducing the diffusion of oxygen when compared to columns with a lower water table. It was evident in this investigation that higher water table or water content increased the performance of the monolayer-desulphurized cover.

These findings further expose the role water and oxygen diffusion in covers making a model that accurately predicts these parameters relevant in combating ARD.

2.8 Effect of temperature and oxygen on pyrite oxidation

Several factors affect pyrite oxidation rates in the tailings especially in the cold regions where they are assumed to have negligible control due to low temperatures. This has been generally assumed in the cold season in the arctic regions of Canada due to low temperatures. Therefore Elberling (2005) suggested thermal covers as a solution that ensures the mine tailings at all times maintain low temperatures to deter oxidation throughout the year.

The study was aimed at evaluating the oxygen consumption and concentrations rates at Nanisivik Mine, which is located on Baffin Island. The observed oxygen concentration and consumption rates were compared with rates observed in the laboratory at a temperature ranging from -12^{0}C to 12^{0}C.

The study findings point out that abiotic and biotic oxygen consumption due to sulphidic oxidation still takes place at temperature as low as -11°C. It was concluded that the freezing temperatures limit but do not eliminate oxygen consumption by pyrite oxidation. It was therefore suggested that thermal covers be designed to maintain temperatures below the freezing point in agreement with the common understanding that pyrite oxidation generally decrease with decrease in temperature according to Nicholas *et al*, (1998) and Elberling 2005 as described by Arrhenius equation. This is despite the fact that sulphidic oxidation rates are complex. Elberling, (2005) argues that several studies by Ahonen and Tuovinen, (1992), Dawson and Morin, (1996) agree that Arrhenius equation is a valid approximation for both chemical and biological reaction rates.

Note should also be taken that Elberling (2005)'s study also suggested that temperature and oxygen control pyrite oxidation and that both are closely linked to each other at freezing temperature.

2.9 Summary and conclusion

It is critical to understand factors that affect ARD such as oxygen diffusion, the rate of oxidation among others since oxygen is considered to be the most significant factor controlling pyrite oxidation under saturated conditions. It was revealed in the literature that diffusion controls the rate of oxidation in sulphidic tailings and that oxygen movement is a result of both diffusion and advection.

A combined effect of both temperature and low oxygen concentrations which control pyrite oxidation are closely related to each other at freezing point. It was concluded that the freezing temperatures limit but do not eliminate oxygen consumption by pyrite oxidation.

To understand ARD, It was crucial also to study previous research in regard to desulphurized tailings cover in limiting oxygen diffusion into the underlying layers of the cover, oxygen rates and diffusion. This Chapter presented a complete picture of current theory on desulphurized cover, factors that control pyrite oxidation, oxygen diffusion, and ARD which formed a starting point to accomplish the objectives of this thesis.

Chapter 3: THEORY OF OXYGEN DIFFUSION IN PROUS MEDIA

3.1 Introduction

In this chapter, reviews of theory analyzing the different phases in unsaturated soil are discussed. The theoretical oxygen equations and the processes that influence the flow of water and oxygen in porous media are also described and examined. Equations approaches to soil phases are described in detail including their interaction between each other under different conditions. The diffusion of gases through unsaturated soil described by Fick's law and the Milling and Shearer (1971) model are also discussed.

Unsaturated soil phases that represent the different phases, air water interaction, and gas diffusion through water, unsaturated water flow and application of Fick's law to unsaturated flow are presented in the section 3.4 of this chapter. Section 3.8 provides the development of oxygen equations, finite difference formulation, partial differential equation and formulations in the porous media.

3.2 Unsaturated soil phases

Unsaturated soil is comprised of different phases. It is essential to understand these phases since they have influence on the permeability and diffusion of oxygen in the soil making them relevant to ARD control. Fredlund and Rahardjo (1993) explain soil phases in unsaturated soil as four phases; soil solids, air, water and the air-water interface which is commonly known as the contractile skin. The fourth phase, contractile

skin is considered as an independent phase, which is justified by possessing differing properties from continuous material with definite boundary surfaces.

Unsaturated soil consists of four phases with air forming another independent phase. Although phases change the state for instance water freezing and vice versa, what is important Fredlund and Rahardjo (1993) argue, is the careful examination of properties and the level of air –water interface. The air-water interface and the contractile skin behave as an elastic skin under tension in the soil. It possesses properties that are distinct from the continuous water phase, Davis and Ridel, (1963), Fredlund and Rahardjo, (1993), Derjaguin, (1965) with reduced density, raised thermal conductivity.

Understanding and recognizing unsaturated soil as a four-phase system is advantageous Fredlund and Morgenstern, (1977), most especially in stress analysis. Mass-volume relations, unsaturated soil can be assumed to be in three phases that is, assuming the volume of the contractile skin is negligible compared to the mass of water. However, in stress analysis of a multiphase continuum, it increasingly becomes a requirement to consider the contractile skin as independent phase.

3.3 Air water interaction

According to Rodebush and Buswell (1958), water molecules have openings that can be filled with water forming a lattice structure. Air fills these structures by dissolving in water to about 2% by volume. This water lattice is rigid and stable Dorsey (1940) and the density of water changes slightly when air is dissolved in water, Fredlund and

Rahardjo (1993). The air volume that dissolves in water is independent of air and water pressures according to Henry's law. Rearranging the ideal gas equation Fredlund and Rahardjo (1993) applied it to the gas dissolving in water at certain temperature and pressure:

$$V_d = \frac{M_d RT}{u_a \omega_a} \qquad 3.1$$

Where,

V_d = volume of the dissolved gas,

M_d = mass of dissolved air in water and

u_a = absolute pressure of the dissolved air.

Under equilibrium conditions, the absolute pressure of the dissolved air is equivalent to the absolute pressure of the free air. Under equilibrium conditions the pressure of free air and the dissolved air is equal. The mass of the dissolved air is dependent on the absolute pressure according to Henry's law. At constant temperature throughout the process, the ratio of mass and absolute pressure of the dissolved air is also constant.

$$\frac{M_{d1}}{u_{a1}} = \frac{M_{d2}}{u_{a2}} = \text{Constant} \qquad 3.2$$

Where,

M_{d1} = mass of the dissolved air, at condition one,

u_{a1} = absolute pressure of the dissolved air, at condition one,

M_{d2} = mass of the dissolved air, at condition two and,

u_{a2} = absolute pressure of the dissolved air, at condition two.

At constant pressure temperature, the volume of dissolved air in water is constant for different pressures.

3.4 Gas diffusion through water

It is important to understand the rate at which gas specifically oxygen diffuses through water if conditions that cause or fuel ARD are to be clearly understood and managed. Fredlund and Rahardjo assume that the rate at which air diffuses through water is according to Fick's law, therefore the rate at which mass is transferred across a unit area is equivalent to the product of the coefficient of diffusion, D, and the concentration gradient. When air diffuses through water, the concentration difference is equivalent to the difference between the free air and the dissolved air in water, (Fredlund and Rahardjo, 1993). Under constant temperature conditions, the density of the air is a function of the air pressure. The pressure difference is the driving potential for free air to diffuse through water. The coefficient of diffusion, D, of combined gases forming air dissolve in water at a rate of about 2.0×10^{-9} m^2/s (U.S Research council, 1933, Fredlund and Rahardjo, (1993).

3.5 Unsaturated water flow

Fredlund and Rahardjo, (1993) describe unsaturated water flow classified into two phases of water and air. The air phase is predominantly continuous at lower degrees of saturation in unsaturated soil and as the degree of saturation becomes high, the air in the unsaturated soil may become occluded. Air moves through the water phase by diffusion through the pore water. The flow of water is caused by the driving potential, which is known as the hydraulic head gradient. The hydraulic head consists of the elevation head and the pressure head.

Diffusion itself is considered to take place due to chemical concentration or thermal gradient Fredlund and Rahardjo, (1993). Water flows through unsaturated soil are due to the driving potentials, which may either be water content gradient, a matric suction gradient or, hydraulic head gradient. They point out that gradient in water content can be used to describe unsaturated water flow.

Water content gradient should not be used as a fundamental driving potential for the flow of water especially in soil of varying types, as hysteretic and stress variation are encountered Fredlund and Rahardjo (1993). Although matric suction is sometimes considered to be the driving potential, water flow through unsaturated soil is not exclusively dependent on matric suction alone.

When the air pressure gradient approaches zero in certain situation, Fredlund and Rahardjo (1993), point out that the matric suction is numerically equal to the pressure

gradient in the water and that the flow of water through saturated soil is not only governed by pressure gradient but also governed by the elevation difference. These two components are combined to give the hydraulic head gradient, which is the fundamental driving potential.

According to Buckingham (1907), Richard (1931), Childs and Collis-George (1950), Fredlund and Rahardjo (1993), Darcy's law states that the rate of water flow through a soil mass is proportional to the hydraulic head gradient also applies to unsaturated flow of water. The only difference is that the coefficient of permeability is not constant. The coefficient of permeability varies as a function of water content and matric suction.

Fredlund and Rahardjo (1993) indicate that water flows through water filed pore spaces and the pore space filled with air usually to allow the flow of water. Also in unsaturated soil, the value of the coefficient of permeability will vary for varying volumetric water content. Whereas in saturated soil, the coefficient of permeability is a function of void ratio, Lambe and Whitman and (1979), Fredlund and Rahardjo (1993) and only assumed to be constant in transient flow. The coefficient of permeability in unsaturated soil is greatly affected by the changes in both void ratio and degree of saturation. It is important to note that, air flows through pore space filled with water are a significant factor.

To further understand unsaturated soil, Fredlund and Rahardjo (1993), highlight that as soil becomes unsaturated, the air replaces the water, which causes the water to move

from the large pores to small pores. This results in increase in tortuosity within the flow path, a further raise in the matric suction and as a result the pore volume occupied by water reduces affecting the coefficient of permeability and the availability of the space for water flow reduces.

3.6 Application of Fick's law to unsaturated flow

As pointed out earlier, the air phase in unsaturated soil is represented as the continuous air phase and the occluded air bubble form and as the degree of saturation reduces to about 85% or less, the air phase attains the continuous form Fredlund and Rahardjo, (1993). This marks the beginning of air flow in unsaturated soil. The flow of air in the soil is affected by variations in barometer pressure, climatic changes like infiltration, temperature variation that affects the air in soil pores. At higher degree of saturation say 90%, the air becomes occluded thereby reducing its flow to diffusion through pore-water Fredlund and Rahardjo, (1993).

The Flow through unsaturated soil porous media is according to Fick's law, which is often used to describe the diffusion of gases through liquids. The mass rate of flow and the concentration gradient are expressed in terms of a unit area and a unit volume of the soil voids according to Fick's law.

$$J_a = -D\frac{\partial C}{\partial y} \qquad 3.3$$

Where,

$J_a =$ mass rate of air flowing across a unit area of the soil,

D_a = transmission constant for airflow through a soil and

C = concentration of the air expressed in terms of the mass of air per unit volume of the soil.

$\frac{\partial C}{\partial y}$ = concentration gradient in the y-direction.

The negative sign in equation (2.3) indicates that the air flows in the direction of a decreasing concentration gradient. The concentration of air with respect to volume can also be written as:

$$C = \frac{M_a}{V_a/(1-s)n} \qquad 3.4$$

Where,

M_a = mass of air in the soil,

V_a = volume of air a soil,

S = degree of saturation, and

n = porosity of the soil.

Substituting the density of air, ρ_a, for (M_a/V_a) in equation (2.4), gives

$$C = \rho_a(1-s)n.$$

Air density is related to the absolute air pressure in accordance with gas law $\rho_a = (\omega_a u_a/RT)$. The concentration gradient can also be expressed with respect to pressure gradient in the air:

$$J_a = -D_a \frac{\partial C}{\partial u_a} \frac{\partial u_a}{\partial y} \qquad 3.5$$

Where,

u_a = pore-air pressure,

$\partial u_a / \partial y$ = pore-air pressure gradient in y-direction.

A modified form of Fick's law is obtained from equation (2.5) above by introducing a coefficient of transmission for airflow through the soils, D_a^* :

$$D_a^* = D_a \frac{\partial C}{\partial u_a} \qquad 3.6$$

Alternatively,

$$D_a^* = D_a \frac{\partial [\rho_a (1 - s) n]}{\partial u_a}. \qquad 3.7$$

The coefficient of transmission, D_a^*, is a function of the volume-mass properties of the soil S and n and the air density. Substituting D_a^*, in equation (3.5) gives,

$$J_a = -D_a^* \frac{\partial u_a}{\partial y} \qquad 3.8$$

The coefficient of transmission, D_a^*, can be related to coefficient permeability which is given a symbol k_a, the coefficient of permeability whose value can be measured in the laboratory. A Steady state flow through an unsaturated soil can be established by assuming the air coefficient of permeability is constant throughout the soil. The second

assumption is that, soil is taken to an element having one value of coefficient of permeability that corresponds to the average matric suction or degree of saturation. In this case the rate of airflow is measured at contestant density, ρ_{ma}. Equation (3.8) can be written as shown below:

$$\rho_{ma} \frac{\partial V_a}{\partial t} = -D_a^* \frac{\partial u_a}{\partial y} \qquad 3.9$$

Or

$$v_a = -D_a^* \frac{1}{\rho_{ma}} \frac{\partial ua}{\partial y} \qquad 3.10$$

Where,

ρ_{ma} = Constant air density corresponding to the pressure used in the measurement of the mass rate,

$\partial V_a / \partial y =$ volume rate of the air flow across a unit area of the soil at the exit point of flow. The pore-air pressure, $u_{a,}$ in equation (3.10) can also be expressed in terms of pore-air pressure head, $h_{a,}$ using constant air density, $\rho_{ma.}$

$$v_a = -D_a^* g \frac{\partial ha}{\partial y} \qquad 3.11$$

Where,

h_a = Pore-air pressure head, and

$\partial h_a / \partial y =$ Pore-air pressure head gradient in the y-direction; designed as $i_{ay,}$

Equation (3.11) has the same form as Darcy's equation for the air phrase.

$$v_a = -k_a \frac{\partial ha}{\partial y} \qquad 3.12$$

Where the relationship between the air coefficient of transmission, D_a^*, and the air coefficient of permeability, $k_{a,}$ is defined as follows:

$$k_a = D_a^* g. \qquad 3.13$$

The transportation of gases; oxygen, carbon dioxide, or water vapor is by diffusion which consists of two mechanisms in unsaturated soil. The first type involves the flow of air through pore-water in both saturated and unsaturated soil. The second diffusion involves the movement of constituents through water phase due to chemical concretion gradient or osmotic suction gradient Matyas, (1967); Barden and Sides, (1967), Fredlund andRahardjo,(1993).

3.7 Oxygen Equations

Oxygen movement in a porous media is through the partially air-filled pores, due to the lower diffusion coefficient in water than in air at low saturation. As saturation increases, both institutional phases and aqueous phase components should be taken into account and research has shown that oxygen movement in porous media is mainly by diffusion (Collin, 1987; Rowe, 1987, Nicholson *et al,* 1989; Collin and Rasmuson, 1990, Yanful(1993b), Aubertin *et al* (1999, 2000a, 2000b), and Aachib *et al* (2004),

Collin, (1987), Collin and Rasmuson, (1988), Fredlund and Rahardjo (1993), Fetter, (1993) Aachib *et al*, (2004) report that in unsaturated porous media, molecular diffusion of oxygen is controlled by concentration gradient between free air, atmosphere and the pore space, dissolved air in water. This kind of diffusion involves the diffusion through water-filled voids.

The advantage of Fick's law is that is applicable to both the aqueous and gaseous phase (Freeze and Cherry, Shackelford, (1991), Troeh *et al*, (1982), Aachib, (1997), Mbonimpa *et al*, (2003). One-dimensional diffusion, which is generally accepted across the spectrum of researchers, is according to Fick's law, Crank, (1975), Hillel, (1998), Aachib *et al*, (2004).

$$F_{O2} = -D_e \frac{\partial C}{\partial Z} \qquad 3.14$$

Where,

F_{O2} = flux of oxygen (kg/m^2/s),

D_e = effective diffusion (m^2/s),

C = oxygen concentration (kg/m^2), and

Z = elevation (m).

