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Numerical Evaluation of Two-dimensional Multi-layer Cover System to Regulate Acid Mine Drainage of Tailing Dams

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ABSTRACT

In the mining industry, cover systems for tailings are an effective means of reducing acid mine drainage. An example of this type of system is the multi-layer cover system that is used in arid climates where the annual evaporation rate is greater than the annual rainfall. For users and designers of mine tailings dams, the current research is aimed at identifying the optimal cover system and engineering of the mine waste disposal site, as well as investigating effective geotechnical parameters in controlling the oxygen gas entering the mine waste disposal site. In this research, after careful examination of scientific literature and data collection, it is first validated using numerical modeling, Finite Element Method (FEM) based on the VADOSE/W software, and then modeling is done based on the collected data. One-dimensional modeling has often been used in studies on the evaluation of cover systems, but in this research, two-dimensional modeling has been used to analyze the behavior of coating systems. The key to the successful operation of cover systems is maintaining the storage layer at a saturation level of about 85% throughout the year. The two cover systems, "storage and release", "optimized storage and release," are ineffective in maintaining the storage layer at about 85% saturation. However, the capillary barrier cover system has worked successfully and maintained the degree of saturation of the storage layer at about 80%. Due to the use of low-sulfide waste material as an oxygen-consuming layer, the performance of all three cover systems was acceptable. However, it is worth noting that the capillarity barrier cover system was able to immediately cut off the diffusion of oxygen due to the high degree of saturation of the storage layer, while in the other two cover systems, this decrease in diffusion and oxygen concentration was gradual. Therefore, the capillary barrier cover system is suggested as the most optimal system according to the weather conditions and the type of waste materials.

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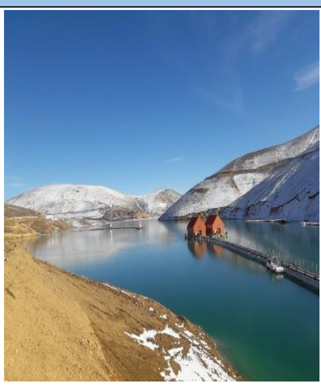
Graphical Abstract

Management and control of acid mine drainage from mining activities



$FeS_{2(s)} + 3.5O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + H^+$

$Fe^{2+} + 0.25H + O_2 \rightarrow Fe^{3+} + 0.5H_2O$

$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_{3(s)} + 3H^+$

Relations of the production process of acid mine drainage

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In the method of separation and concentration of copper deposits by flotation method, low-grade minerals are separated, which is the main factor in the production of acidic mine drainage, and the lack of efficient management will bring irreparable environmental consequences.

The resulting low-grade minerals should be collected in tailings dams, and in order to prevent the production of acidic mine drainage, a suitable covering system should be used according to the climatic and economic conditions of the region.

The most important environmental effects of acid mine drainage

The negative impact on agriculture industry

Economic problems caused by the mentioned disturbances and their effects on human societies

Disturbance in aquatic and terrestrial ecosystems

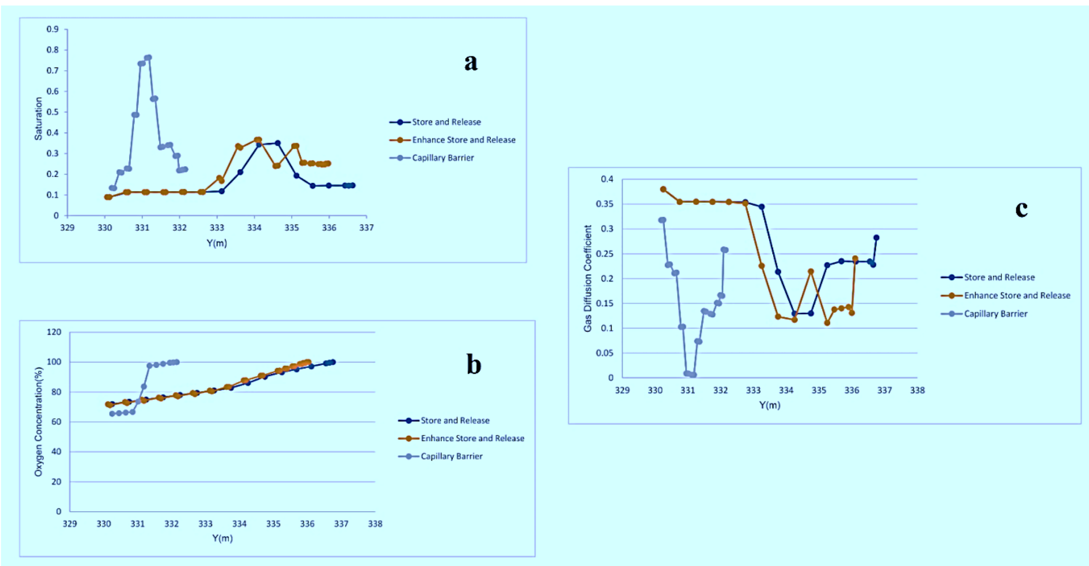
The spread of various diseases

The details of the coating systems evaluated for the climatic conditions of the region studied in this research as a solution for the management of acidic mine drainage

The key point in the successful performance of multilayer coating systems

Keeping the storage layer in the cover system at about 85% saturation throughout the year by using capillary, capillary break, suction, and seepage properties

By comparing the performance of the storage layer and examining the results of the modeling done by the software, we find that the performance of the storage layer itself is a function of the performance and relationship of the other layers of the evaluated coating systems, and therefore, the capillary barrier coating system show the best performance and it is the most suitable suggestion for the study area.



1. INTRODUCTION

Every mining activity change and disturbs, more or less, the condition of the natural environment by mainly energy consumption, deformations of the earth, various changes in water relations, emission of gas, dust, and noise, and others [1, 2]. The effects of mining activities, uncontrolled mining, and tailings produced can adversely affect the environment, resulting in water, air, and soil pollution. Mining can also adversely affect human health because the pollutants may directly or indirectly enter into human body [3].

The tailings dams must be designed according to the volume of mining activities; some large-scale orebodies extend from the surface to the extreme depths of the ground. Such orebodies should be extracted by combining surface and underground mining methods; therefore, many waste materials will be produced [4]. The stability of tailings dams is another important issue that must be considered because the leakage or destruction of tailings dams will lead to environmental disaster; therefore, the geological information is beneficial for determining the geotechnical domain. It can be used for guidance on developing pit slope design parameters in open pit mining or the design of tailing dams and other geotechnical purpose such as defining the probability of failure, slope movement guidance, and risk assessment [5]. Using engineering cover systems on mineral tailings is practiced for several reasons. These include preventing tailings erosion and dust generation, controlling the entry of oxygen and water into tailings (to prevent acid drainage production), preventing the spread of contaminants to the environment by controlling seepage, and providing conditions for establishing a sustainable vegetation system. Regulating water penetration into hazardous industrial, urban, mineral, and radioactive waste disposal areas is one of the most significant reasons for implementing cover systems [6-9]. In the course of mining and afterward, sulfuric acid and metal ions are produced as a result of the oxidation of pyritic materials. A range of water chemistries are created by the reaction between these products and the host rock, surface water, and groundwater [10, 11]. Acid Mine Drainage (AMD) is acidic runoff containing heavy metals and sulfates. Mine drainage is referred to as AMD [12]. It is obtained from the oxidation of sulfide minerals, mainly pyrite, in the tailings of sulfide processing plants and low tailings dumps of sulfide and coal mines. Sulfide is one of the most critical environmental problems in the mining industry [13-15]. Sulfur-oxidizing bacteria (SOB) can also increase AMD production resulting in environmental problems [16-18]. The control of such disease, once it has developed at a mine, can be difficult and expensive. AMD must be collected and treated if it cannot be prevented. As a general rule, the treatment of AMD is more expensive than the control of AMD, which is often carried out early on in the mining process and may remain necessary for many years after the mining activity has ended. There is a difference between tailings and waste rock in terms of particle size, porosity, the surface area of sulfide minerals, and the homogeneous distribution of sulfide and alkaline minerals. These differences affect the rate of potential oxidation and neutralization processes and the quality of AMD. Waste material characterization and quantification is the first step for designing and implementing AMD control measures [19].