The concentration C varies over space and time, and is related to effective diffusion coefficient D_e. it is controlled by the relative volume of voids and tortuosity of the

material, Mbonimpa, (2003). Aubertin *et al*, (2000), Mbonimpa *et al*, (2003) use equivalent porosity instead of air-filled porosity, Aubertin *et al*, (1995), Yanful, (1993a).

$$\frac{\partial}{\partial t}(\theta_{eq}C) = \frac{\partial}{\partial z}\left(\theta_{eq}D^{*}\frac{\partial C}{\partial z}\right) \qquad 3.15$$

$$\frac{\partial}{\partial t}(\theta_{eq}C) = \frac{\partial}{\partial z}\left(D_{e}\frac{\partial C}{\partial z}\right) \qquad 3.16$$

Where,

θ_{eq} = equivalent porosity (m^3m^3),

D_e = effective diffusion (m^2/s),

D^* = bulk diffusion coefficient (m^2/s),

C = oxygen concentration (kg/m^2), and

Z = elevation (m).

Equivalent porosity, Aubertin *et al*, (1999), 2000b, Aachib *et al*, (2004), takes into account the movement of oxygen in both aqueous and gaseous phases Yanful, (1993b), Aubertin *et al*, (1995). Equivalent porosity for gaseous and aqueous transport is defined by Aubertin *et al*, (1999, 2000a, 2000b), Aachib *et al*, (2004) as follows:

$$\theta_{eq} = \theta_a + H\theta_w \qquad 3.17$$

Also re-written as,

$$\frac{\theta_{eq}}{\theta_a} = 1 + \frac{HS_r}{1 - S_r} \qquad 3.18$$

Where,

H is the Henry's equilibrium constant (dimensionless),

$\theta_a = (n - \theta_w)$=volumetric air content,

$n =$ Porosity,

$\theta_w = ns_r = (n - \theta_a)$= volumetric water content, and

$s_r =$ degree of saturation.

Fick's law second law takes into account the mass loss both due to diffusion and reaction with the media, Crank, (1975), Shackelford, (1991), Mbonimpa *et al*, (2003). Assuming that gas diffusion in sulphidic mineral oxidation first order kinetic reaction is restricted, Elberling and Nicholson *et al* (1996), Yanful et al, (1999), Mbonimpa *et al*, (2003) then Fick's law can be rewritten as

$$\frac{\partial}{\partial t}(\theta_{eq} C) = \frac{\partial}{\partial z}\left(\theta_{eq} D^* \frac{\partial C}{\partial z}\right) - \theta_{eq} K_r^* C \qquad 3.19$$

$$\frac{\partial}{\partial t}(\theta_{eq} C) = \frac{\partial}{\partial z}\left(D_e \frac{\partial C}{\partial z}\right) - K_r C \qquad 3.20$$

Where,

$K_r =$ effective reaction rate coefficient, and

$K_r^* =$ bulk effective reaction rate coefficient.

Aachib *et al*, (2004) summarize single-phase models most of them using air filled porosity θ_a. The models attempted over the years to develop an estimate of effective

diffusion coefficient D_e from porous media properties, Penman, (1940), Marshall, (1959), Currie, (1961), Troeh *et al*, (1982), Sallam *et al*, (1984), Reardon and Moddle, (1985), Jin and Jury, (1996) according to equation 3.21:

$$D_e = D_a = \theta_a T_a D_a^o \qquad 3.21$$

Where,

T_a = gas phase tortuosity,

D_a = effective diffusion in a gas phase (m^2/s), and

D_a^o = unobstructed diffusion coefficient in air (m^2/s).

To include the diffusion in water phase that is neglected in the one-dimensional model, Collin, (1987) modified the Millington and Shearer (1971) model. The model takes into account both air and water phases in unsaturated soil. With both phases considered effective diffusion is written as,

$$D_e = D_a + HD_w \qquad 3.22$$

Where,

D_a = effective diffusion in gas phase (m^2/s), and

D_w = Effective diffusion in water phase (m^2/s).

$$D_w = \theta_w T_w D_w^o \qquad 3.23$$

Where,

T_w = water phase tortuosity,

D_w = effective diffusion in water phase (m^2/s),

D_w^o = unobstructed diffusion coefficient in water (m^2/s)

Collin and Rasmuson, (1988), and Mbonimpa *et al*, (2003) modified the Millington and Shearer (1971) model to obtain the tortuosity coefficients T_w and T_a as follows:

$$T_a = \frac{\theta_a^{2x+1}}{n^2} \qquad 3.24$$

$$T_w = \frac{\theta_a^{2y+1}}{n^2} \qquad 3.25$$

$$\theta_a^{2x} + (1 - \theta_a)^x = 1 \qquad 3.26$$

$$\theta_a^{2y} + (1 - \theta_a)^y = 1 \qquad 3.27$$

Aachib *et al*, (2004) highlight that it is very important to note that the E-N model used in the equation above was actually initially formulated using s_r as the only material dependent variable. By comparing the predicted and experimental results obtained by the model, Aachib *et al*, (2004) evaluated the accuracy of the model using statistical indicators based on goodness of fit measures. These two categories were used to measure residual based measurement such as the mean difference (MD), Sum of Square Errors the root and Means of Square Errors (SSE), and Root Square Errors (RSE), which

provided the quantitative estimates of deviation between the prediction, and observations. The measurement of statistical association such as the coefficient of correlation (R) and the correlation coefficient of determination (R^2) indicated the statistical co-variation between the predicted and observed values, (Aachib *et al*, 2004). They further, investigated the capacity of the model to predict the effective diffusion coefficient D_e for unsaturated soil. The results showed that the Penman (1940) and the M-Q (1960) models over predicted the diffusion coefficient, however, the M-Q (1961), MM-S and E-N models showed a linear trend between the predicted and measured D_e. After these comparisons Aachib *et al* (2004), proposed an alternative formulation for estimating D_e as follows:

$$D_e = \frac{1}{n^2}\left(D_a\theta_a^{p_a} + HD_w^o\theta_w^{p_w}\right) \qquad 3.28$$

Where, The expression $p_a = 2x + 2$ and $p_w = 2y + 2$ in equations 3.26 and 3.27 before the advantage of the p_a and p_w is that they are not obtained by the iterative processes, but rather given as functions of θ_a and θ_w using the x and y values are determined form the MM-S model, Aachib *et al*, (2004) referencing Collin and Rasmuson, (1998). The results showed that x and y should be between 0.70 and 0.76, and P should also be between 3.4 and 3.5. Dobchuk, (2002), and Kabwe, (2007) cite Mbonimpa *et al*, (2002, 2003) as reasonable estimation of x and y as 0.75. Therefore by combining and

substituting these values in the equation 3.2.15 for coefficient of diffusion above can be written as follows:

$$D_e = \frac{1}{n^2}\left(D_a\theta_a^{3.5} + HD_w^o\theta_w^{3.5}\right) \qquad 3.29$$

In order to account for oxygen reaction with the tailings containing sulphur then, the kinetic reaction rate coefficient K_r is introduced Aubertin *et al*, (200b) and Mbonimpa *et al*, (2000, 2002,2003).

3.8 Development of partial differential equation for oxygen diffusion

Partial differential equation developed below describes the change in oxygen concentration with depth and time as a function of oxygen diffusion and consumption. Considering a representative element volume (REV), the law of conservation of matter/mass/volume entering a system in terms of flux minus the mass flux leaving the system is equivalent to the change in storage as illustrated in figure 3.1 below.

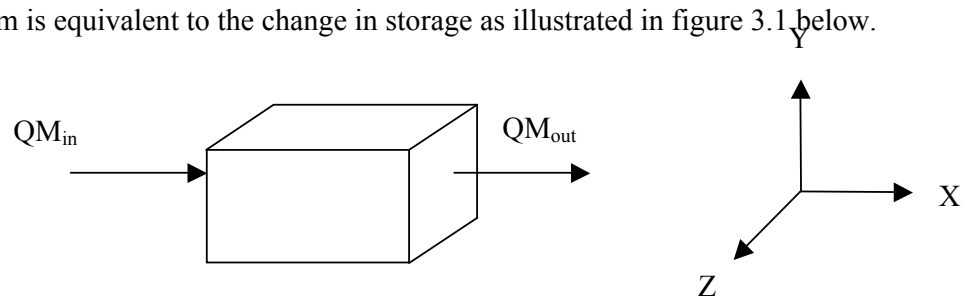


Figure 3.1- Representative element volume

$$q_{in}dxdz - q_{out}dydz = \frac{\partial M}{\partial t} \qquad 3.30$$

$$q_{in} + \frac{\partial q_{in}}{\partial x} dx = q_{out} \qquad 3.31$$

$$q_{in} dydz - \left(q_{in} + \frac{\partial q_{in}}{\partial x} dx \right) dydz = \frac{\partial M}{\partial t} \qquad 3.32$$

$$-\frac{\partial q_{in}}{\partial x} dxdydz = \frac{\partial M}{\partial t} \qquad 3.33$$

The mass entering is the representative volume element in all directions with dimensions: dx, dy, dz is due to diffusion described by Fick's law. Both diffusion and mineral oxidation affect the change in storage.

$$q_{in} = -D_e \frac{\partial C}{\partial Z} \qquad 3.34$$

$$\frac{\partial M_{Oxid.}}{\partial t} = -K_r C dxdydz \qquad 3.35$$

$$\frac{\partial M_{Oxid.}}{\partial t} = -K_r C dxdydz \qquad 3.37$$

The mass flux diffusing represents the mass of oxygen entering the REV, and the mass flux due to oxidation represents a mass of oxygen leaving the rev. combining both equations and rearranging equation 3.34 gives equations 3.9 which represents the mass source and sink.

$$-\frac{\partial}{\partial x}\left(-D_e \frac{\partial C}{\partial x} \right) dxdydz = \frac{\partial}{\partial t}\left(n_{eq} C \right) dxdydz - (-K_r C dxdydz) \qquad 3.41$$

Assuming that $D_e =$ constant with respect to depth and $n_{eq} =$ constant with respect to time, then equation 3.1.9 above can be re-arranged and re-written as equation 3.43 below:

$$D_e \frac{\partial^2 C}{\partial x^2} - k_r C = n_{eq} \frac{\partial C}{\partial t} \qquad 3.43$$

The above equation 3.43 is comparable to the mass loss due to diffusion and reaction with the tailings discussed previously, Crank, (1975, Mbonimpa *et al*, 2003) which assumed that gas diffusion in sulphidic mineral oxidation first order kinetic reaction is restricted, Elberling and Nicholson *et al* (1996), Yanful *et a*l, (1999), Mbonimpa *et al*, (2003), in equation 2.26.

$$\frac{\partial}{\partial t}(\theta_{eq} C) = \frac{\partial}{\partial z}\left(D_e \frac{\partial C}{\partial z} \right) - K_r C = n_{eq} \frac{\partial C}{\partial t} \qquad 3.44$$

Where,

$K_r =$ effective reaction rate coefficient.

3.9 Development of finite difference formulation

For a given node, defining the change in concentration three nodes are considered in order to develop the finite difference formulation as illustrated in Figure 3.2 below. The three nodes in the figure also represent the center of an element of the finite difference element.

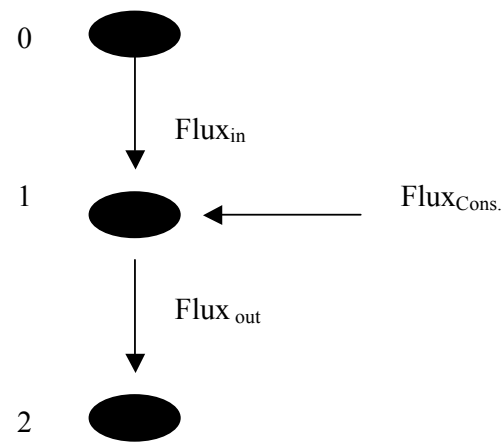


Figure 3.2 -Representations of the three nodes and mass fluxes

The mass per unit area in terms of concentration entering and exiting the nodes can be expressed in equation form as shown below to illustrate mass leaving volume subtracted from mass entering equivalent to the overall change in volumetric storage.

$$\frac{\partial M}{\partial t} = QM_{in} - QM_{out} \qquad 3.45$$

$$q_{in} dxdz - q_{out} dxdz - q_{cons} dxdz = \frac{\partial M}{\partial t} = n_{eq} \frac{\partial M}{\partial y} dxdydz \qquad 3.46$$

For sign conversion the direction is assumed as follows: negative sign in the downward direction as shown in the equations below defining the mass fluxes in the three nodes above (Figure 3.2).

$$q_{in} = -D_e \frac{\partial C}{\partial x} = -D_{e0,1} \frac{(C_1 - C_0)}{(x_1 - x_0)} \qquad 3.47$$

$$q_{out} = -D_e \frac{\partial C}{\partial x} = -D_{e1,2} \frac{(C_1 - C_0)}{(x_2 - x_1)} \qquad 3.48$$

$$q_{oxid} = k_r C dx = k_{r_1} C_1 \Delta y_{0,1,2} \qquad 3.49$$

When the three equations above substituted into equation 3.46, equation 3.50 is obtained.

$$-D_{e0,1} \frac{(C_1 - C_0)}{|(x_1 - x_0)|} + D_{e1,2} \frac{(C_2 - C_1)}{|(x_2 - x_1)|} - k_{r1} C_1 |\Delta x_{0,1,2}| = \frac{n_{eq} \Delta C_1 |\Delta x_{0,1,2}|}{\Delta t} \qquad 3.50$$

Solving Equation 3.50 for the change in concentration (ΔC_1) gives Equation 3.50 which represents the change in concentration at node 1 over time-step (Δt) given.

$$\Delta C_1 = \frac{\Delta t}{|\Delta x_{0,1,2}| n_{eq_1}} \left[-D_{e_{0,1}} \frac{(C_1 - C_0)}{|(x_1 - x_0)|} \right] + D_{e1,2} \frac{(C_2 - C_1)}{|(x_2 - x_1)|} - k_{r1} C_1 |\Delta x_{0,1,2}| \qquad 3.51$$

The purpose of defining the x term as absolute an value is to avoid problems when using elevation versus depth values for x. Using the formulation, either depth or elevation can be used without changing equation 3.51 above. The variable defined as ($\Delta x_{0.1.2}$) in Equation 3.50 is the average of the two spaces on either side of the node 1. This defines the thickness of the element associated with that node. For all the variables, the subscripts numbers separated by commas indicate the node(s) from which the variable must be calculated Dobchuk (2002).

The (k_r) in Equation 3.51 represents, the oxygen consumption for the reactive material. If the material is not reactive then, the (k_r) cancels out.

3.10 Boundary conditions

Boundary conditions for the finite difference solution are a constant oxygen concentration of 280 g/m^3 and constant atmospheric concentration at the top and bottom of the profile. This assumption is satisfied if the portion of the profile modeled is under saturated conditions or below the water table, where the concentration of oxygen significantly tends to zero at the base of the profile, Dobchuk, (2002). In VADOSE/W, when the climatic boundary condition is applied at the top of the profile, the model automatically applies oxygen concentration, as atmospheric concentration therefore the oxygen boundary condition does not have to be specified in that case.

Boundary conditions are very important to successful modeling of the unsaturated problem. The importance of boundary conditions was highlighted by Wilson (1990) research which points out that the requirement to accurately predict boundary condition especially flux boundary outweighing the accuracy required for material properties (coefficient of permeability, storage function). This was evident according to Wilson (1990), ground investigations in southern Saskatchewan with the assumption that 90 percent of the precipitation falls on the ground surface evaporates or runs off, gave accurate Modeling results. Changes in the precipitation value by 5 or 10 percent gave unreasonable results, which did not fit the field observations whereas varying the

coefficient of permeability by the same amount caused little difference in the solution. Wilson (1990) further notes that soil behavior is controlled by pore water and changes in pore water pressure with the largest variations in the water pressures often occur at or very near the ground surface influencing the soil mass processes and evaporative fluxes Wilson (1997).

Boundary conditions are for oxygen modeling among exposed tailings based on assumptions like the tailings being homogenous under steady state conditions where the change in concentration with respect to time equals zero. The initial boundary conditions are as follows: at elevation equal to zero, time greater than zero, concentration is equal to initial concentration. As elevation tends to infinity, with time greater than zero, then the concentration at infinity is equal to zero according to Nicholson *et al*, (1989), Elberling *et al*, (1994), and Mbonimpa *et al* (2003) highlighting that in many situations; the boundary condition for oxygen distribution at depth tending to infinity with concentration being equal to zero may be unrealistic. This is because that for reactive tailings oxygen consumption is expected to take place near the surface.

Mbonimpa *et al*, (2003) further present a more general approach that is used to evaluate both transient and steady state concentration profiles as the same boundary conditions highlighted above for steady state conditions but the only difference is that the depth at which the concentration becomes zero has to be determined to apply these conditions. Yanful, (2003) profile investigation results are cited which showed that oxygen profiles calculated for time between days (1 to 60 days) remained unchanged close to the

solution obtained using steady state solution which showed that steady state is reached quickly with highly reactive tailings, but this may not be true for the desulphurized tailings.

Dobchuk, (2002) applied boundary conditions of constant concentrations for the finite difference at the top and bottom nodes of the mesh. For the boundary conditions Dobchuk (2002) adopted to be true required the portion of the tailings to be below the water table. This was to meet the requirement of zero concentration at the bottom of the profile. The boundary conditions assume that oxygen diffusion in saturated system is zero at the base node which may be true as the concentration tends to zero however, oxygen is also known to diffuse through water according to Fick's law and according to Fredlund and Rahardjo,(1993) air dissolves in Water to about 2% by volume. The following assumptions were adopted:

1. At saturation the volumetric water content is assumed to be equivalent to porosity of the material
2. Oxygen concentration at the top of the column is assumed to be atmospheric and also assumed as oxygen diffuses through the unsaturated to saturated material the oxygen diffusion tends to zero at the bottom of the column.
3. Diffusion is most dominant factor in oxygen movement in fine-grained soils.

3.11 Essential difference between VADOSE/W and finite difference model

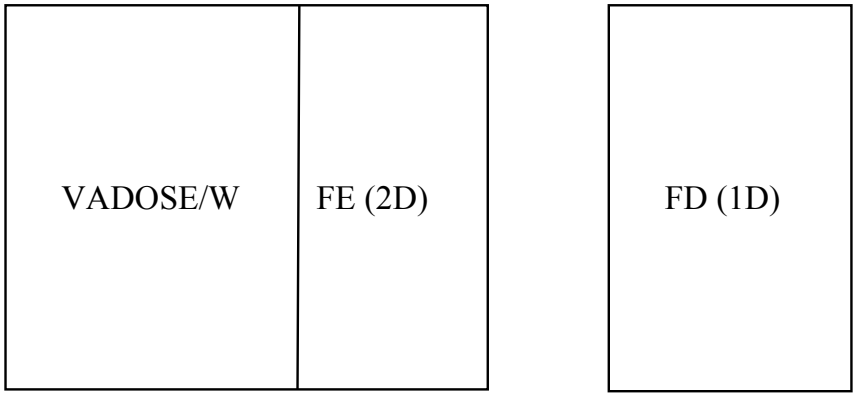


Figure 3.3-Differences between finite difference model and VADOSE/W model

This section is intended to highlight clearly the differences between the model that used by Dobchuk (2002) and the VADOSE/W model. Figure 3.3 above shows the two models highlighted in his thesis. It is clear that first difference between VADOSE/W and the model used by Dobchuk, (2002) is that the Dobchuk, (2002) model is one dimension Finite Difference (FD) model where as the VADOSE/W model is a two dimensional Finite Element (FE).

According to Simpson and Clement, (2003) the main difference between the FD and FE is how the numerical schemes spatially average the variation of material properties. The Simpson and Clement, (2003) study further shows that the FE solution avoids the erroneous results encountered in the FD solution for coarsely discredited problems. The FE is two dimension and tends to maintain a more reasonable approximation than the

one dimensional FD because of intrinsic averaging of material properties and improved representation of specific boundary conditions. The differences between boundary conditions in FD and FE are highlighted in boundary conditions of FD model in this section. The VADOSE/W boundary conditions are discussed separately in this chapter.

Furthermore, Benson, 2003 study highlights the FD method tends to be more stable when solving problems with large contrasts in hydraulic properties that exist at the layer interface fine over coarse layer. Dimensionally these kinds of problems are more realistic in 2D or 3D because the surface of the cover is sloping or the layering of the profile promotes multi-dimensional flow.

3.12 VADOSE/W model verification process

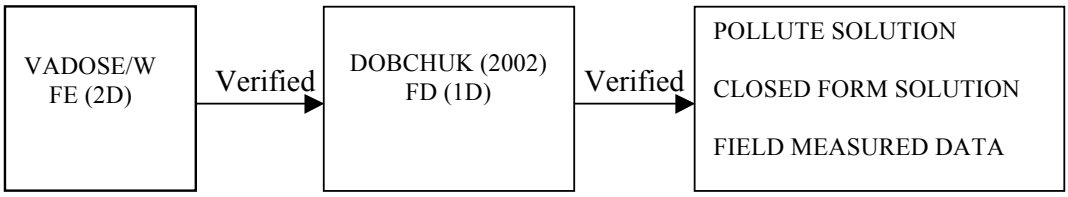


Figure 3.4- Model Verification process

Dobchuk (2002) utilized the FD model to predict oxygen diffusion and consumption in the tailing at the Detour Lake Mine. The saturation output from one dimension. Soil cover was used as input for diffusion; consumption in FE model equations was calculated using a programming language MATLAB which is designed specifically for mathematical problems. Then results of the FD model were compared using POLLUTE

which is a finite layer contaminant transport program, a closed form solution Crank (1975), as well as measured published results at Heath Steele Mines Site in Newcastle, New Brunswick of oxygen concentration profile (Yanful (1993b).

The study done by Dobchuk (2002) is utilized to verify the VADOSE/W model in this thesis. The VADOSE/W model was verified against the FE model developed by Dobchuk (2002) which was verified by POLLUTE solution, Closed Form solution and checked using measured field data as shown in the Figure 3.4 above.

The FD model which is a numerical method utilized to solve partial differential equations that describe oxygen diffusion and consumption through the tailings. These equations that describe oxygen diffusion are highly non-linear so the FD Model solves the equations in linearity over small time increments (Dobchuk, 2002). The FD model therefore solves the partial differential equation 3.43 shown below in which further details of derivation can be found in CTRAN/W manual (1999) according to Dobchuk, 2002 :

$$D_e \frac{\partial^2 C}{\partial x^2} - k_r C = n_{eq} \frac{\partial C}{\partial t} \qquad 3.43$$

The FD formulation is developed to determine the change of concentration from one node to another and within each time-step and each node involving material properties that vary with depth and time. Boundary conditions for the FD solution are a constant oxygen concentration of 280 g/m3 and constant atmospheric concentration at the top and bottom of the profile. This assumption is satisfied if the portion of the profile modeled is

under saturated conditions or below the water table, where the concentration of oxygen significantly tends to zero at the base of the profile, Dobchuk, (2002). To make sure that the base node must always be zero, the base node must also always include a portion below the water.

Dobchuk, (2002) utilized MATLAB program Math Works, (1997) to solve the FD model solution of oxygen diffusion and consumption equation 3.43 shown above. MATLAB is a matrix laboratory which is a programming language that is used to solve mathematical equations. Manipulating the program's formulations greatly reduces the time need to solve the problem.

3.13 VADOSE/W modeling Procedure

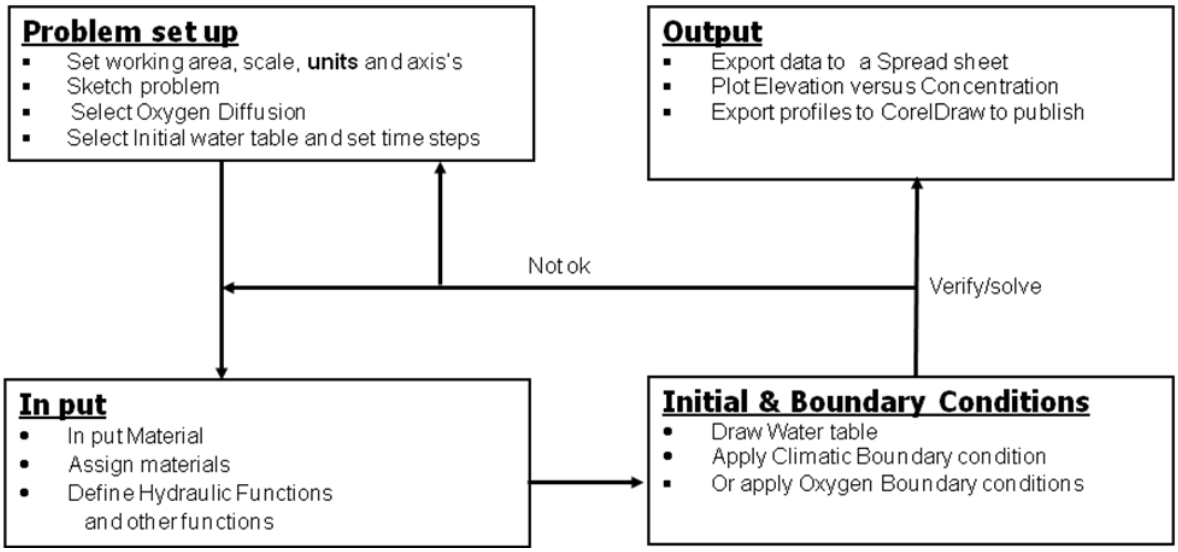


Figure 3.5-VADOSE/W modeling Flow chart

VADOSE/W is used to solve a problem at hand and it begins with defining the problem by creating the geometry. This involves setting the working area which is basically a page set up. The next step is to set the scale and correct units. It is always a good idea to set the grid to display. This is helpful to sketching the geometry and it is advisable to save the problem. The next step is to choose the type of analysis as transient, specify 2D analysis and the solver as well. Remember to choose gas diffusion and select oxygen. Set the time steps.

The next stage is to define Hydraulic conductivity functions and storage functions, other functions such as thermal functions. Define climatic data as well as other functions like leaf area index and plant limiting function. Define and specify material properties of generate cover.

The next step is to define boundary conditions which include an initial condition which is specified by drawing a position of water table and applying the oxygen boundary condition at the top of the geometry. The last stage is to verify the geometry, solve and select the data of interest from output file, export to spread sheet, draw graphs and export to CorelDraw in order to publish. In summary is as follows: creating geometry, assigning materials, defining boundary conditions, verify/ solve and finally out-put.

3.14 Discussion of the VADOSE/W model

VADOSE/W model utilizes the inbuilt Richard and Fick's laws, which are coupled with heat and vapour movement and solved using the finite element method, Demers *et al* (2009).

It is worth noting that the VADOSE/W model is capable of solving non-linear analyses. The model also allows the user to specify the position of initial water table for transient analysis. However, the user can simulate a problem by first performing a steady state analysis. The initial temperatures of the simulation can also be specified as initial conditions. VADOSE/W model predicts the water balance of the data, which greatly enhanced comparisons of Cumulative flux data in terms of precipitation, evaporation, runoff, transpiration, snow depth, and potential evaporation. The water balance is also used to interpret the accuracy of the solution in terms of water volume error. The percentage water balance error with respect to the total amount of precipitation applied should make sense. The value of water balance is interpreted relative to the entire volume of water supplied or removed by boundary conditions, VADOSE/W user's manual, (2004)

The VADOSE/W model is currently used to predict precipitation, evaporation, and snow accumulation, run off, infiltration, water seepage, and ground freezing and thawing. The model uses coupled heat and mass equations to predict the aforementioned and it has the

ability to predict oxygen movement in a porous media, surface boundary conditions; a significant variable in quantifying the magnitude of infiltration and actual evaporation which is relevant in understanding ARD.

Dobchuk (2002) research predicted oxygen concentration in tailings based on simplified representation of the tailings and called for accurate measurement of actual oxygen to determine the sulphidic oxidation rate in the sulphidic tailings to permit more definitive conclusions with respect to potential for ARD at the Detour Lake Mine.

The management of tailings using covers is challenging and has not been tested for long time as for example the design of steel reinforced concrete structures that are well known and respond linearly in the case of steel/concrete structures, the governing equations are linear so it can be assumed that the model will predict the performance of such structures. However, variation in hydraulic conductivity with pore water pressure makes the governing equation nonlinear. In order to overcome this kind of challenge iterative process is applied. In the VADOSE/W model such non-linear analyses are computed to converge to a realistic solution by checking the iterative solver. According to Geo-slope it is advisable to use the iterative solver for problems where the number of elements greatly exceeds a few thousands (VADOSE/W user's manual, 2004).

It was noticed during the simulations that VADOSE/W analyzes processes such as infiltration, precipitation, runoff; transpiration, actual evaporation and potential evaporation are computed based on the inbuilt equations and not necessarily the user

defined boundary conditions. The VADOSE/W model utilizes hydraulic conductivity, water content functions of pore water pressure, thermal conductivity, and volumetric specific heat as functions of water, air, and ice content to transition from saturated to unsaturated zones regardless of whether the ground conditions are frozen or unfrozen.

The model allows the user to specify the position of initial water table for transient analysis but it was noticed also that the best way to simulate a problem is to first perform a steady state analysis; drawing of the water table may give unrealistic results sometimes. The model is not intended for steady state seepage analysis therefore the steady state should be used to generate initial conditions for transient analysis. The initial temperatures of the simulation can also be specified as initial conditions. It was also determined that there was no significant effect of vegetation on the results of the simulations.

The model is designed to analyze both saturated and unsaturated flow, both of which follow Darcy's law. The flow of liquid is known to be proportional to the hydraulic conductivity and hydraulic gradient. The difference between unsaturated flow and saturated is that in unsaturated flow, the hydraulic conductivity varies greatly with changes in pore water pressure and as the material becomes saturated, hydraulic conductivity is no longer sensitive to pore water pressure.

VADOSE/W modeling results were compared to the results obtained by the FD model developed by Dobchuk (2002) and a reasonable match was attained. The results suggest that oxygen diffusion is controlled by the availability of water in the soil. As the soil moisture increased, oxygen diffusion in the soil was predicted to be reducing which makes sense. A model that is already released to public and is in current use for predicting the performance of tailing covers should be able to perform in accordance to its specified assumptions. It should be noted that during the development and use of the model assumptions are arrived at therefore the results of modeling should be reasonable, this calls for engineering judgment and experience.

Park (2005) highlights the limitations to keep in mind when interpreting the predictions obtained from the model namely: -

- The conceptual model assumes that the materials within the tailing profile are homogenous, however it well known that tailings material properties are heterogeneous.
- The moisture movement within the tailings is governed by hydraulic conductivity and volumetric water content of the material.

Park (2005) findings indicated that moisture infiltration reduced by approximately 80% due to the geo synthetic capillary break and oxygen diffusion was reduced by 20 to 25%. It was also noted that a slight change in hydraulic conductivity could greatly change the results of net percolation that the model predicts. The accuracy of the predictions depends on the model's ability to accurately simulate the problem.

Generally, the model user should have a good knowledge of the conceptual; and the underlying theory of the model as well as the physical situation in the real world or else situations of unreasonable results may result. It is therefore reasonable to predict that whatever is input and the understanding it is based on determines the output, following the "*garbage- in- garbage out*" rationale. That said, the engineering judgment and expert experience is key, to interpretation of the results, what they mean and also if they are reasonable.

3.15 VADOSE/W model oxygen diffusion

VADOSE/W gas movement is formulated within the model for oxygen diffusion. The governing equations of oxygen depend on the way oxygen is dissolved from the atmosphere to the saturated soil, which depends on a number of factors like temperature, and to a greater extent on a solubility coefficient relationship with the oxygen concentration in the atmosphere.

It is worth noting that VADOSE/W does not include Oxygen movement because of advection in the air phase. It is assumed that the pressure of oxygen in the soil is atmospheric and therefore the movement of oxygen is by diffusion in the air phase. The conclusion is reached that gas can be dissolved into water phase without necessarily being transferred in the water phase according to Fick's law which the oxygen diffusion through the porus media is valid by making assumption that a portion of the material known as effective porosity is available for diffusion, Dobchuk, (2002). Aubertin *et al*,

(2000) suggest that for the theoretical prediction of air filled porosity, which is assumed to be effective porosity to be represented by equivalent porosity.

Although there is no oxygen assumed to diffuse through saturated section of the tailing profile; VADOSE/W uses the effective diffusion (diffusion through both water and air) the diffusion of oxygen through water is accounted for in VADOSE/W model in transient analysis. The model utilizes the Milling and Shearer method modified by Collin and Rasmuson, (1988) to predict the effective diffusion, Demers *et al*, (2007).

VADOSE/W utilizes decay rate for the oxygen units of time in years with the value of zero indicating no internal consumption, the user is advised to use other types of oxygen sinks using boundary conditions options in the VADOSE/W manual. Oxygen movement in the VADOSE/W model is based on differential equations for oxygen transportation through soil with regard to transfer through the soil and losses into water phase due to dissolution, and decay. VADOSE/W user's manual does give details of the theory VADOSE/W, for more information refer to GEO-SLOPE (2004).

In the model, Richard's and Fick's law are coupled with heat and vapour movement and solved using the finite element method, Demers *et al,* (2009).