Sulfide minerals are oxidized by oxygen and water, producing sulfuric acid. AMD contamination in mining areas is associated with problems related to surface, groundwater, and soil pollution. In areas where surface and groundwater are contaminated by AMD, purification of water resources for drinking and industrial use is very laborious and costly; Therefore, reducing and avoiding AMD production over the past few decades has been challenging for researchers. It requires the prevention of oxidation by limiting the penetration of oxygen and water into reactive wastes, which can be controlled by implementing a suitable cover system on tailings [20]. Before the development of AMD control measures, possible options such as dry cover, water cover, AMD collection, and treatment are evaluated for technical and economic feasibility. The decision is made primarily based on the total cost of the option and the effect of the option on the generation of AMD and its life span. In the case where AMD has already developed, the treatment may be the most feasible method. The water treatment process will depend on the plant water chemistry and the discharge permit but will typically include pH adjustment, removal of dissolved metals, and removal of suspended solids. An appropriate passive system is selected based on water chemistry, flow rate, local topography, and site characteristics [21].

There are two types of passive treatment technologies: biological and geochemical. As part of biological passive treatment technologies, bacterial activity is generally stimulated, and organic matter is used to adsorb contaminants and stimulate microbial sulfate reduction. Prior to selecting an appropriate treatment technology, AMD conditions and chemistry must be characterized. Passive treatment is often considered when AMD severity and available resources do not warrant active treatment. As a means of neutralizing acidity, alkaline chemicals are continuously added, including lime, slaked or hydrated lime, anhydrous ammonia, or sodium hydroxide [22, 23]. However, since air and water are considered key ingredients of AMD, control methods usually aim to reduce the flux of air or water by isolating the waste material. Oxygen diffusion cover systems that various researchers have studied to reduce AMD production include:

- Single-layer sand cover system
- Sulfide-containing monolayer cover system with raised water leveling mechanism (using desulfurized tailings as cover)
- Multi-layer cover system with store and release mechanism
- Multi-layer cover system with capillary barrier mechanism

The effectiveness of a dry "soil" cover system relies on the presence of low hydraulic conductivity and high moisture retaining layer**;** a low-permeability soil cover containing a layer of compacted clay can be constructed as a single-layer or multi-layered system over either tailings or waste rock dumps [24]. In single-layer sand cover systems with a water leveling mechanism, the material of the cover system is selected so that water penetrates the mineral tailings in wet seasons. A cover on the tailings limits evaporation and increases the static level of water inside the tailings. As a general rule, according to Figure 1a, the position of the water level should be controlled so that the height of the part of the tailings that is above the static level of water is less than the AEV value of the tailings. Controlling the water level causes capillary saturation to increase the degree of saturation of tailings located above the static surface and prevents oxygen penetration to the waste (below the static level of water). In such a manner, the oxygen diffusion coefficient to the mineral tailings is significantly reduced, and the production of AMD decreases [25-27]. Dagenais et al. [28] numerically studied the behavior of a sand monolayer cover system (with rising water level) and the effect of various parameters such as cover properties and thickness, water level depth, and hydraulic properties of tailings by numerical modeling applying Soil Cover software. The importance of the effect of sand layer thickness on tailings water content profiles was also investigated. Based on their finding, if the sand layer is used as a cover system, the degree of saturation of the surface area of the tailings rises to more than 95%, and oxygen diffusion to the tailings materials decreases. However, if the sand layer is not used, the degree of saturation in the range of the tailings surface remains 70 to 74%, and oxygen diffusion to the tailings materials increases. The results of this study revealed that if a 30 cm layer of sand is used on the tailings, and if the depth of water level from the surface of the tailings (d) is less than half of AEV of materials (according to Figure 1a), the surface area of the tailings keep conditions near saturation for 60 days and penetration of oxygen into the tailings is limited.

As such reducing the oxidation rate of sulfide minerals, AMD production is also controlled. In this study, instead of using the sand layer, which the idea was taken from the work of Dagenais et al. [28] a suitable layer for the growth of vegetation was used so that the capabilities of the vegetation system were used to control evaporation and transpiration, and the results of the analyzes show proper efficiency and matches with the results of the work of Dagenais et al. [28]. Ouangrawa et al. [29] investigated the effect of the rising static level of water (change of parameter d as shown in Figure 1(a)) on the reduction of AMD production by performing column experiments and analyzing various parameters. This study investigated the effect of changing the height of static water levels by measuring pH and the concentration of major ions, including sulfate, iron, zinc, copper, and lead. The results uncovered that if the depth of the static water level (d) is about half the AEV of the waste material, there will be a significant reduction in AMD production. Also, if the tailings have lower hydraulic conductivity and higher AEV due to reduced drainage capability. The performance of the cover system (with a rising water level) will be improved, and AMD production will be reduced.

Another type of cover system is the sulfide-containing monolayer cover system (Figure 1(a)). As discussed, the main role of the oxygen diffusion cover system with a raised water leveling mechanism is to help create near-saturation conditions in the surface area of the tailings, which leads to a reduction of oxygen diffusion into the tailings. However, some oxygen seeps into the tailings through the cover system. If a compound such as a sulfide in the cover system material initiates a chemical reaction with some of the penetrating oxygen and precipitates in the cover system, the oxygen penetration into the tailings will be further reduced, and AMD will be more controlled. In a similar vein, Demers et al. [30] investigated the behavior of a monolayer cover of desulfurized tailings on mineral tailings and used an instrumentalized column to evaluate the oxygen flow. The results of the present study showed that placing low-sulfide tailings as an oxygen-consuming layer significantly reduces the production of AMD, which is consistent with the results of the work done by Demers et al. [30].