Elberling and Nicholson, (1996), Nicholson *et al* (1998), that suggested that the oxidation rate can be predicted with uncertainty especially oxygen rate was assumed to be of order one as well as coupling the adsorption/desorption and decomposition into the

governing equations of the model. It is normally assumed that the first order reaction is sufficient to calculate the change in concentration in pore spaces with time, Dobchuk, (2002).

The VADOSE/W puts into account in its governing equations gas diffusion, decay and dissolution in the analysis to predict the concentration of oxygen in the material being modeled.

A desulphurized cover that was installed at the Detour Lake Mine was aimed at reducing the oxygen penetration into underlying sulphidic tailing, Dobchuk *et al*, (2003). The single layer cover presents a best scenario for numerical Modeling verification because in numerical Modeling is always advisable to start from simple to more complex solutions GEO-SLOPE,(2004). This does not in any case affect the expected out come at all, it is not straightforward to make a mathematical representation of all the field conditions.

Modeling is based on a list of assumptions, well known physical laws, mathematical equations that involve identifying the physical, biological and chemical processes that govern the conservation of energy, momentum, rates of mass flow, MEND (1990).

3.16 Potential and actual evaporation

Climatic conditions have the ability to influence the diffusion of oxygen into the cover by either encouraging or hindering oxygen movement. This is because the change in climate either increases precipitation, infiltration or runoff, which changes the state of

moisture in the layers of the dump cover. The influence depends on the amount of rainfall, duration according to Freeze (1969) and Carlson (1997).

Flux at the surface of the soil is predominantly by two major processes, Wilson, (1990), infiltration and evaporation. The soil surface fully saturated conditions occur for a short period of time; therefore most of the soil layers became unsaturated after a short period of time following rainfall. The change in flux into the layers is driven and controlled by the condition on the ground surface, which is controlled by the climate changes in the atmosphere. Covers are engineered and constructed on waste dumps to as either oxygen limiting barriers or water limiting barriers.

Fully saturated conditions do occur for the short period during precipitation after rainfall, and what follows is evaporation from unsaturated surfaces. It is well known that increase in water content decreases the ability of oxygen flux in the soil layers due to low diffusivity of air filled pore space than water in water, Aachib *et al*, (2004). The effect of water content on oxygen diffusion through the soil layers is more pronounced when the saturated water content of the soil are high. The design of cover system (store and release) is based on the theory that high saturation is maintained to deter any flux of oxygen through the cover layer (Wilson, 2006).

Evaporation in general especially from the surface of mine waste covers is part of the wider picture of the hydrological cycle which part and partial of the water balance which

includes precipitation, actual evaporation, actual transpiration and runoff. Infiltration into to the ground contributes to soil saturation.

The VADOSE/W software utilized its inbuilt capabilities to predict the Actual Evaporation by correctly predicting the boundary condition at the surface on the cover. The software is also capable of predicting the surface infiltration that is in put in terms of unit flux at the surface boundary by coupling moisture, vapor and heat stress variables. According to VADOSE/W, GEO-SLOPE (2004) it's advisable not to compute the Actual Evaporation as a function of drying time or soil water content. The actual evaporation has to be computed as a function of soil surface negative pressure, which is a stress variable. This is because the actual evaporation computed at the soil surface as a varying function of potential evaporation, which is dependent on total suction and temperature condition independent of soil type and previous drying.

VADOSE/W utilizes inbuilt ability to model both saturated and unsaturated flow making it possible to tackle a variety of engineering problems and enabling full or detailed analysis. In VADOSE/W Actual evaporation is based on computed soil water stress conditions, not empirical user defined relationships.

The physical relationships required for calculating of actual evaporation in VADOSE/W include fully coupled heat and mass transfer with vapour in the soil and across the soil-atmosphere continuum. VADOSE/W model predicts the infiltration; evaporation and water flow in the tailings cover. The model computes the LAI for poor, good and

excellent grass growth types based on the estimates of LAI from the first day of growing season to the last day of growing season.

The ability of the VADOSE/W model to compute LAI, evaporation, infiltration, water flow among others make it relevant in understanding ARD precursors and thereby seek to control or exclude them in designing effective covers. In this thesis the details of potential, actual evaporation and coupled soil atmosphere are not included. For more details refer to Wilson 1990, The Unsaturated Soils Group (USG), (1997). VADOSE /W advanced methods, equations; procedures including mass and heat transfer differential equations are also not presented here but details to enhance understanding of VADOSE/W model user's manual (GEO-SLPOE (2004).

Chapter 4: THE DETOUR LAKE MINE

4.1 Introduction

The study presented in this section represents a description of the Detour Lake Mine site location, time line of the operations of the mine and the methods used to treat the enormous amount of tailings produced. This section further summarizes the geochemical composition of the tailings, method of deposition and the extensive program utilized in the design of a wet cover. Detour Lake Mine climate is also briefly highlighted giving an indication of precipitation and evaporation range.

Climate relevance derives from the fact that oxygen movement in the tailings is dependent on the saturation levels, which in turn depend on seasonal weather changes. It must be understood that the data used to verify the VADOSE/W model is derived from this site, necessitating understanding of the conditions for proper application of the model and to understand limitations if any.

4.2 Detour lake mine site location

The Detour Lake Mine site is located in the North Eastern part of Timmins, Ontario. The gold mine processed nearly about 14.3 million tonnes of ore and was operated by Placer Dome Inc. Mining operations began in 1983 as an open pit mine and later continued with underground operations by the year 1987. Production ended by 1999 and the mill operations had generated 15 million tonnes of tailings which were contained in an impoundment. The deposited tailings contained sulphur and as a result had a potential to

ARD formation therefore steps were taken to abate the contamination and degradation of the surface water quality with the construction of tailings impoundment which covered an area of almost 300ha.

Dobchuk, (2002) indicates that the method of deposition of these tailings was by slurry discharge. The tailings were known to have sulphide content of about 1 to 2.5 percent with a net neutralization potential of -5 to -75 tonnes of calcium carbonate equivalent to in each of 1000 tonnes material. The tailings therefore had potential for producing ARD. The engineering design philosophy arrived at by the mining authorities was what is well known, to cover almost all the tailings with a water cover. The remainder of the tailings was catered for by the construction of a desulphurized tailings cover.

This research was part of a program undertaken and specifically designed to include a flotation process used to desulphurize the tailings from the mill. The research included aspects of hydrology, geochemistry, kinetic tests, and geotechnical analysis in order to achieve objectives such as, choosing a representative sample of the desulphurized tailing, saturated hydraulic conductivity and soil water characteristics curve. It was therefore necessary to have such extensive monitoring and field measurements program to achieve all the above. This was vital to understanding the processes and mechanisms by which oxygen diffuses through the tailings profile.

The design of the desulphurized tailings cover was to have a capillary barrier effect that has shown to be successful in retaining water thereby reducing oxygen diffusion and in

turn minimizing ARD occurrence. Mbonimpa, Aubertin, Aachib, and Bussière, 2003, 2004 further argue that, this kind of cover normally consists of a layer of fine textured soil sandwiched between coarse materials. Dobchuk, (2002) in her thesis describes the cover and its purpose as,

> '*... to create a capillary barrier effect when placed above the sulphidic tailings. The purpose of this capillary barrier was to create a layer which would remain saturated throughout the year and act as an oxygen barrier" Dobchuk,(2002 p.53).*

There is evidence that covers designed to possess capillary barrier effects have been installed and used successfully in sites around Canada Yanful (1994); Wilson *et al*, (1997); Richard *et al*, (1997); Aubertin *et al*; (1997a, 1999, 2002b); O'Kane *et al*.(1998), Dagenais *et al*, (2001); CANMET (2001); Mbonimpa *et al*, (2003), Bussière *et al*, (2003) and Dobchuk, (2002). In these cases, the designed covers are intended to act as an "oxygen scavenger when the small quantity of remaining sulphide minerals oxidized".

Dobchuk (2002) highlights the use of a cover to act as an 'oxygen scavenge' and also that the desulphurization process was designed to reduce the sulphide sulphur content to a value between 0.5percent and 1 percent. This sulphurized cover was also designed to have thickness that increased from 0.5meters at the pond to greater than 1meter at the

dam as shown below Figure 4.1.Subsequently, a desulphurized cover was installed on the tailings facility early 1998. The installation of the cover continued until production ceased in the mid of 1999.

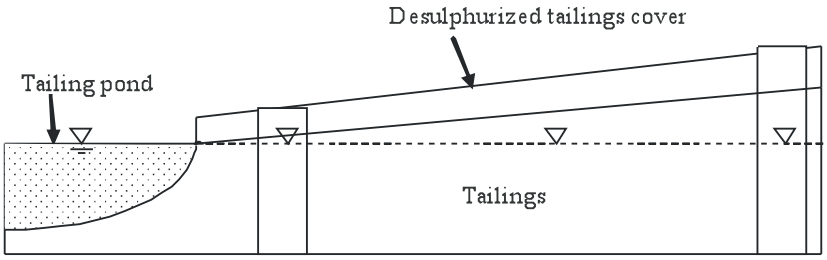


Figure 4.1-Profile showing desulphurized tailings cover layout

4.3 Detour lake mine site climate

The Detour Lake Mine site climate is summarized as moist continental, mid-latitude with annual precipitation of approximately 920 mm by Dobchuk, (2002). In general, a third of the precipitation falls as snow during some periods of the year. The total potential evaporation of the mine site is approximately 800 mm, with relative humidity during the months of May and October that fluctuates daily between 50% and 90%, Dobchuk, (2002), and Barbour et al. (1993). The temperature at the Mine site fluctuates between 37°C during summer and as low as -47 ^{o}C in the winter. Such weather

conditions perpetuate melting snow water infiltration and run off providing increased occurrence possibilities for ARD at the mine site.

4.4 Data collection at the detour lake mine site

Data was collected by Dobchuk (2002) using the instruments installed at the Detour Lake Mine site in July 2000. The detailed data was subsequently extracted to measure climatic data, water levels and water content profiles at various locations. This kind of instrumentation and data collection was carried out throughout the desulphurized cover.

The instrumentation installed at nine locations included a piezometer which was used to measure the depth of water table and neuron probe access tube which was utilized to measure the water content profiles. In addition, a weather station was installed at the site to measure detailed hourly meteorological data including wind speed, direction, relative humidity, temperature, net radiation and rainfall. This kind of data is crucial for the prediction of saturation water profile using the VADOSE/W model. However, according to Dobchuk (2002), the weather station install at the Detour Lake Mine site was not suitable to measure precipitation because of snowfall.

It should be noted that the instrumentation was installed when the tailings impoundment was under construction. The aim of raising the level of the pond was to cover the majority of the tailings as much as possible. It was noted that, the water table in the area instrumented continued to drop between 2000 and July, 2001, the water table had

dropped below the screens of five of the nine piezometers installed Dobchuk (2002) noted.

The depth was observed to fluctuate between 4 and 5 meters below the surface of the tailings. The water table level of 4meters was later selected based on these results measured in the field for the simulations in the VADOSE/W model. Dobchuk further points out that water content profiles fluctuation represented the heterogeneity of the particle size within the tailings profile.

> *"The tailings were layered with the grain-size of the tailings layers varying from silt and clay-size particles to fine sand-sized particles. The layering is attributed to segregation of the tailings during deposition. The coarser tailings settled out closer to the discharge pipe whereas the finer tailings traveled further towards the pond. Variations in flow rates could account for the variation in grain-size at any given location. It was determined that the layering was due to a combination of factors." (Dobchuk, 2002)*

The Detour Lake mine investigation was aimed at determining the effectiveness of desulphurized tailings cover. According to Dobchuk (2002), the tailings dam was designed in such a way that, the pond covered the larger portion of the tailings. The water content fluctuated with depth and there were observations that particles segregated

during deposition with coarse tailings settled closer to the discharge point and fine tailings moved away towards the pond.

4.5 Field measurements

The weather data station established at the Detour Lake Mine measured hourly temperature, relative humidity, wind speed, wind direction, net radiation, and precipitation inform of rainfall. The data obtained from the station was compared with the detailed data measured by the climate station at Timmins, Ontario, which was chosen, based on its proximity to the Detour Lake Mine. Three cores close to the boreholes were taken to determine the *in situ* water content and porosity. The obtained results of these two are among the most important parameters used to verify the VADOSE/W model reflected in my findings.

It must be remembered that as saturation increases, soil porosity tends to zero; as such oxygen also will be zero or completely consumed making it relevant due to the reduced potential of ARD formation.

4.6 Laboratory test measurements

In this section, a summary of the laboratory tests measurements carried out by Dobchuk (2002) are described. The laboratory analyses were performed on the tailing samples filed at the Detour Lake tailings impoundment. It is highlighted that the tailings samples for laboratory tests were during field instrumentation and after July 2000 from a number of instruments. These investigations included boreholes; core sampling and neutron

probe access tubes. The aim of these detailed laboratory analyses was to obtain the representative sample for both the sulphidic and desulphurized tailings at the Detour Lake Mine.

The main objective of the laboratory analyses was to obtain measurements of the geotechnical and geochemical characteristics for both the sulphidic and the desulphurized tailings in the Detour Lake tailings facility. Representative samples of both types of tailings were required for the laboratory analysis. It was also necessary to establish the thickness of the cover as well as differentiating between the sulphidic and desulphurized tailings since there was no visible physical difference between the two types of tailings. Grain size analysis tests were conducted to distinguish between the two types of tailings. This was based on the theoretical assumption that sulphidic minerals occur in a specific grain size. Grain size tests were also carried out and the results of the tests indicate that the tailings became finer with depth. It was also confirmed by laboratory tests that field observations of interbedded layers of silt-clay size materials as well as fine sand sized particles.

4.7 Determination of the saturated hydraulic conductivity function

Further tests were carried out to determine the saturated hydraulic conductivity tailings samples using a modified consolidation falling-head permeameter, Dobchuk, (2002). The results of the saturated hydraulic conductivity (*Ksat)* tests indicated that the values of *Ksat* were in the range of 2×10^{-6} to $1 \times I0^{-7}$ ms^{-1} leading to the general conclusion that

the saturated hydraulic conductivity for all samples were in the range of 2 x 10^{-6} to 1 x I $0^{-7}ms^{-1}$.

4.8 Soil water characteristic curve

The Soil Water Characteristic Curve (SWCC) also known as the moisture retention curve is a function that represents water storage capacity of the soil. This function is a relation between volumetric water content and matric suction. SWCC is used to derive and linking soil behavior such as permeability, Fredlund *et al*, (1987). SWCC consists of three zones namely:

- The capillary saturated zone where the pore water pressure is under tension but the material such as soil or tailings remains saturated due to capillary forces. At this stage the air enters the pore spaces as matric suction over comes the capillary water force.
- The de-saturation zone where the water is displaced by air in the pore space. Therefore the liquid water is drained from the pores and replaced by the air. The de-saturation zone ends at the residual water content, where the water becomes occluded and the permeability is greatly reduced.
- The last stage is the residual saturation zone where the water is tightly absorbed onto the soil particles and at this point the flow occurs in form of vapor. Fredlund *et al*, (1987)

Laboratory studies have shown that SWCC has a relationship with properties such as material hydraulic conductivity, storage, unfrozen water content, specific heat, diffusion, and adsorption, Fredlund *et al*, (1987), and Fredlund and Rahardjo, (1993b). It was also earlier on discovered that grain size distribution relationship exists Arya, (1981).

SWCC of the samples taken was measured using the pressure plate apparatus. The results of the test illustrated that the air-entry values of desulphurized were in the range of 8 and 50 kPa. It was concluded that generally air entry value ranged between 50 kPa than 8 kPa which showed that the air entry value of the sulphidic tailings were higher than that for the desulphurized tailings. These same values are utilized and adapted to verify the VADOSE/W model in this research.

4.9 Acid base accounting tests

Acid base accounting tests are usually performed to recognize the sources of contamination, incorporate control measures, assess environmental liabilities, determine the rate of ARD generation, the rate of sulphur oxidation , as well as accessing alkalinity depletion, Veiga, (2005). At Detour lake Mine the kinetic tests were conducted to distinguish sulphidic and desulphurized samples.

This section summarizes the acid base accounting tests, mineralogy evaluations, and diffusion and kinetic tests that were performed on a total of 38 samples that were selected to represent both the desulphurized and sulphidic tailings. The tests conducted were more conclusive in differentiating the samples that were sulphidic as well as those

that were desulphurized. The results were placed into two categories; lower sulpur content of less than 1 percent and those with greater than 1 percent sulpur content. This helped to determine that the desulphurized tailings cover at Detour Lake Mine ranged in thickness from 1 to 1.5 m. The objective of establishing the thickness of the cover was achieved on top of a conclusive distinction made between the sulphidic and desulphurized tailings since there was no visible physical difference between the two types of tailings, Dobchuk, (2002).

4.10 Specific gravity analysis

Specific gravity tests were conducted on both the sulphidic and desulphurized the samples. The objective of the tests was to determine the values which are required for computation of grain distribution, soil water characteristic curve, saturated hydraulic conductivity tests, diffusion as well as kinetic cell tests. This was done using a standard test method ASTM d845-92 that is used to determine the specific gravity of soils.

The specific gravity of the desulphurized sample and sulphurized tailings sample were determined to be 2.87 and 2.91 respectively. These values of specific gravity are important in the computation of grain distribution, soil water characteristic curve; saturated hydraulic conductivity tests, diffusion as well as kinetic cell tests which are crucial input parameters in the verification of the VADOSE/W model.

Chapter 5: VERIFICATION OF VADOSE/W MODEL

5.1 Introduction

In order to verify oxygen diffusion and consumption modeling of the representative profiles, it was necessary to add geochemical characteristics to the profiles. This section describes the selection of the kinetic constants selected for tailings layers.

Oxygen diffusion analysis using VADOSE/W modeling is presented using formula that are included in the VADOSE/W model to analyze the effect of climate on transfer of oxygen in waste material. The model predicts gas diffusion, decay and dissolutions based on a ground concentration equivalent to $280gm^{-3}$ representing the atmospheric concentration at the top of the profile.

5.2 Model Verification

Among the challenging issues associated with ARD is lack of full-scale long-term performance data to verify and correct designs therefore there is a high reliance of conceptual and numerical modeling. Wilson (2008) highlights most of the issues and points out the high reliance of numerical model. It is therefore imperative to verify models that are currently used in predicting the performance of cover designs if tailing cover benefits in minimizing oxygen diffusion are to be successfully implemented in industry and long term predictions made. Humans cannot simply accurately predict what and how changes may affect mines and operations but model simulations can aid with

such long-term predictions that are much needed considering the amounts of investment, caution and security required to contain tailings.

Verification of a model is usually considered to be a general process, which is in most times part of the total model development process, Sargent (2007). Model verification processes include experimental tests and even if the model passes the experimental tests, that alone cannot guarantee that the model will be valid in every aspect of its applicability domain. Therefore conducting verification is part of the model development and this study aims to make a contribution in the verification of some parameters critical to ARD prevention especially oxygen diffusion prevention among tailing covers. This study does not claim to prove or disprove the validity of the model but ascertain its abilities to predict ARD forming parameters when compared with another model's findings.

Sargent (2007) summarizes the four basic approaches that are part of the model development process. In one of the approaches, the model development team is directly involved and the decision is made based on the results of the various tests and evaluations. Another approach that Sargent (2007) suggests is having the users of the model heavily involved in model verification and validation thus giving the users an opportunity to use, scrutinize and present any inconsistencies if any. In this case the verification moves away from the model developers thereby enhancing model credibility he argues. The other approach, which is known as the independent verification and

validation, utilizes a third independent party to verify the model. This allows for the model verification team to be independent of the developers as well as the model users. Sargent (2007) recommends this approach when large-scale models are being developed involving several teams.

The last approach is using a score model and then the simulation model is determined to be valid if it passes certain scores. Sargent, (2007) quotes Balci, (1989), Gass (1993). However, this last approach is usually seldom used in practice. Sargent does not consider this approach practical because a model may receive a passing grade when it still has to be corrected. He further argues that the approach should be objective not subjective as this may create over confidence in one model and score being used to suggest that one model is better than another.

Rabe *et al*, (2008) suggest that the process of model verification is intended not to prove the correctness of the model, but rather the correctness of the transformation from one stage of the process to another and that model validation objective is to analyze the suitability of the model related to a given task as well as the accuracy of the Modeling system at hand. This research focuses on the former part of modeling development process.

5.3 Challenges dealing with model verification

There are other common methods used to verify models such as comparing analytical solutions to a numerical model solution. If the numerical code does not reproduce the analytical solution, then the model formulations should be checked since many numerical models are designed and developed to go beyond the range of available analytical solutions and models cannot be verified in practice unless an exact analytical solution exists de Marsily *et al*, (1992), Oreskes *et al*, (1994), Freedman, and Ibaraki, (2003).

de Marsily *et al*, (1992), Freedman and Ibaraki, (2003). Liu and Narasimhan, (1989) and Freedman *et al*, (2003) present that it is challenging to completely verify a model, and they suggest that in such cases, verification of the model can be carried out by checking the model results versus the solutions obtained using other codes. The results for numerical model may be different from the errors that are introduced because of variation in formulations and may also give different results depending on the accuracy of the derivatives Anderson *et al*, (1992), Freedman and Ibaraki, (2003). It should be noted that different models make different assumptions during the development process from those made in other model being compared with for verification and this may make verification comparison complicated. This was not observed in this present study.

5.4 Cover Profile Development

In this thesis, the cover profile generation and subsequent evaluation is aimed at finding the solution that best fits the design requirements for proper function of the engineering cover system. The profile was developed to represent the design system and was simplified to represent practical simulations in order to obtain reliable results as expected.

5.5 Cover Profile Geometry

The initial profile generated was aimed at representing the general profile based on the available data of the tailings. The two types fine and coarse tailings were chosen to represent the variation of tailings properties. A value of 1.8 meters was selected to reflect the same height that was chosen based on the geotechnical profiles that were developed by Dobchuk, (2002). This was because the expected results are used to verify her findings with the VADOSE/W model findings. The first profile was chosen to represent the engineering cover modeled and these are illustrated in Figure 5.1 shown below. The coarse tailings profile rather than fine was modeled because it was understood to be the most representative profile of the tailings facility at Detour Lake Mine and the fine over coarse was chosen to represent the capillary break design..

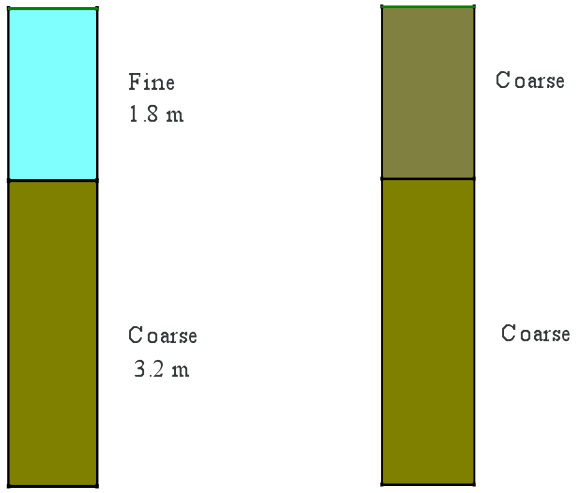


Figure 5.1-Profile selected to represent capillary break tailing profile and coarse tailings Cover system.

The profile height that was first chosen for the numerical Modeling was 5 m, which could easily represent the water table variation from 1m to 4m depth. This option was chosen to determine the effect of water on depth on oxygen movement. It was determined that the 5m profile performed well and acceptable results were obtained.

Dobchuk (2002) indicated that the kinetic oxidation coefficient was related to grain-size distribution of the tailings for example with the same pyrite content; the finer tailings showed that they possessed a higher kinetic oxidation coefficient than the coarse tailings. It was also argued that the increase in particle surface area increased exposure to oxygen and water. It was considered reasonable to conclude that that since the coarse and fine particle size distributions represented the high and low values measured, then

kinetic coefficients represent high and low that could be expected at Detour Lake Mine tailings.

It was necessary to choose the most likely profile that represents the Detour Mine tailings to run oxygen diffusion and consumption modeling in order to predict as close as possible the tailings conditions at the tailings site. Using the above observations, a homogenous coarse tailings profile was chosen to represent the worst-case profile of the tailings profile. The most reasonable profile to design the tailings cover that would act as a capillary break was to come up with a profile of fine tailings over coarse tailings. However the profile that best represented the tailing profile was observed to be coarse over fine tailings profile.

The kinetic coefficient that was used to model the Detour Lake mine coarse tailings of 10 1/yr was from the measurement taken from the sample of coarse desulphurized tailings diffusion/kinetic cell. That said, Dobchuk (2002) suggested that the kinetic coefficient for most desulphurized tailings would probably be higher than that calculated for the coarse tailings sample with low pyrite content since the desulphurized tailings were observed to be generally finer than the coarse tailing. It was therefore considered reasonable to conclude based on this assumption, that the measured value kinetic coefficient would probably represent a value lower than the actual value in the field.

5.6 Verification of VADOSE/W model

Demands on model reliability and predictive accuracy have become crucial aspects for model relevance in industry as such; models have to be thoroughly verified for accuracy, acceptability, applicability, consistency and compatibility with current legacy systems, robustness and relevant improvements or inconsistencies highlighted to improve the current body of knowledge. Verification aims to minimize costly errors arising in terms of socio-economic costs, time delays in project implementation and or abandonment.

It is therefore crucial to verify that the VADOSE/W model currently utilized in industry agrees with current theory and is able to predict consistent results when applied to field data and available published data. Dobchuk's findings arrived at using another model are used to verify VADOSE/Wand its abilities in successfully predicting oxygen diffusion, water flow, evaporation, infiltration and run off among others in a bid to validate its applicability in minimizing ARD.

It must be noted that the effectiveness of the model greatly depends on the measure to which it effectively represents the system it is modeling; and by accounting for oxygen diffusion and movement in the tailings cover as well as saturated water content profiles in a manner consistent with theory, it was observed that the model can be effectively used to predict the performance of the cover.

Findings indicate that the VADOSE/W model is effective and consistent with theory in predicting the factors that affect ARD production in tailings cover using the available

published data. The available data did not allow direct comparison between the predicted and measured values but values obtained by the model developed to predict oxygen diffusion and consumption for the Detour Lake Mine tailings that were desulphurized. VADOSE/W verification therefore showed that oxygen profiles developed using a FD model based on the saturation profiles calculated from soil cover were comparable.

It must be noted that the purpose of this research was to verify the VADOSE/W model using published data not measure filed data; the findings can be used to further highlight relevance of the model in understanding and evaluating the oxygen movement in the cover, saturation profile which are crucial to ARD mitigation.

Since oxygen concentration and consumption profiles are among the most critical components to understanding ARD and the VADOSE/W model can be significantly effective in predicting soil water profiles and oxygen movement profiles as well as predicting the performance of the desulphurized cover, the model is therefore relevant in understanding ARD and its prevention.

Chapter 6: RESULTS DISCUSSION AND ANALYSIS

6.1 Introduction

Results analysis and discussion are described in this section of the chapter. The purpose of data analysis is to discuss the findings discovered while verifying the VADOSE/W model and compare the relative prediction of oxygen consumption and diffusion through the simplified desulphurized cover using VADOSE/W model with findings from published data obtained using the finite difference model developed by Dobchuk, (2002). It should be noted that not all modeled results are presented in this chapter and it is assumed that the dry year represented one in fifty years. The design concept for cover assumes that the cover should perform well when exposed to ultimate conditions, and the dry year satisfies that scenario.

This research involved numerical simulations to predict oxygen movement in the tailings profile and to evaluate the relative effect of variations climatic data. The role of simulations was to find out whether the changes in climatic data had the same effect on these predictions by the VADOSE/W model and the results obtained by the finite difference model developed for the Detour Lake Mine Tailings. The results from the numerical and study evaluating governing equations formed the basis for verifying the VADOSE/W model.

The data obtained from the numerical program that was used to predict the performance of the desulphurized tailings cover at the Detour Lake Mine was utilized to determine

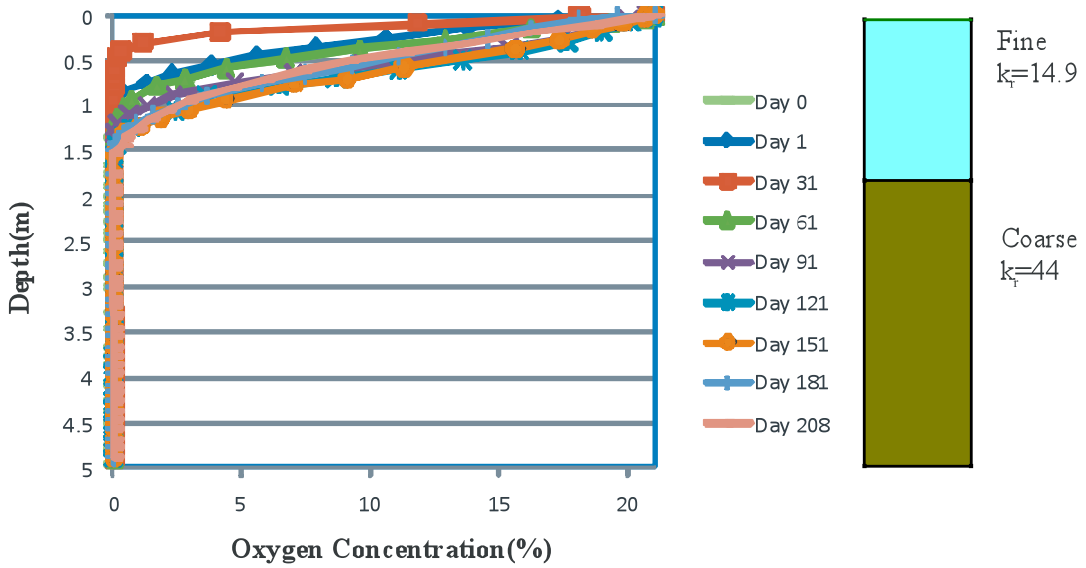
the relative effect of various weather scenarios, water depths and vegetation scenarios. It was reasonable to use this data to find out if the relative effect of weather was the same when applied to VADOSE/W model. It was also necessary to understand how seasonal weather changes affect oxygen diffusion in the tailings profile.

It was discovered that the results of the weather, and vegetation were in good agreement with the results obtained by the Dobchuk (2002) FD Model.

6.2 Analysis of predicted oxygen concentration

The VADOSE/W model was used to predict the oxygen concentration for fine over coarse tailings for a dry year. The predicted results were determined to be a match when compared with the results generated by the finite difference model. It was determined as shown in the following figures that the results from the different models gave similar results for oxygen diffusion and kinetic oxidation. The predicted oxygen concentration through the tailings cover is presented in the figure below (Figure 6.1).

VADOSE/W model oxygen concentration profiles



FD model oxygen concentration profiles

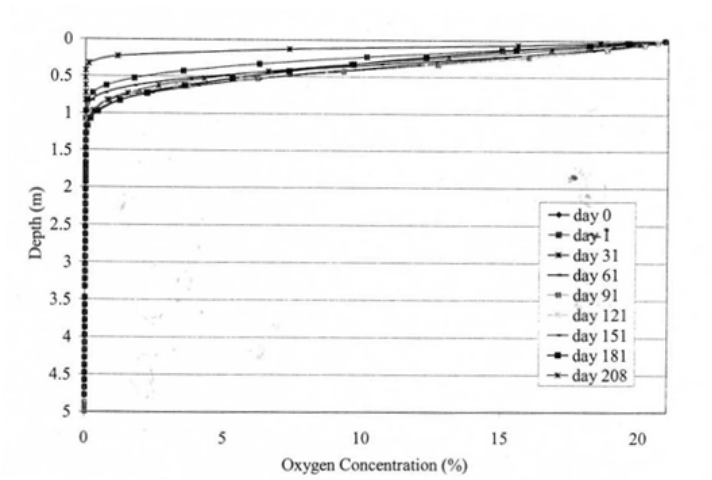


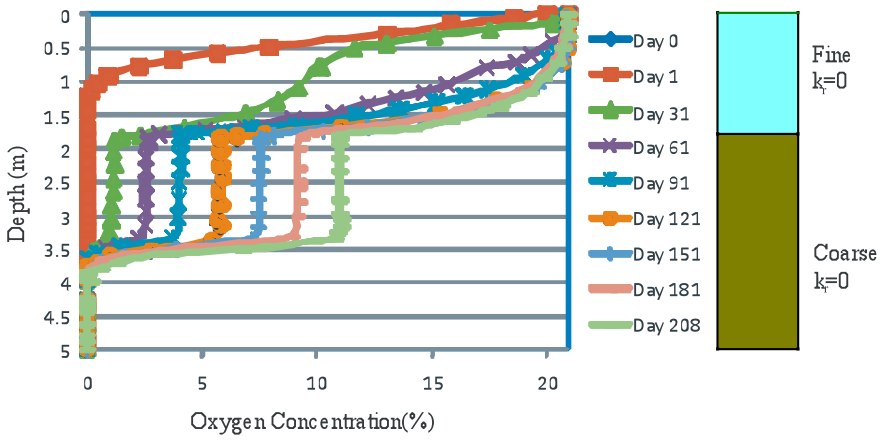
Figure 6.1-Oxygen concentration profiles for 1.8m thick layer of fine over coarse tailings,4m water table for a dry year and k_r=44 and 10 respectively. (Figure 6.17 Dobchuk, 2002)

To obtain the results showed in the figure, a constant concentration of oxygen was applied at the top of the profile at the start of the simulation. The atmospheric oxygen concentration of 21% is assumed at the top of the profile and it is assumed that at the end of the profile a concentration of zero is assumed. Comparison between the results predicted and obtained by using other methods other than the VADOSE/W model showed that the model predicted similar oxygen concentration.