Using a multi-layer oxygen diffusion covering system with a capillary barrier mechanism and a storage-diffusion mechanism (in both integrated and incremental types) is another method applied by researchers to regulate AMD (Figure 1(b)). Two or more layers can be used in a design, including from top to bottom: a revegetated soil layer to retain moisture; a coarse layer to provide lateral drainage of infiltration; a compacted clay layer to prevent oxygen penetration; and a compacted alkaline layer to facilitate cap construction and minimize the reaction of water in the waste with the clay layer. In some cases, instead of revegetation, a layer of coarse material is placed for erosion control. To be effective, clay or other low-permeability soil must be saturated with water to limit oxygen. Using an organic layer at the

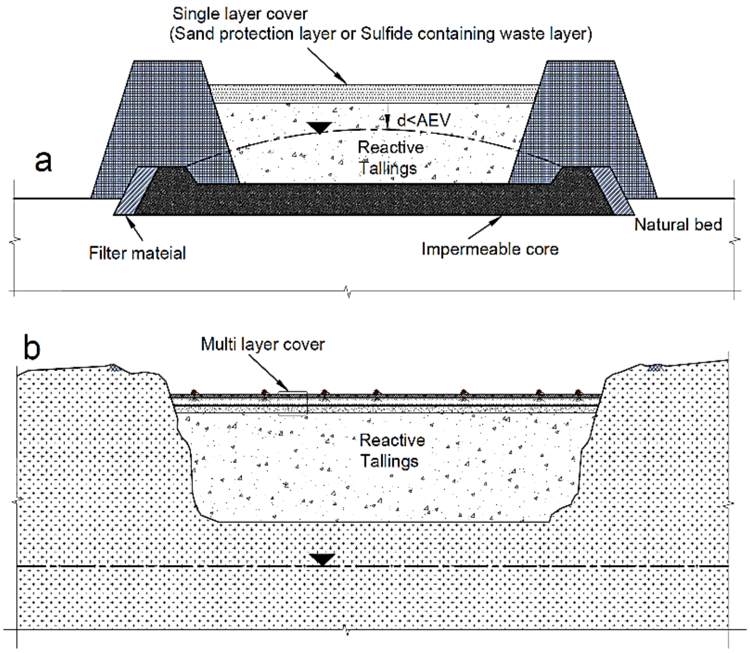


Figure 1. Raised water level cover system (monolayer of sand or monolayer of sulfide-containing tailings) (a) [29], multi-layer cover system (b) (these shapes are not scales and the height of the cover is much lower than the height of the tailings)

tailings/water interface effectively improves the effectiveness of water covers [31, 32]. The erosion of dams due to wind and rain can affect stability and produce environmental problems. Many methods are used to combat this, such as vegetation of the dam banks and chemical stabilization to form an air and water-resistant crust. An ideal soil cover consists of a sufficiently thick soil layer and appropriately regraded slopes that can induce runoff, resist erosion and retain water. The top layer can be vegetated to maximize the evapotranspiration of water to decrease infiltration and resistance to erosion. Furthermore, the presence of plants in the tailings impoundment, especially emergent plants growing at the edges, improves the physical stability of the tailings through their roots. The efficiency of a revegetated soil cover can be further increased by placing a layer of coarse rock beneath the cover to form a capillary break and decrease percolation.

A general rule in the design of multi-layer covering systems with storage-diffusion mechanisms is that the storage layer (moisture retention layer) can store water in wet seasons and release water in dry seasons through evaporation and perspiration to prevent oxygen diffusion and accordingly control AMD production [33]. One of the advantages of this type of cover system is that it can be more successful in dry climates than other cover systems. The basis of multi-layer covering systems is to keep the storage layer near high saturation, in which the oxygen diffusion coefficient is low, consequently reducing the oxidation rate of sulfide minerals and AMD production to a minimum [34].

In another study, Bosse et al. [35] examined the storage and diffusion covering systems made of phosphate limestone tailings in a semiarid climate to control AMD and tested the performance of the covering system at two different states, i.e., thicknesses and critical. According to the results, it was found that the designed cover system has succeeded in storing rainwater in wet seasons and releasing it in dry seasons. It was also found that the geometry of the designed cover is another important factor that should be considered in their design.

One-dimensional modeling has been used to evaluate covering systems so far, and the effect of the oxygen infiltration process and thickness change of the storage layer of a multi-layer covering system in controlling AMD has not been scrutinized to the best of researchers' knowledge.

Therefore, in the current paper, various coating systems suitable for semiarid climates have been examined. Among the available scenarios, using software analysis, the most optimal and most suitable coating system has been selected according to the climatic conditions of the region and the type of tailings from Songun copper mine; in addition, the sensitivity analysis of covering systems to changes in the thickness of the storage layer and the effect of oxygen infiltration on AMD control (Songun copper mine tailings) was evaluated using two-dimensional modeling in several different scenarios. Furthermore, the effect of the arrangement of low and high sulfide materials in the upper and lower parts of the covering system to increase oxygen consumption and improve the system's efficiency has been challenged for the first time. Also, for the first time, a multi-layer capillary barrier covering system containing a fine-grained layer between two coarse-grained layers to control AMD (Songun 2copper mine tailings) was proposed and evaluated. The most important parameter to control the efficiency of coating systems is its ability in terms of the connection of different layers to maintain the storage layer in near-saturation conditions, which controls the diffusion of oxygen and also limits the reach of water to the waste materials and thus minimizes the production of acidic drainage.

Applying numerical modeling, the behavior of these covers in regulating the oxygen-percolating copper tailings was evaluated. Different scenarios were elucidated for modeling, which includes three types of multi-layer cover systems in the order of the layers, and the material of the layers is very important. The comparison of the oxygen diffusion coefficient in the proposed coating systems has been discussed, and according to the graph presented, the oxygen diffusion coefficient in the engineering layer of the capillarity barrier coating system and especially in the storage layer, is much lower than the other two coating systems, which is in good agreement with the other two diagrams.

2. MATERIALS AND METHODS

This research aims to design an optimal coating system to control and reduce acid drainage from mineral waste materials, which is one of the problems of human societies, especially in Iran. Due to the arid and semiarid conditions of the country, where the annual evaporation rate is higher than the annual rainfall in most months of the year, and we are always facing problems in providing a sustainable water source, we must use multi-layer soil cover systems. The main condition for the production of acidic sewage, which causes soil and water pollution downstream and many problems caused by it, is the access of oxygen or water to the waste materials, which during chemical reaction with the waste materials of Boise containing sulfide materials such as pyrite causes the production of acidic sewage, so to control the production of acidic sewage should be prevented from penetration and reaction of these two with waste materials. The key point in the design of these covering systems is to create conditions with the design of different layers so that the water from rainfall in wet seasons is stored in the layers of the covering system, and in hot and rainless seasons, it can keep the storage layer saturated as well as the underlying layer. The storage layer must create a vacuum and negative suction conditions to prevent water seepage from the storage layer so that both the storage layer remains saturated and prevents water from reaching the waste materials. The saturation of the storage layer around 85 % is the condition of preventing oxygen from reaching the waste materials through the diffusion process. The research flowchart for the current study is illustrated in Figure 2. Geomaterial parameters used in modeling are presented in Table 1.

2. 1. Site Description

Northwest Iran has a cold semiarid climate [36]. Songun copper mine is in northwestern Iran in East Azarbaijan, Varzeqan City. It is located in a mountainous area with cold, icy winters and mild summers. The average maximum temperature was recorded at 33 °C in summer and 4 °C below zero in winter. The average annual rainfall is 250 mm, and relative humidity per year ranges from 52 to 82%. The prevailing wind direction is south to west. It is foggy

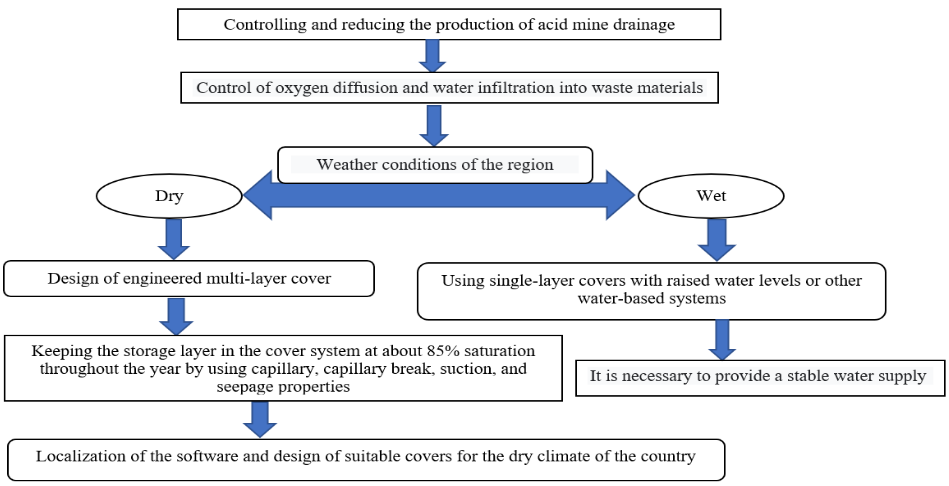


Figure 2. Research flowchart for the current study

TABLE 1. Geomaterial Parameters Used in Modeling

Angel of internal friction(ϕ°)	
Bed Rock	30°
Waste Material with high sulfide	35°
Waste Material with low sulfide	34°
Coarse-Grained Layer	35°
Fine-Grained Layer	37°
Growth Layer	31°
Silty Sand (Storage Layer)	29°
Compacted Layer	43°
Unit weight(ϒ)(KN/m3)	
Bed Rock	26.5
Waste Material with high sulfide	19.5
Waste Material with low sulfide	19.5
Coarse-Grained Layer	19
Fine-Grained Layer	16
Growth Layer	18
Silty Sand (Storage Layer)	17
Compacted Layer	21
Porosity(e) (%)	
Bed Rock	1
Waste Material with high sulfide	40
Waste Material with low sulfide	30
Coarse-Grained Layer	38
Fine-Grained Layer	32
Growth Layer	42
Silty Sand (Storage Layer)	25
Compacted Layer	12
Poisson's ratio(υ)	
Bed Rock	0.1
Waste Material with high sulfide	0.33
Waste Material with low sulfide	0.27
Coarse-Grained Layer	0.22
Fine-Grained Layer	0.17
Growth Layer	0.38
Silty Sand (Storage Layer)	0.25
Compacted Layer	0.19
Young's Modulus (E)(Mpa)	
Bed Rock	65
Waste Material with high sulfide	85
Waste Material with low sulfide	105
Coarse-Grained Layer	45
Fine-Grained Layer	15
Growth Layer	12
Silty Sand (Storage Layer)	22
Compacted Layer	59

around the mine on most days of spring and summer. The highest temperature occurs between July and August, and the lowest is between January and February. According to the statistics related to precipitation and evaporation published by the Meteorological Department of Varzeqan City, the evaporation rate in most months of the year is more than precipitation, so the climate of the mining area is dry. Due to the region's arid climate, the use of monolayer covering to control AMD tailings is not recommended, and the design of multi-layer covering systems is preferred. Due to the sulfide nature of Songun copper mine tailings (presence of pyrite and chalcopyrite at the rate of 1 to 10%) and also the presence of high seasonal rainfall in the area, AMD production is one of the environmental problems of the region. Unfortunately, AMD from the tailings dam of Songun copper mine is discharged into the river, and the negative environmental effects on Arasbaran forests are obvious [37]. pH parameters and sulfate, copper, and manganese amounts are excessive [38]. Hence, to prevent environmental pollution, in addition to installing an acid wastewater treatment system at the output of Songun copper mine, it is essential to use a suitable covering system on tailings to reduce AMD production.

2. 2. Modeling Scenarios According to Figure 3, an uncovered scenario as the baseline scenario (case a) and three scenarios (cases b, c & d) for covering Songun copper mine tailings dam was evaluated so that the thickness of the systems varies depending on the type of system. The storage and diffusion cover system, the upgraded storage and diffusion covering system, and the capillary barrier system are referred to as the first, second, and third scenarios, respectively. In the baseline scenario, the basis of all tailings is high-sulfide. However, in other scenarios, it has been proposed innovatively that the sulfide materials are first accumulated, and then the low sulfide tailings are applied to it. In these scenarios, firstly, the vegetation layer used in the upper part of all cover systems (0.20 m thick) must survive the dry season to maintain its performance with the least delay after the start of the wet season. Secondly, the storage layer below the vegetation layer should be able to store all the annual rainfall that may occur in a relatively short time (wet season).

- Baseline scenario (a), Uncovered condition (to evaluate the performance of tailings in uncovered condition)

- Scenario 1 (b), store and release cover system
- Scenario 2 (c), optimized store and release cover system
- Scenario 3 (d), capillary barrier cover system

Baseline scenario: In this scenario, the cover system is not used, and the natural bed in the area is under the tailings. To assess the most critical situation regarding AMD production, the groundwater level is considered the lowest annual level. Tailings from the mining activities of Songun copper mine are transferred to the tailings dam on the bed layer through pumping pipes. The base state cross section and the specifications of their materials are presented in Figure 3(a).

As shown in Figure 3(b), a section of the storage and diffusion cover system is shown as the first proposed scenario. The key concept of this system is to store water in the storage layer in wet seasons and to release water stored by evapotranspiration in dry seasons. This cover system consists of three layers placed on low-sulfide tailings materials with a thickness of 70 meters (low-sulfide tailings are located on 210 meters of high-sulfide tailings materials). For the lower layer of the cover system, coarse-grained materials with a thickness of 5 m are proposed. For the middle layer, referred to as the store layer, 1.3 m thick layered sand is proposed, designed to break the capillary. The top layer is 0.2 m thick vegetation designed to prevent erosion and dust.

According to Figure 3(c), the second proposed scenario for the cover system was called the "optimized store and release cover system", similar to the first scenario with three layers. Due to the high cost of building the storage layer (middle layer) and also to control the sensitivity, the covering system against changes in the thickness of the storage layer is proposed. In the second proposed scenario, the thickness of the storage layer was reduced from 1.3 m to 0.65 m to investigate and analyze the effect of reducing the thickness of the storage layer on improving the performance and efficiency of the covering system.

As shown in Figure 3(d), the capillary barrier cover system is the third proposed scenario for Songun copper mine tailings with four layers. Songun copper mine has a cold and humid climate in one part of the year and a hot and dry climate in the other part of the year. Therefore, this scenario is designed and proposed exclusively Suitable for the weather conditions of this region. This cover system has effectively maintained the storage layer at a saturation level of nearly 85% throughout the year to prevent the AMD production process. The upper (vegetation) layer is similar to the previous two systems. The third layer of fine-grained material is 0.5 m thick and between two coarse grains layers. The second and fourth layers are composed of coarse-grained materials with a thickness of 0.6 m. The second layer acts as a drainage layer, limiting water reduction in the third layer (moisture retention) through evaporation. The fourth layer, the capillary bier layer, restricts the downward movement of water and prevents desaturation.