Numerical Modeling using VADOSE/W model predicted the changes in oxygen concentration due to water content which also leads to changes in effective diffusion coefficient of oxygen in the profile. The results of the simulations show that oxygen diffused through the fine layer and it is most likely that diffusion did not occur in the coarse layer by the end of the simulation period. These case further shows that the sulphide minerals remaining in the fine layer could be responsible for consuming the oxygen.

Comparison between the data obtained using the POLLUTE model and VADOSE/W model suggested that there was reasonable agreement between the results predicted by both models. Although this study was to verify the VADOSE/W model as depicted by the above figures, the results as shown in the figures below depict that the fine tailings consume oxygen indicating that changes in oxygen diffusion occur at the interface of the desulphurized fine tailings and the coarse. This is applicable for cover designs that have been proposed aiming to limit oxygen diffusion using the capillary break mechanism.

VADOSE/W model oxygen concentration profiles



FD model oxygen concentration profiles

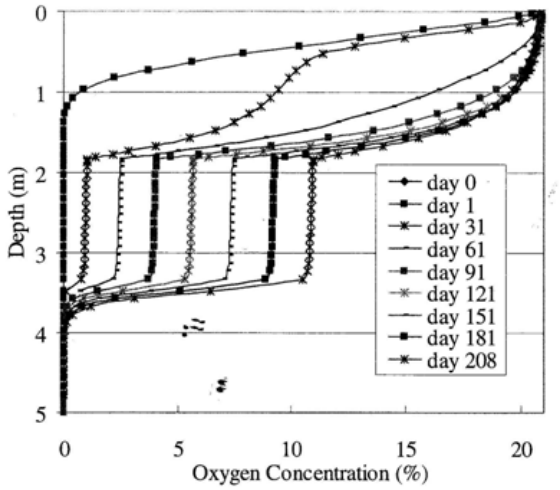


Figure 6.2-Oxygen concentration profiles for 1.8m thick layer of fine tailings over coarse tailings, 4m water table for a dry year and k_r=0.

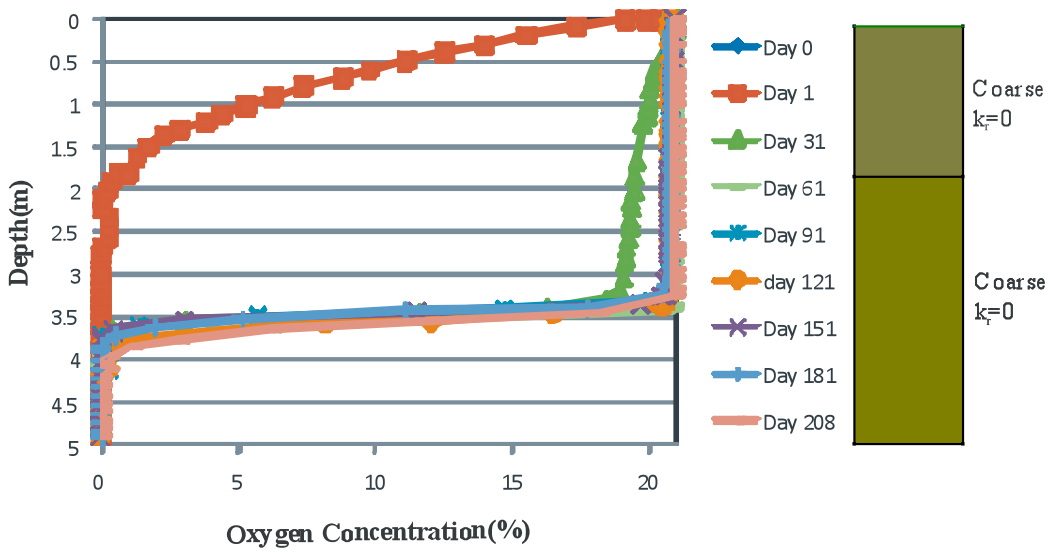
As noted earlier, it is likely that the fine layer is consuming part of the oxygen that is diffusing through it. It also shows that the fine layer is most likely not fully saturated so the diffusion of oxygen through the fine layer is evident from the Figure 6.2 below. Results of oxygen diffusion and kinetic oxidation-predicted oxygen concentration through tailings cover is presented in all the figures (6.1-6.4).This is significant in verifying VADOSE/W and representing one of the most effective design criteria of tailings covers.

The results of this simulation further shows that oxygen diffused through the fine material. It is most likely that diffusion did not occur in coarse layer by the end of the simulation period. This case further show, that the sulphide minerals remaining in the fine layer could be responsible for consuming the oxygen.

The output shown in Figure 6.2 is for a homogeneous coarse tailings profile with four meters to water table. These results were obtained using the VADOSE/W model and are compared to results obtained by Dobchuk FD model. Figure 6.2 further shows the results of oxygen movement without considering the oxygen consumption of the desulphurized tailings material.

In general, a reasonable fit was achieved using VADOSE/W simulations, except for day 31 oxygen concentration profiles for homogeneous coarse tailings, 4 meters to water table, dry year, which showed slight variation as shown in Figure 6.3 below. That said,

VADOSE/W model oxygen concentration profiles



FD model oxygen concentration profiles

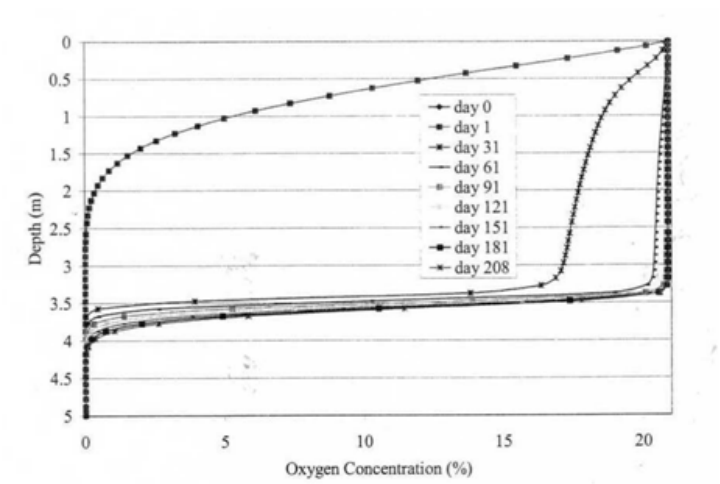


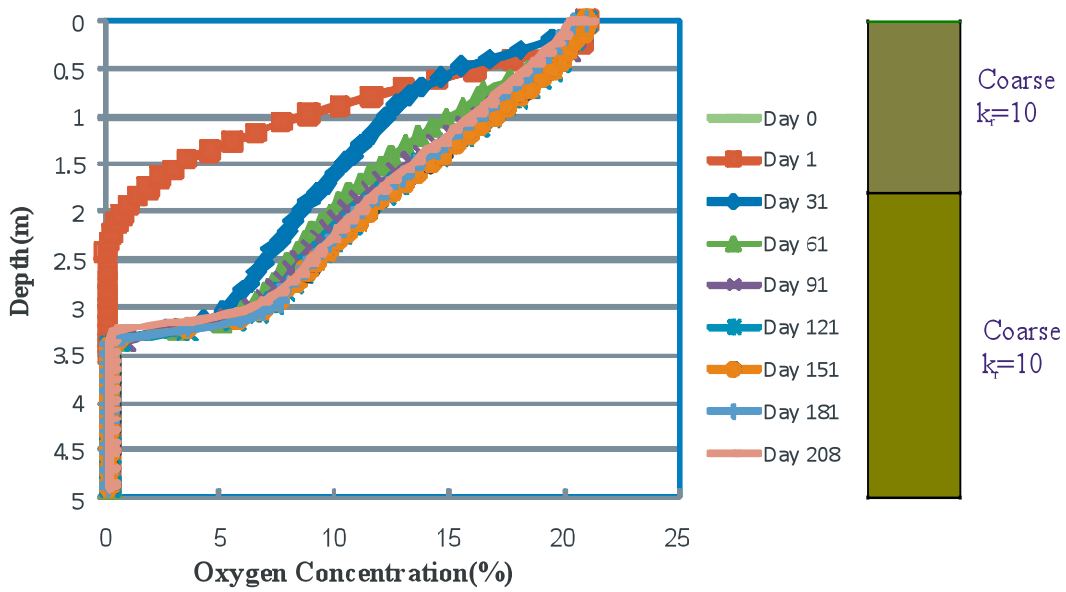
Figure 6.3 Oxygen Concentration profiles for coarse tailings, 4m water table for dry year and k_r=0.

, predicted oxygen concentrations were a reasonably good prediction by Dobchuk Finite Difference model when compared.

The reason is because the model has a different complete set of governing equations for water balance from the oxygen diffusion equations. It is therefore prudent to specify different boundary conditions when simulating for different results. The simulations were carried out for the dry year which represented the worst case scenario for the cover performance. This was decided based on assumption that if the cover performed well in dry year then it would perform in the best case scenarios. In addition, simulations using VADOSE/W, vegetation was found to have little effect on the oxygen concentration results which were consistent with the Dobchuk (2002) FD model results observations.

Research has also shown that water content is an important factor that influences the performance of the desulphurized tailings covers. In unsaturated or negative pore water pressure, coarse layers drain rapidly whereas fine layers retain the water content. However; other factors are at play in the tailings cover system like oxygen consumption by the remaining sulphide minerals. Variation in seasons affect the saturation in the tailings and water table levels especially after rainfall invents. Simulations aimed at verifying the VADOSE/W model showed consistent water balance data of the finite difference model and oxygen diffusion data obtained based on saturated profiles.

VADOSE/W model oxygen concentration profiles



FD model oxygen concentration profiles

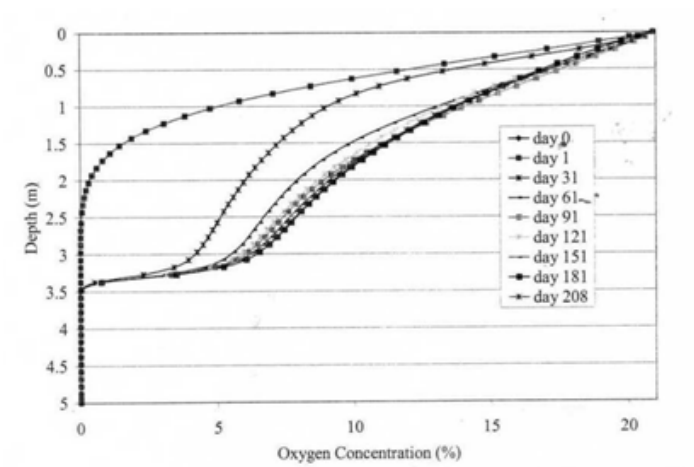


Figure 6.4-Oxygen concentration profile for coarse tailings, 4m water table for Dry year, k_r =10 (Figure 6.15 Dobchuk, 2002).

It was also determined (Figure 6.4) that for homogeneous coarse tailings, 4 meters to water table, dry year and 10 1/year kinetic coefficient show that the oxygen concentration profiles results obtained. It is also worth noting that the Figure 6.4 did not take into account vegetation, which was found not to affect oxygen simulations. The figures further show that the coarse layer does not show the changes that were observed for fine over coarse layer interface. It is most probable that the coarse layer is unsaturated as the coarse layer is not expected to retain much moisture.

Although numerical models are developed for more generalized case scenarios, they have proved to be powerful to predict and evaluate cover designs. Model verification by use of the available models published as well as field measured data is very relevant to the VADOSE/W model currently used by the Industry.

The model results presented above have demonstrated that reasonably accurate predictions are obtained when utilized correctly by ensuring correct boundary conditions. It has been determined that the VADOSE/W model is reasonably accurate when utilized correctly by ensuring that correct boundary conditions are specified. In general, there is reasonable agreement between the results obtained using VADOSE/W for close to more than two hundred simulations carried out. More selected results of oxygen concentration can be found in appendix D.

In conclusion, despite all the varying factors, the results showed that the VADOSE/W model if used correctly is sufficient to predict oxygen diffusion through the tailings

cover. Each model needs to be continually improved, calibrated, verified, and validated to make it more accurate. The VADOSE/W model has shown its significance in predicting oxygen diffusion which is critical to understanding desulphurized tailings covers that have a significant potential to reduce oxygen diffusion, as well as providing an alternative cover material where the mine does not have alternative cover material readily available on site.

Chapter 7: SUMMARY AND CONCLUSIONS

The research showed that the VADOSE/W model is sufficient if used correctly to predict oxygen diffusion through the tailings. Each model needs to be continuously improved, calibrated, verified and validated to make it more accurate. This is a significant and time consuming task. This study contributes to the general verification that the VADOSE/W model accurately predicted the oxygen diffusion and movement through the tailings and predicted the potential, evaporation, transpiration, infiltration, runoff, and the effect of vegetation – parameters that are relevant in understanding and controlling ARD.

Most of this type of research relies on the Engineer's judgment and experience. There are checks and balances to this kind of judgment which are important to the modeler most especially if the results obtained are outside the expected output. It is always a good question to ask if the output obtained makes sense in the real world situation. This is where a call to sound engineering judgment comes into play. Tailings depending on different mechanism of deposition are segregated differently.

Comparison of the predictions for the results of the desulphurized Detour tailings with lower sulphuric content was a success and the VADOSE/W model was considered to be verified. The VADOSE/W model results should be tested to further verify the model using other tailings data since the simulations were based on the simplified

representation of the conditions at the Detour lake mine tailings. Many factors still are at play and the simulations were not that straight forward. The modeler needs to be familiar with the theory basis of the model to come up with reasonable and realistic boundary conditions to obtain the correct solution. There should be more room for improvement using more complex and advanced scenarios especially given the fact that there are assumptions such as material properties being homogeneous, the remaining oxygen is consumed by the traces of un-desulphurized material.

Further research should be carried out to verify the VADOSE/W model across several mine sites and field data since this research focuses on a single mine site. Verification of the model is challenging and it is recommended that data from several other sites be used for further verification of this model. The model should also be applied to several measured field data for further verification. It should be noted that this verification was limited to the Detour Lake Mine desulphurized tailings cover. This kind of research would greatly enhance cost reduction in tailings management by ensuring that quantitative models can be used to predict the performance tailings cover.

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Appendix A-Map of detour lake mine and location

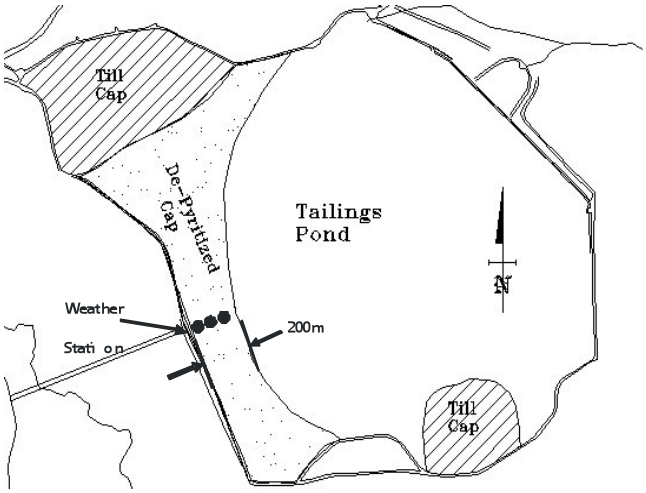

Figure 4.1(a) - Map of Detour lake tailings desulphurized tailings cover from Dobchuk (2002) figure 4.1

Figure 4.1 (b)-Map of Ontario (not to scale), modified to indicate approximate location of Detour lake mine tailings facility (http://images.google.ca/images?)