In all the proposed scenarios, the groundwater level from the natural bed floor as the base level is considered to be 50 meters, which is the lowest level during the year. If the cover system effectively controls acid drainage for the lowest groundwater level selected (as the most critical condition) in other seasons of the year, it will show successful performance when the groundwater level is higher.

2. 3. Numerical Modeling This study used VADOSE/ W computer code for numerical analysis. This software is a two-dimensional finite element software from the Geo-Studio software e package. The software formulation includes the analysis of simple and complex problems, from the simple analysis of precipitation to complex problems, including snow, plant transpiration, surface evaporation, runoff, and gas diffusion (radon and oxygen) [39] [39] [39]. The finite element grid used has a uniform rectangular mesh. Model geometry was selected in different identical scenarios with different layering. In Figure 4, The geometry covered the storage and release system, and boundary conditions were illustrated. In the VADOSE/W software, four types of boundary conditions are defined, which include the weather boundary conditions obtained from the study area, a zero percent oxygen, seepage, groundwater flow, and climate boundary condition has been applied.

2. 3. 1. Applied Equations The VADOSE / W computer program has coupled heat and water transfer to simulate the flow of water, heat, and steam through saturated and unsaturated soils. Oxygen transfer depends on the degree of saturation in the storage layer; However, it does not calculate the flow of water and heat; thus, the oxygen flow is simulated separately. The characteristics of the equations applied for water flow and heat transfer are expressed using Equations (1) and (2) [40, 41].

$$\frac{1}{\rho}\frac{\partial}{\partial x}\left[D_v\frac{\partial P_v}{\partial x}\right]+\frac{1}{\rho}\frac{\partial}{\partial y}\left[D_v\frac{\partial P_v}{\partial y}\right]+\frac{\partial}{\partial x}\left[k_x\frac{\partial\left[\frac{P}{\rho g}+y\right]}{\partial x}\right]+\frac{\partial}{\partial y}\left[k_y\frac{\partial\left[\frac{P}{\rho g}+y\right]}{\partial y}\right]+Q=\lambda\frac{\partial P}{\partial t} \tag{1}$$

$$L_v\frac{\partial}{\partial x}\left[D_v\frac{\partial P_v}{\partial x}\right]+L_v\frac{\partial}{\partial y}\left[D_v\frac{\partial P_v}{\partial y}\right]+\frac{\partial}{\partial x}\left[K_{tx}\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{ty}\frac{\partial T}{\partial y}\right]+Q_t+c_P v_x\frac{\partial T}{\partial x}+c_P v_y\frac{\partial T}{\partial y}=\lambda_t\frac{\partial T}{\partial t} \tag{2}$$

where P pressure, P_v soil moisture vapor pressure, mv slope function of volumetric water content, k_x and k_y applied hydraulic conductivity in x and y directions, Q applied boundary flow, D_v vapor diffusion coefficient, y elevation head, ρ specific mass of water, g gravity, t time, L_v latent heat of vaporization, K_{tx} and K_{ty} values of thermal conductivity in x and y direction, T temperature,

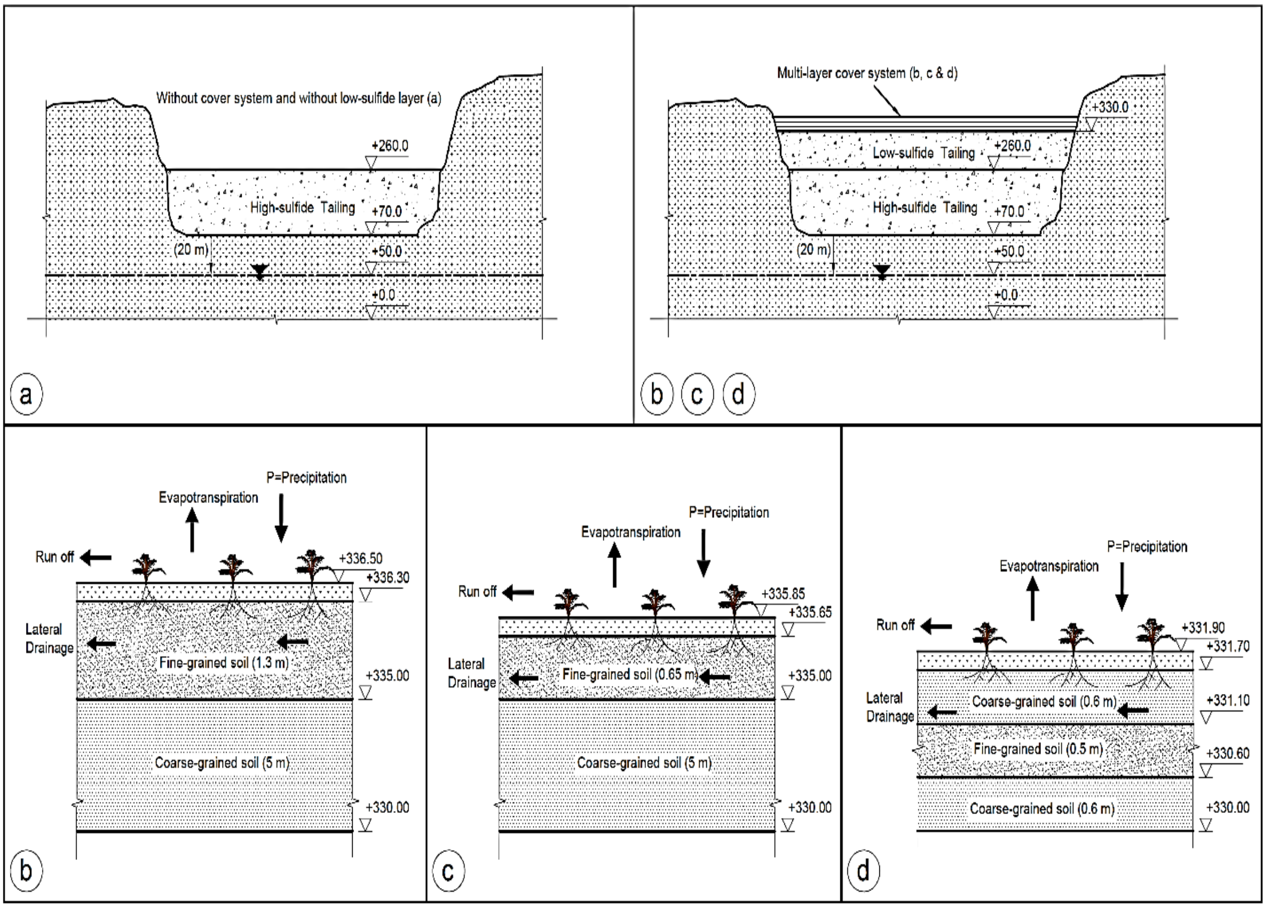


Figure 3. Baseline or exposed Scenario (a), depository and diffusion top scheme (b), upgraded depository and spread cover system (c) blood flow pathway bar, rear top structure (d)

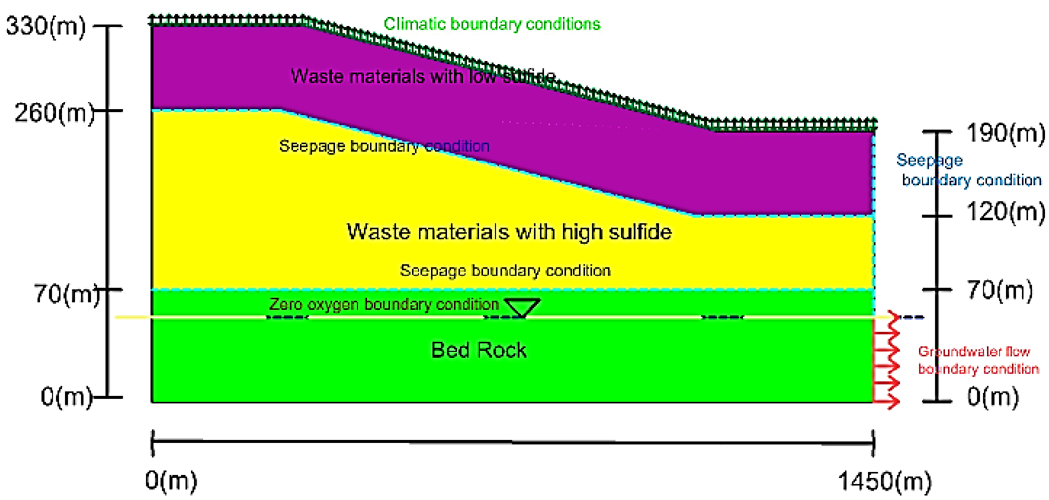


Figure 4. The geometry Covered the storage and release system and Boundary conditions

Qt boundary flow of temperature applied, C_p specific volumetric heat, λ_t apparent volumetric heat capacity of soil and v_x and v_y are the Darcy velocities in the *x* and *y* directions. The vapor pressure is obtained from Equation (3):

$$\boldsymbol{P_v = P_{vs}\left(e^{\frac{-P.w}{\rho.R.T}}\right) = P_{vs}h_{r_{air}}} \tag{3}$$

P_{vs} is the pressure of saturated vapor for pure free water, *w* is the molecular mass of water vapor, *R* is the universal constant coefficient of gases, *T* is the temperature in Kelvin, and h_{rair} is the relative humidity of the air. Actual evaporation is calculated using the Batman-Wilson method (Equation (4)) in which *E* is the actual evaporation (mm/day), Γ is the slope of the vapor pressure saturation temperature curve at average air temperature (kPa / oC), *Q* is the net radiant energy at the surface (mm/day), *v* is a constant psychometric coefficient, *Ea = f (u) Pa (B-A), f (u) = 0.35 (1 + 0.15Ua), Ua* wind speed (km/h), *Pa* steam pressure in the air the evaporation level (kPa), *B* is the inverse of the relative humidity of the air, and *A* is the inverse of the relative humidity of the soil surface [42, 43].

$$\boldsymbol{AE = \frac{\Gamma Q + vE_a}{vA + \Gamma}} \tag{4}$$

In the software, Equations (1) to (4) are solved simultaneously by the finite element method to obtain the actual evaporation rate (*E*), vapor pressure (*Pv*), water pressure (*P*), and temperature (*T*). The primary method of gas transfer in a porous environment is molecular diffusion or adduction through the cavity space. In a porous environment, oxygen is transported through small air-filled cavities at lower saturation levels due to the low diffusion coefficient of oxygen in the water. According to research, oxygen is transported in a porous environment primarily through diffusion, as saturation increases through both the aqueous and gaseous phases [44-53].

For one-dimensional molecular diffusion in an unsaturated porous environment that consumes oxygen at a first-order rate, the instantaneous oxygen flow and oxygen concentration at location *z* and time *t* are determined using Fick's first and second laws (Equations (5) and (6)) [46].

$$\boldsymbol{F(z,t) = -D_e\frac{\partial(z,t)}{\partial z}} \tag{5}$$

$$\boldsymbol{\frac{\partial(\theta_{eff}C)}{\partial t} = \frac{\partial}{\partial y}\left(D_{eff}\frac{\partial C}{\partial y}\right) - k_vC} \tag{6}$$

In these equations, *C* is the concentration of oxygen in the pore air (in terms of mass per unit volume), θ_{eff} is the equivalent porosity for diffusion defined as $\theta_a + H\theta_w$, θ_a is the volumetric content of air, θw is the volumetric content of water, *H* is the Henry equilibrium constant, D_{eff} is the effective diffusion coefficient (m^2/ s), and *kr* are effective reaction rate coefficient (1/ year).

2. 3. 2. Initial and Boundary Conditions To describe the scenarios in VADOSE/W software, five types of boundary conditions have been used, including the boundary condition of meteorological data type, the boundary condition of oxygen concentration 280 g/m^3 (normal concentration of oxygen in the air) on top of the cover system, the boundary condition of water level and zero oxygen concentration at the bottom of the covering system and the boundary condition of seepage from the side of the waste material. Prerequisites for nodes include pressure, temperature, and initial concentration of oxygen gas. For the initial pressure conditions, temperature, and oxygen gas concentration, the water level, the temperature of the first day, and the initial concentration of zero were used, respectively.

2. 3. 3. Data Input to the Software To run the VADOSE/W program, meteorological and vegetation data, soil characteristics, including soil moisture characteristic curve, unsaturated hydraulic conduction function, and thermal conductivity, were entered into the software. Thermal specifications for materials are presented in Table 2. The decay coefficient was also required for the materials modeled in the simulation of oxygen gas flow. In the current study, according to Table 3, part of the measured meteorological data of Songun mine is presented, and the whole data was entered into the software (in Table 3, the first day of the solar calendar corresponds to March 21 in the Gregorian calendar). Vegetation of grass enjoying excellent quality was used. Vegetation data required to enter the software include leaf area index (LAI), plant moisture limit function (PML), root depth, and length of the growth period. Diagrams of unsaturated hydraulic conductivity curves and moisture characteristics are presented in Figure 5.

Given that the "optimized store and release cover system" is a particular condition of the "store and release cover system"; Therefore, the material is the same, and as a result, the unsaturated hydraulic conductivity curves and the moisture characteristic are the same for both cover systems.

Specific heat capacity parameters, including mass and soil thermal conductivity (parameters describing heat

TABLE 2. Thermal specifications for materials (Geo-Studio, 2012)

Thermal conductivity (KJ/days/m/°C)	Volumetric heat capacity (KJ/m³/°C)
150	2500
125	2300

TABLE 3. Meteorological data used in the Vados/W software

Day	Temp (°C)		RH (%)		Wind (m/s)	Precip (mm)	Evpo (mm)
	Max	Min	Max	Min			
1	4.8	-3	98	43	31	0.00	0.0
2	6	-5.3	92	43	32	0.00	0.0
3	1.9	-1	98	84	25	0.00	0.0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
153	27.2	9.6	87	33	24	8.30	6.9
154	29.1	12.3	89	32	26	6.40	9.0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
270	6.2	-9.9	72	42	31	6.60	0.0
271	9.6	-2.7	86	34	34	11.80	0.0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
364	2.4	-1.6	98	73	31	0.00	0.0
365	10.3	-7.1	96	18	24	0.00	0.0

transfer in soil) used in the software, are presented in Table 1. Water content and soil thermal behavior can affect each other because unsaturated soils contain air, water, and solid particles, whereas air and water have different thermal behavior. The material of cover depends on the type of cover system and is selected according to local conditions, including the availability of materials and weather conditions. Also, based on Figure 6, the average percentage of air humidity (a), evaporation (b), rainfall (c), and temperature (d) for each of the 12 months in the period 2009 to 2017 and the average annual rainfall (e) as input information to the software is provided.