Appendix B-Net cumulative water balance

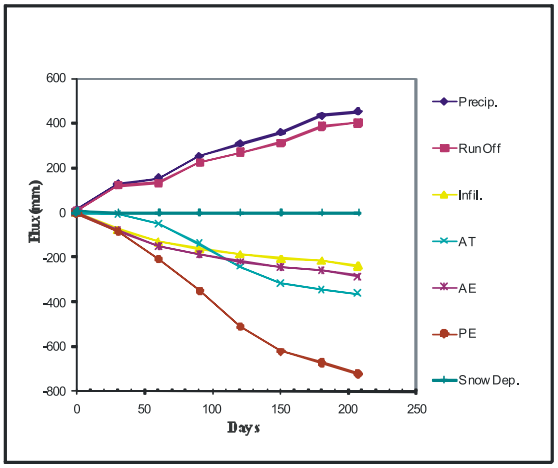

Figure 6.5-Net cumulative flux comparison for dry year coarse tailings, water table, 1m, and poor vegetation

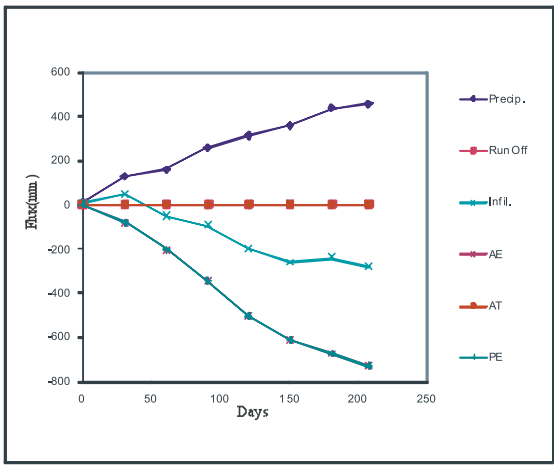

Figure 6.6-Net cumulative flux comparison for dry year coarse tailings, watertable 4m and poor vegetation

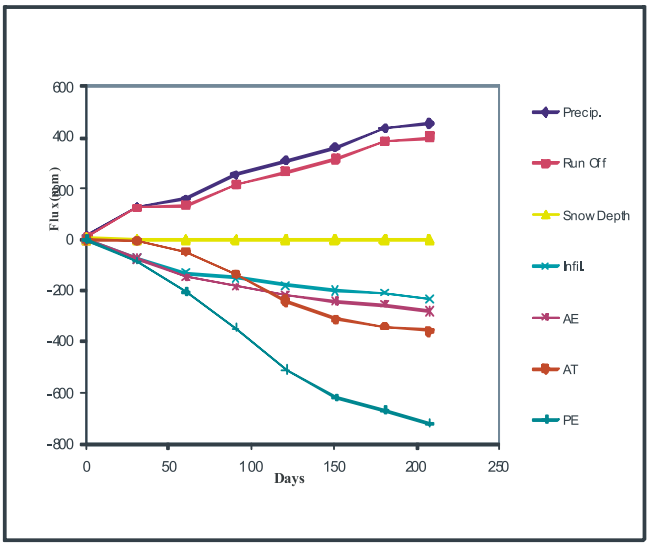

Figure 6.7-Net cumulative flux comparison for dry year coarse tailings, 4m water table, and good vegetation

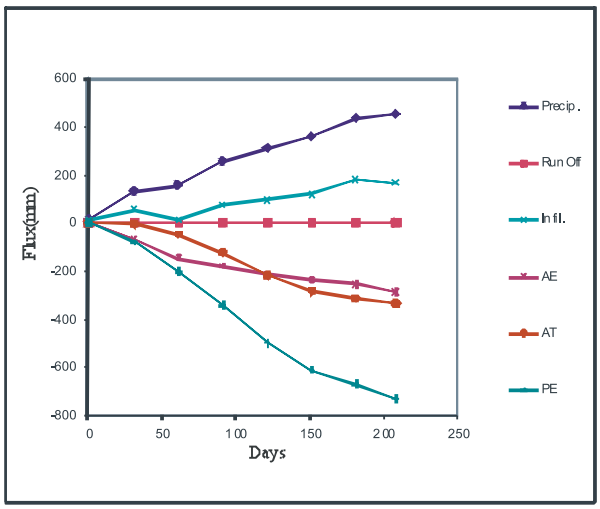

Figure 6.8-Net cumulative flux comparison for dry year coarse tailings, 4m water table, and poor vegetation

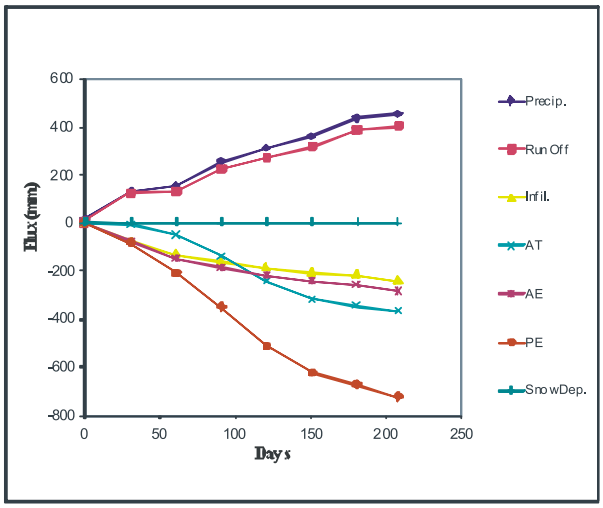

Figure 6.9-Net cumulative flux comparison for dry year coarse tailings, 4m water table, and no vegetation

Appendix C-Detour lake mine weather data(2001/2002)

Dry Year		Detour Lake 2000/2001				Dry Snow	
Date	Max Temp	Min Temp	Max RH	Min RH	Wind Speed	Daily Precip.	Net Rad.
	ºC	ºC	dec	dec	m/s	mm/day	MJ/m2 Day
8-Apr-01	5.63	0.00	0.95	0.85	5	14.88	2.52
9-Apr-01	-0.16	0.00	0.94	0.84	5.99	5.78	2.70
10-Apr-01	4.76	0.00	0.92	0.43	2.11	6.38	6.20
11-Apr-01	11.04	0.00	0.85	0.29	3.32	6.18	8.84
12-Apr-01	7.61	3.03	0.97	0.40	5.39	15.28	2.79
13-Apr-01	6.91	0.00	0.95	0.57	5.21	6.68	3.94
14-Apr-01	2.59	0.00	0.91	0.29	2.04	6.28	9.94
15-Apr-01	2.35	0.00	0.85	0.26	3.84	5.68	14.29
16-Apr-01	0.68	0.00	0.89	0.28	4.43	5.78	14.29
17-Apr-01	-3.49	0.00	0.81	0.49	5.02	5.68	10.31
18-Apr-01	1.11	0.00	0.87	0.37	2.44	5.68	14.83
19-Apr-01	11.40	0.00	0.85	0.26	2.04	5.68	13.40
20-Apr-01	16.70	0.00	0.64	0.26	2.55	5.68	12.93
21-Apr-01	12.68	2.81	0.97	0.45	3.67	13.58	6.16
22-Apr-01	6.30	0.00	0.97	0.42	5.27	2.50	16.37
23-Apr-01	11.25	0.00	0.97	0.67	3.39	7.90	14.50
24-Apr-01	4.31	0.00	0.95	0.55	4.72	4.20	11.70
25-Apr-01	11.97	0.00	0.91	0.25	2.83	1.00	13.57
26-Apr-01	14.20	0.00	0.92	0.50	5.16	3.40	4.34
27-Apr-01	3.42	0.00	0.74	0.31	4.52	0.00	16.30
28-Apr-01	9.14	0.00	0.82	0.23	1.93	0.00	15.99
29-Apr-01	19.35	0.00	0.76	0.17	4.39	0.00	13.75
30-Apr-01	27.75	10.23	0.57	0.23	4.98	0.00	14.10
1-May-01	23.17	12.54	0.75	0.36	3.46	0.00	10.78
2-May-01	22.40	9.92	0.96	0.30	4.02	0.10	8.37
3-May-01	17.14	6.07	0.50	0.35	4.66	0.00	15.20
4-May-01	7.57	0.00	0.92	0.52	3.94	0.00	9.82
5-May-01	13.97	0.00	0.94	0.14	2.16	0.70	16.71
6-May-01	20.32	0.00	0.75	0.15	2.96	0.00	14.97
7-May-01	25.38	3.61	0.59	0.18	4.13	0.00	14.00
8-May-01	21.08	13.80	0.80	0.20	5.1	0.00	9.34
9-May-01	18.19	5.98	0.67	0.26	4.05	0.00	13.79
10-May-01	22.12	0.29	0.94	0.23	3.5	1.80	8.04

11-May-01	12.93	0.00	0.94	0.61	4.78	0.00	9.69
12-May-01	9.10	0.00	0.90	0.30	3.9	0.00	13.89
13-May-01	12.60	0.00	0.90	0.20	3.01	1.30	13.53
14-May-01	14.89	0.00	0.93	0.16	1.89	0.00	15.20
15-May-01	19.12	1.89	0.63	0.11	1.04	0.00	14.33
16-May-01	21.75	5.60	0.89	0.27	5.38	0.51	11.19
17-May-01	20.45	10.54	0.91	0.47	4.49	0.00	8.94
18-May-01	17.21	10.60	0.95	0.56	3.01	3.40	7.95
19-May-01	21.35	10.04	0.96	0.37	1.54	0.00	11.04
20-May-01	26.78	7.57	0.94	0.22	1.88	0.00	12.75
21-May-01	26.67	10.82	0.78	0.24	5.01	0.00	13.12
22-May-01	21.83	14.51	0.67	0.41	7.09	0.00	4.65
23-May-01	17.79	10.47	0.96	0.65	4.77	12.00	2.70
24-May-01	22.37	7.84	0.97	0.49	2.1	1.10	10.70
25-May-01	25.30	11.85	0.93	0.30	3.76	0.00	14.66
26-May-01	21.18	13.39	0.89	0.38	2.9	0.40	7.90
27-May-01	20.27	11.03	0.93	0.50	3.24	0.00	9.50
28-May-01	12.86	0.63	0.90	0.82	5.17	1.10	2.93
29-May-01	6.18	-0.54	0.93	0.61	7.28	0.50	12.23
30-May-01	9.10	-2.01	0.92	0.47	5.99	0.10	10.87
31-May-01	20.32	-1.66	0.92	0.21	1.88	0.00	13.43
1-Jun-01	21.45	4.98	0.75	0.25	2.41	0.00	7.65
2-Jun-01	14.60	5.67	0.96	0.49	4.02	3.60	25.10
3-Jun-01	9.51	4.91	0.97	0.93	4.39	1.10	5.07
4-Jun-01	10.82	3.44	0.97	0.78	4.54	0.70	4.98
5-Jun-01	16.35	5.04	0.92	0.26	5.4	0.20	15.05
6-Jun-01	19.13	1.33	0.54	0.17	4.66	0.00	15.24
7-Jun-01	15.96	-0.55	0.84	0.24	3.48	0.00	14.55
8-Jun-01	22.13	-0.06	0.86	0.25	2.13	0.00	13.66
9-Jun-01	27.27	6.41	0.84	0.24	3.16	0.00	10.90
10-Jun-01	27.34	3.44	0.90	0.20	1.92	0.00	9.68
11-Jun-01	27.30	11.89	0.78	0.30	2.51	0.00	9.81
12-Jun-01	20.98	5.41	0.94	0.57	4.17	7.90	6.27
13-Jun-01	16.90	2.54	0.89	0.40	2.3	0.00	11.22
14-Jun-01	34.33	10.56	0.94	0.24	3.86	19.20	13.69
15-Jun-01	33.55	17.03	0.95	0.35	3.7	0.00	12.06
16-Jun-01	26.04	14.09	0.95	0.19	5.05	7.10	15.65
17-Jun-01	17.64	9.03	0.86	0.32	3.33	0.00	13.56
18-Jun-01	22.13	1.57	0.94	0.22	2.89	0.00	13.90

19-Jun-01	24.11	11.71	0.96	0.41	7.67	6.60	8.54
20-Jun-01	19.31	7.95	0.88	0.31	3.22	0.00	11.41
21-Jun-01	20.54	7.46	0.91	0.35	3.07	0.20	13.48
22-Jun-01	14.48	9.35	0.88	0.52	3.71	0.70	3.86
23-Jun-01	25.96	8.64	0.93	0.26	2.76	0.00	15.37
24-Jun-01	23.23	7.35	0.93	0.41	3.48	0.50	8.50
25-Jun-01	28.59	5.08	0.93	0.42	2.8	0.00	7.57
26-Jun-01	35.10	20.91	0.66	0.32	6.33	0.00	13.88
27-Jun-01	27.27	9.15	0.82	0.39	4.95	0.00	11.40
28-Jun-01	21.45	7.45	0.88	0.29	1.78	0.50	10.87
29-Jun-01	26.60	10.94	0.96	0.63	4.93	20.40	7.86
30-Jun-01	14.46	7.54	0.94	0.66	3.81	0.80	6.96
1-Jul-01	10.70	2.75	0.95	0.52	6.59	8.30	3.11
2-Jul-01	10.70	2.75	0.95	0.52	6.59	8.30	3.11
3-Jul-01	10.70	2.75	0.95	0.52	6.59	8.30	3.11
4-Jul-01	10.70	2.75	0.95	0.52	6.59	8.30	3.11
5-Jul-01	16.11	4.93	0.94	0.42	4.76	0.00	15.41
6-Jul-01	17.13	4.80	0.91	0.39	5.25	0.00	11.70
7-Jul-01	19.94	5.79	0.93	0.32	3.61	0.00	14.00
8-Jul-01	23.09	6.44	0.91	0.30	1.94	0.10	7.39
9-Jul-01	18.70	13.14	0.97	0.84	2.87	22.40	3.31
10-Jul-01	20.85	8.20	0.96	0.36	4.94	0.00	19.13
11-Jul-01	20.76	5.75	0.90	0.31	3.79	0.00	17.75
12-Jul-01	26.86	2.46	0.97	0.23	1.63	0.00	16.46
13-Jul-01	23.39	11.42	0.83	0.36	2.48	0.00	6.34
14-Jul-01	22.09	14.83	0.94	0.57	3.39	3.00	7.53
15-Jul-01	25.55	12.82	0.93	0.44	2.19	0.00	10.50
16-Jul-01	26.95	13.11	0.97	0.39	2.99	0.00	14.94
17-Jul-01	26.25	10.57	0.91	0.42	4.04	5.10	8.93
18-Jul-01	12.30	6.32	0.94	0.58	3.79	0.10	5.75
19-Jul-01	18.67	3.35	0.89	0.33	3.52	0.00	11.26
20-Jul-01	18.89	6.61	0.93	0.42	2.04	1.70	5.80
21-Jul-01	13.77	9.01	0.91	0.68	3.99	0.20	6.46
22-Jul-01	17.02	8.12	0.96	0.63	1.97	0.00	5.58
23-Jul-01	23.39	10.34	0.81	0.32	2.13	0.00	11.13
24-Jul-01	25.88	10.42	0.88	0.32	3.15	0.00	13.22
25-Jul-01	26.80	16.70	0.81	0.36	4.55	0.00	10.18
26-Jul-01	28.18	14.97	0.79	0.33	3.67	0.00	10.85
27-Jul-01	28.32	13.63	0.93	0.39	2.88	0.00	9.51