3. SIMULATION RESULTS AND DISCUSSION

This section presents the results of two-dimensional numerical modeling, including saturation degree diagrams, oxygen concentration diagrams, and diffusion

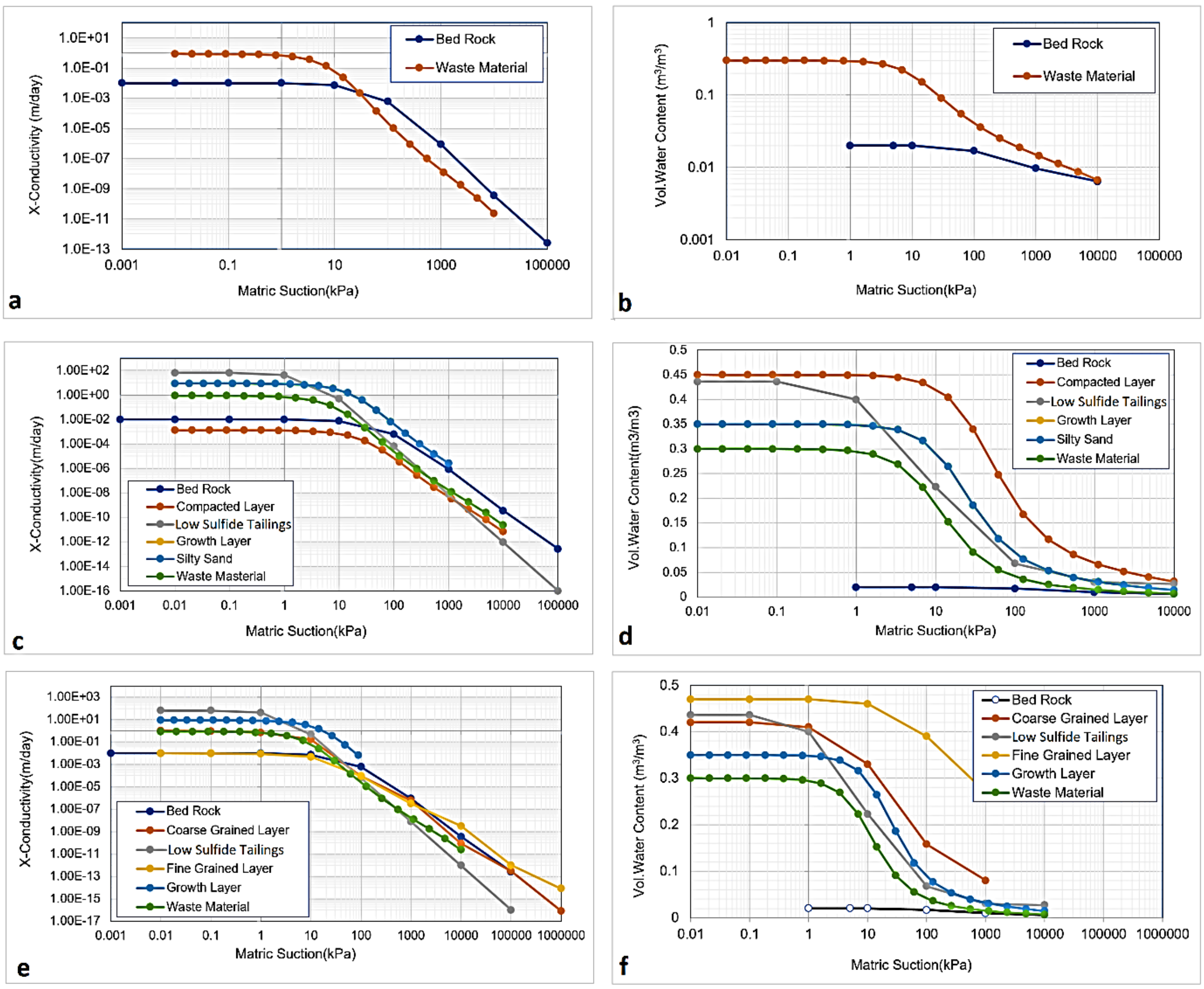


Figure 5. Unsaturated hydraulic conductivity curve and characteristic moisture curve for tailings (a, b for uncovered condition), (c, d for store and release cover system as well as optimized store and release cover system), and (e, f for barrier Capillary cover system)

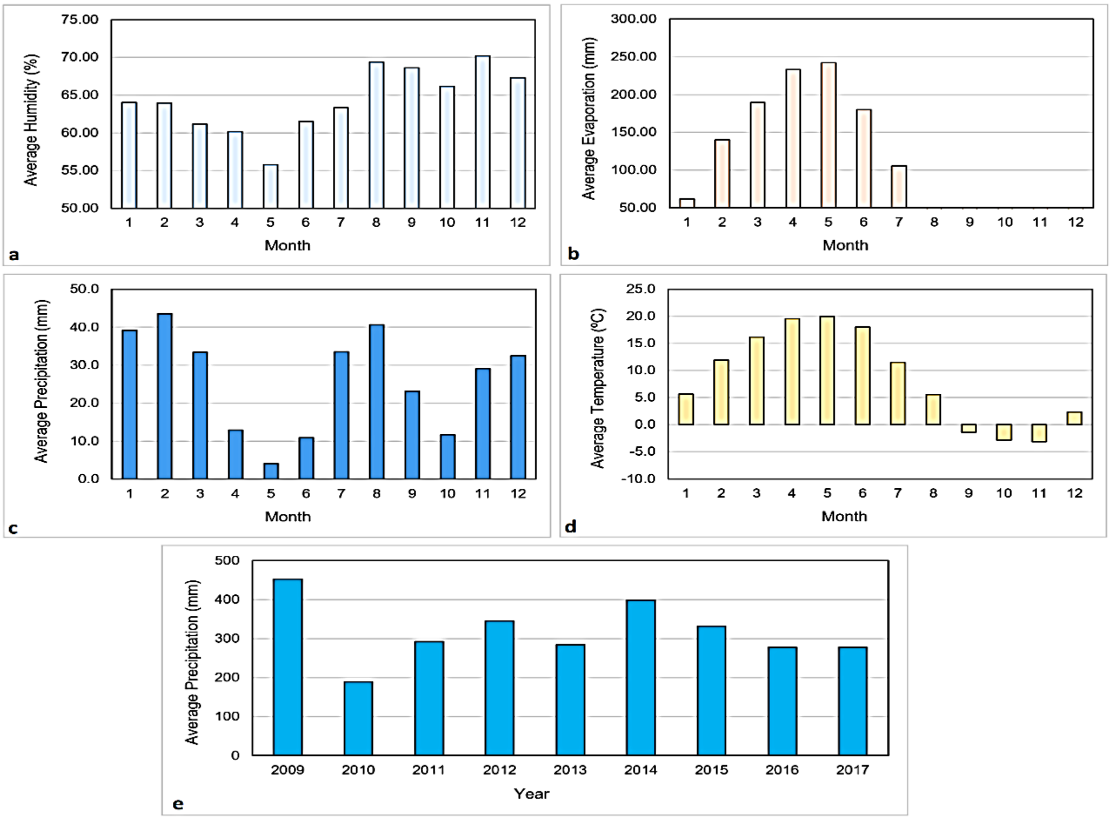


Figure 6. The average percentage of humidity (a), evaporation (b), precipitation (c), and temperature (d) for each of the 12 months from 2009 to 2017 and average annual rainfall (e)