28-Jul-01	20.63	9.48	0.97	0.48	4.28	0.00	13.18
29-Jul-01	27.06	8.35	0.97	0.33	2.2	0.00	13.39
30-Jul-01	30.95	11.04	0.94	0.22	2.28	0.00	12.65
31-Jul-01	30.23	15.49	0.85	0.38	3.15	0.00	10.37
1-Aug-01	27.20	15.78	0.97	0.32	2.03	8.00	6.03
2-Aug-01	15.32	9.18	0.97	0.39	2.56	9.60	4.13
3-Aug-01	10.96	7.53	0.96	0.87	3.68	3.60	4.66
4-Aug-01	20.17	8.84	0.93	0.30	4.12	1.50	12.29
5-Aug-01	26.23	4.92	0.94	0.30	2.16	0.00	12.36
6-Aug-01	22.75	14.38	0.91	0.48	1.71	0.10	5.00
7-Aug-01	17.68	15.47	0.94	0.86	2.59	3.40	2.39
8-Aug-01	24.72	14.35	0.97	0.44	2.46	0.00	9.56
9-Aug-01	25.12	10.32	0.80	0.31	3.98	0.00	14.37
10-Aug-01	24.42	8.16	0.82	0.30	3.67	0.00	12.87
11-Aug-01	24.75	9.10	0.93	0.35	3.44	0.00	11.37
12-Aug-01	27.39	8.41	0.96	0.29	3.15	0.00	10.61
13-Aug-01	21.45	12.91	0.86	0.37	3.8	1.80	3.14
14-Aug-01	24.96	5.66	0.97	0.30	1.49	0.00	12.43
15-Aug-01	23.34	12.24	0.94	0.60	3.29	6.90	3.77
16-Aug-01	12.27	6.34	0.94	0.75	4.82	4.20	5.20
17-Aug-01	18.77	4.36	0.91	0.32	2.42	0.00	12.91
18-Aug-01	15.24	7.86	0.95	0.57	2.31	8.00	4.19
19-Aug-01	11.86	5.63	0.95	0.71	3.73	3.30	8.22
20-Aug-01	17.34	3.38	0.96	0.36	2.43	0.00	13.01
21-Aug-01	19.22	1.08	0.96	0.42	2.34	0.00	8.35
22-Aug-01	22.54	12.82	0.94	0.56	3.32	1.50	10.49
23-Aug-01	20.74	11.39	0.97	0.50	2.41	0.70	8.61
24-Aug-01	23.64	12.18	0.96	0.39	2.61	2.80	8.18
25-Aug-01	28.96	14.82	0.94	0.30	4.18	0.10	11.50
26-Aug-01	18.62	9.23	0.95	0.41	3.53	2.10	11.67
27-Aug-01	23.00	6.01	0.94	0.17	1.68	0.00	9.42
28-Aug-01	25.08	7.21	0.83	0.19	3.07	0.00	7.84
29-Aug-01	19.32	10.87	0.96	0.53	3.69	8.80	2.80
30-Aug-01	22.45	9.68	0.89	0.34	2.11	0.00	11.96
31-Aug-01	23.64	6.58	0.94	0.64	4.75	5.80	3.82
1-Sep-01	10.17	3.83	0.93	0.56	5.06	0.20	9.87
2-Sep-01	14.77	1.32	0.94	0.39	3.14	0.00	9.62
3-Sep-01	14.68	1.67	0.96	0.35	2.49	0.00	7.10
4-Sep-01	10.25	0.32	0.96	0.52	3.44	0.30	6.68

5-Sep-01	15.43	-1.10	0.96	0.35	1.7	0.00	8.10
6-Sep-01	19.10	3.58	0.90	0.25	3.61	0.00	5.34
7-Sep-01	22.60	12.60	0.83	0.41	4.91	0.50	5.86
8-Sep-01	16.74	6.54	0.95	0.50	4.23	1.60	2.75
9-Sep-01	22.97	4.69	0.97	0.42	2.28	0.10	7.76
10-Sep-01	24.99	15.10	0.86	0.68	5.38	0.00	5.24
11-Sep-01	24.37	9.73	0.86	0.57	3.62	0.40	1.90
12-Sep-01	19.81	8.15	0.95	0.45	13.74	9.80	4.14
13-Sep-01	18.00	7.78	0.96	0.50	3.5	7.10	5.98
14-Sep-01	15.00	3.72	0.97	0.42	2.53	0.20	7.52
15-Sep-01	10.50	5.18	0.94	0.63	5.65	0.70	6.96
16-Sep-01	12.60	3.83	0.95	0.48	4.74	1.60	8.33
17-Sep-01	12.64	5.92	0.94	0.47	3.87	2.80	6.47
18-Sep-01	11.87	6.16	0.89	0.65	2.53	0.00	2.82
19-Sep-01	24.40	9.61	0.95	0.51	3.96	0.40	5.45
20-Sep-01	19.03	11.93	0.95	0.56	3.78	1.50	4.86
21-Sep-01	12.38	2.54	0.95	0.80	4.18	3.30	2.40
22-Sep-01	9.95	0.45	0.89	0.45	3.18	0.00	6.07
23-Sep-01	7.22	0.52	0.96	0.75	2.41	7.30	1.62
24-Sep-01	4.53	-1.54	0.95	0.61	3.76	1.00	4.30
25-Sep-01	9.01	2.21	0.94	0.48	3.77	1.00	7.03
26-Sep-01	6.10	0.16	0.94	0.62	3.42	3.60	2.53
27-Sep-01	2.51	-4.58	0.93	0.38	3.13	0.00	3.54
28-Sep-01	6.04	-5.47	0.79	0.33	2.91	0.00	4.96
29-Sep-01	16.78	2.70	0.85	0.60	3.49	0.10	4.09
30-Sep-01	15.83	8.86	0.97	0.59	3.53	0.50	2.80
1-Oct-01	21.90	6.41	0.97	0.48	3.97	1.30	4.55
2-Oct-01	19.20	5.78	0.94	0.63	4.76	27.80	2.39
3-Oct-01	13.90	3.11	0.95	0.49	3.12	3.60	6.91
4-Oct-01	5.89	-0.29	0.87	0.45	2.71	0.00	1.90
5-Oct-01	6.99	-1.17	0.85	0.35	2.32	0.00	3.25
6-Oct-01	6.76	0.87	0.81	0.50	3.8	0.00	4.23
7-Oct-01	3.36	-2.22	0.92	0.43	4.58	0.00	3.48
8-Oct-01	1.43	-1.75	0.94	0.64	3.16	1.00	3.14
9-Oct-01	11.01	-2.03	0.91	0.38	1.72	0.00	4.85
10-Oct-01	13.96	-3.28	0.94	0.24	1.87	0.00	5.68
11-Oct-01	6.73	-2.79	0.95	0.61	3.04	0.00	2.34
12-Oct-01	17.82	-2.06	0.95	0.37	4.35	0.10	5.11
13-Oct-01	6.64	0.99	0.96	0.62	2.32	0.10	4.24

14-Oct-01	5.63	-1.83	0.92	0.64	3.67	0.10	2.53
15-Oct-01	4.25	-4.97	0.91	0.34	1.63	0.00	4.13
16-Oct-01	8.04	-6.67	0.89	0.31	1.56	0.00	2.55
17-Oct-01	10.86	-5.77	0.94	0.34	1.87	0.00	4.59
18-Oct-01	8.67	1.56	0.94	0.75	2.54	1.10	0.68
19-Oct-01	10.96	1.40	0.95	0.43	2.25	0.00	3.62
20-Oct-01	17.76	6.20	0.93	0.55	3.87	1.60	2.03
21-Oct-01	7.63	-0.46	0.90	0.59	5.16	0.70	1.65
22-Oct-01	7.96	-3.18	0.85	0.33	3.27	0.00	2.35
23-Oct-01	11.03	4.23	0.89	0.50	3.43	1.20	1.03
24-Oct-01	13.84	2.05	0.88	0.44	3.44	0.10	2.33
25-Oct-01	17.06	-0.12	0.94	0.25	2.76	0.80	2.84
26-Oct-01	15.16	10.07	0.97	0.84	3.76	9.90	0.84
27-Oct-01	15.26	-1.77	0.94	0.75	6.83	1.50	2.22
28-Oct-01	1.34	-4.55	0.89	0.58	4.83	0.00	2.07
29-Oct-01	8.92	-9.15	0.93	0.25	1.03	0.00	3.42
30-Oct-01	10.62	-7.58	0.90	0.13	0.93	0.00	1.89
31-Oct-01	12.23	-1.96	0.70	0.26	2.09	0.00	2.15
1-Nov-01	14.21	2.79	0.82	0.38	1.38	0.00	2.22

Appendix D-VADOSE/W Results of oxygen concentration profiles

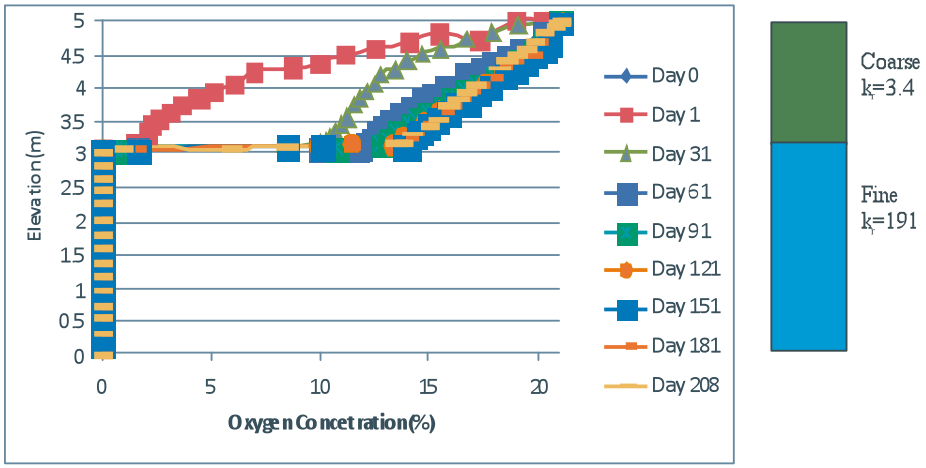

Figure 6.10-Oxygen concentration profile for 1.8m thick coarse layer over fine tailings, 4m water table for a dry year and k_r=0

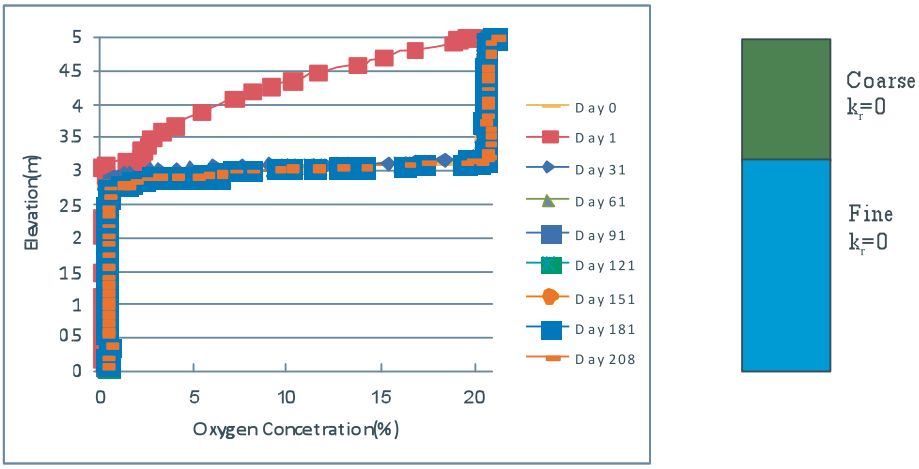

Figure 6.11-Oxygen concentration profile for 1.8m thick coarse over fine tailings,4m water table for a dry year and k_r=3.4 and 191 respectively

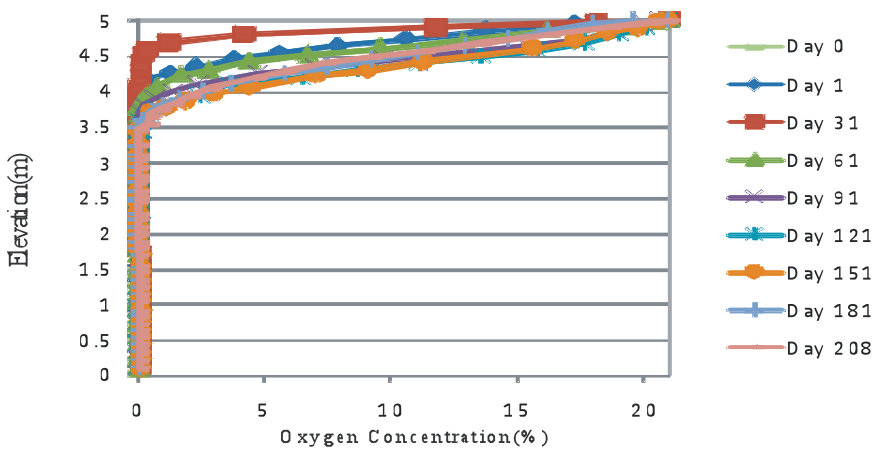

Figure 6.12-Oxygen concentration profile for 1.8m thick layer of fine over coarse tailings, 4m water table for a dry year and k_r=14.9,44 respectively

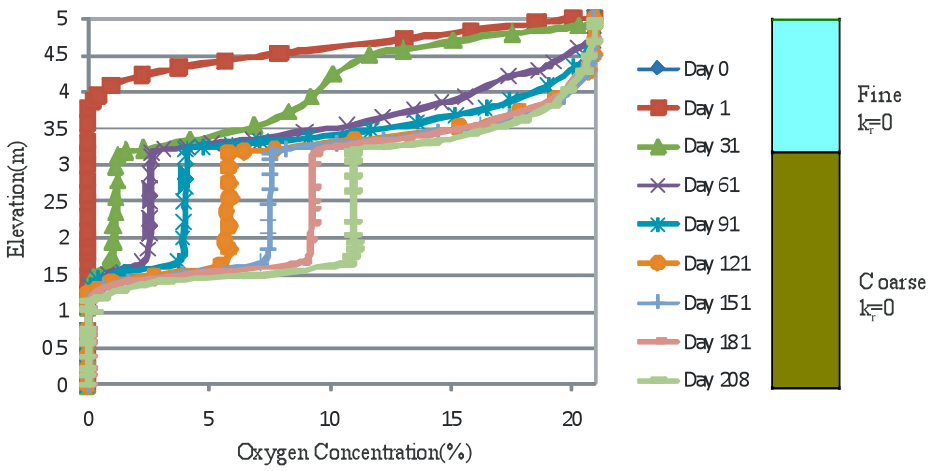

Figure 6.13-Oxygen concentration profile for 1.8m thick layer of fine over coarse tailings, 4m water table for a dry year and k_r=0

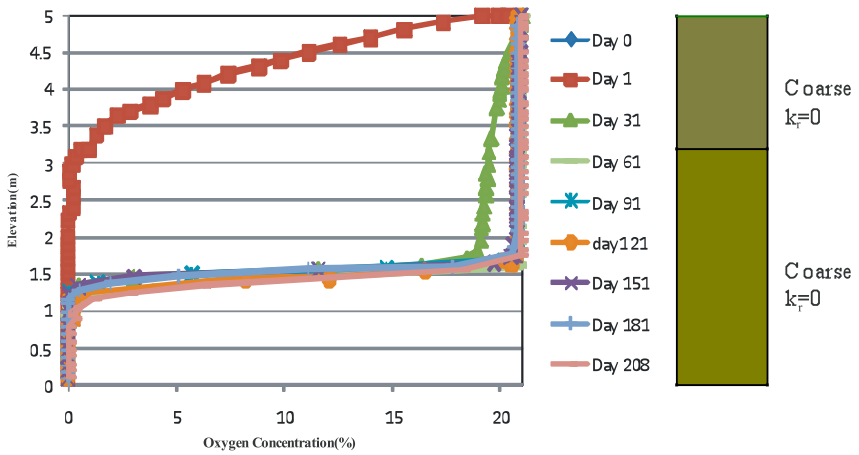

Figure 6.14-Oxygen concentration profile for coarse tailings, 4m water table for dry year and k_r=0

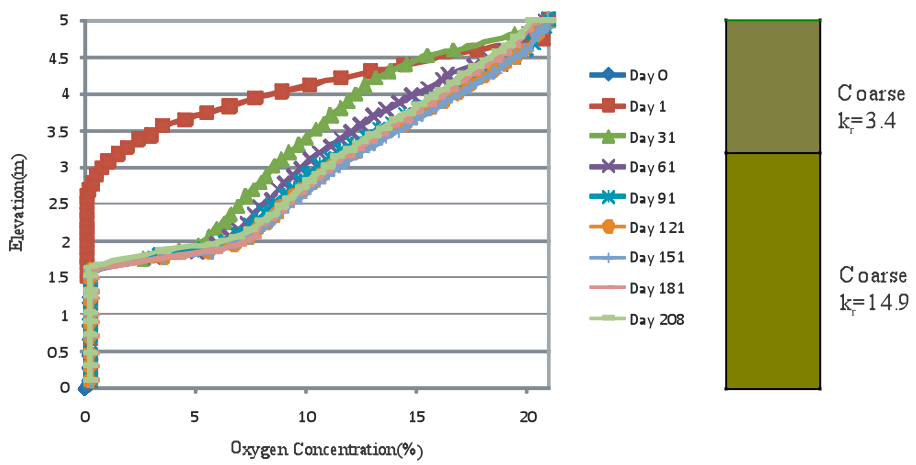

Figure 6.15-Oxygen concentration profile for 1.8m thick layer of fine over coarse tailings, 4m water table for a dry year and k_r=3.4,14.9 respectively