coefficient diagrams for different scenarios. Also, in the second scenario, the effect of lowering the thickness of the store layer of the sulfide-containing multi-layer cover system on the oxygen permeation process and the control of AMD of tailings dams is discussed. Graphs of saturation degree, oxygen concentration, and oxygen diffusion coefficient are presented for the base scenario (without cover) and the three scenarios (first to third) according to Figures 7, 8, and 9, respectively. In the analysis of the following graphs, especially concentration graphs, analysis of changes at the reference level was performed. The reference surface is the same as the upper level of the accumulated tailings with high sulfide content, which is 260 meters high, and the reduction of oxygen concentration at this level is very important, and the base surface is the lower surface of the bedrock. In this study, it has also been suggested that in all cover systems, materials with higher sulfide content can initially be accumulated. Then materials with lower sulfide content be placed on high-sulfide materials to create a naturally oxygen-consuming cover system. In this case, some oxygen penetrates this layer, so AMD production is lessened. However, if multi-layered engineering cover systems are not used and single-layer cover systems are preferred, the performance will not be successful since these systems are effective in a humid environment. Considering the climatic conditions of Songun copper mine, which is hot and dry for most of the year, multi-layered engineering cover systems should be used instead.

3. 1. Baseline Scenario (No Cover Mode) Based on the results of software analysis according to the diagram in Figure 7(a), in the baseline scenario, the saturation degree was about 20%, and only in the part of the year where the rainfall is high the saturation degree goes to about 40%, which is much less than the permitted limit (about 85%). Based on the saturation degree diagram, we realize that the uncovered tailings cannot retain moisture throughout the year, and the need to design an efficient cover system stands out. Based on the obtained results, according to the diagram of Figure 8(a), the oxygen concentration at the reference level was estimated to be about 91%. Therefore, this scenario has a high potential for the production of acid drainage due to the high penetration of oxygen. Also, according to the diagram in Figure 9(a), the oxygen diffusion coefficient is about 0.23, and only at the end of the year, due to the consumption of oxygen by tailings during the year, the amount of oxygen diffusion coefficient has decreased slightly that is practically ineffective since abundant oxygen is provided to the tailings throughout the year. At a depth of 50 meters from the base surface (equal to the groundwater level), the oxygen diffusion coefficient reached zero due to the presence of water and its effect on oxygen penetration. According to the above results, the performance of the baseline scenario in terms of control of diffusion and saturation factors and oxygen concentration was unsuccessful, so using a cover system to control the production of AMD is necessary.

3. 2. Scenario 1 (Store and Release Cover System) According to the diagram in Figure 7(b) in the first scenario, the degree of saturation in the store layer (335 m depth range) was less than 85%, indicating that using this system to keep the store layer close to saturation is unsuccessful. According to the diagram in Figure 8b, the oxygen concentration at the reference surface was about zero, indicating the proposed design's success in placing low-sulfide tailings on high-sulfide tailings. The diagrams also depicted that the layer containing low-sulfide tailings is crucial in reducing oxygen concentration at the reference level. The performance of the designed cover system depends on the performance of the store layer, but the performance of the designed cover system should be evaluated by examining the oxygen diffusion coefficient for the store layer throughout the year. According to the diagram in Figure 9b, the oxygen diffusion coefficient in the cover system varies between 0.08 to 0.40 (m^2/day), which is insufficient to control oxygen diffusion and AMD production.

3. 3. Scenario 2 (Optimized Store and Release Cover System) This scenario was designed to analyze the performance sensitivity of the cover system to modification of the thickness of the storage layer and to notice how the efficiency of the cover system changes with this modification.

Here, according to the diagram in Figure 7(c), the degree of saturation in the store layer (depth range 335 meters) was much less than 85%, and therefore, this cover system could not keep the store layer saturated and reduce layer thickness. Reduction of the store layer has slightly reduced the saturation degree of this layer, but it was found that the thickness of the storage layer is not the main factor in controlling the saturation degree of this layer, and the efficiency did not improve; therefore, we must design a system that is both economical and efficient. In the second scenario, the amount of evapotranspiration is also lower due to the lower water store (less thickness of the store layer). The evapotranspiration rate in a cover system depends on the plant root depth, root distribution, and negative pore water pressure (suction). The root depth and distribution are the same for both proposed scenarios, but the amount of suction varies depending on the amount of water in the storage layer. According to Figure 8(c), the oxygen concentration at the reference level is about zero, similar to the previous case. As a result, the performance of this cover system is desirable because our goal is to consume oxygen in low-sulfide materials to reduce and control the production of AMD. According to Figure 9(c), the diffusion coefficient for the cover system varies between 0.08 and 0.43 (m^2/day). Despite the reduction of the thickness of the storage layer in this scenario, the oxygen diffusion coefficient does not change much compared to the previous scenario, which is completely consistent with the results of the previous diagrams.

3. 4. Scenario 3 (Capillary Barrier Cover System) In this scenario, according to the diagram in Figure 7(d), the degree of saturation for the store layer (depth range of 330 meters) is about 80% (around 85% is desirable). Due to the region's arid climate in most seasons, the cover system of this scenario has been more successful than previous scenarios in keeping the store layer saturated. Here, due to the high degree of saturation of the store layer, almost no oxidation takes place, so AMD production is minimized. According to the diagram in Figure 8(d), oxygen concentration at the reference level is similar to previous cover systems at about zero, indicating that the factor controlling the oxygen concentration of tailings is low-sulfide. As shown in Figure 9(d), the value of the oxygen diffusion coefficient in the capillary barrier cover system varies between 0 and 0.39 (m^2/day). This cover system has reduced the oxygen diffusion coefficient from 0.39 to zero stepwise. The system's efficiency in regulation and reduction of oxygen coefficient will be well shown in the following diagrams. In addition, the success of this system in regulating all three parameters and comparing its performance with other systems indicates the significance of layering and type of cover systems.

3. 5. Comparison of Cover Systems at Store Layer As depicted in Figure 10, graphs of saturation degree, oxygen concentration, and oxygen diffusion coefficient in the store layer are presented for comparison with the three proposed scenarios (cover systems). According to Figure 10a, the optimal performance of the capillary barrier cover system in maintaining the store layer in the near-saturation state is quite evident. As shown in Figure 10b, the use of the store layer in all scenarios has decreased oxygen concentration infiltration, but the capillary barrier cover system prevents this reduction in steps. The gradual reduction in this system is due to the high degree of saturation in the store layer, which causes the connection of oxygen with the materials under the store layer to be largely cut off and, in turn, leads to better performance in regulating oxygen penetration. However, as explicated in the diagrams, low-sulfide tailings are the

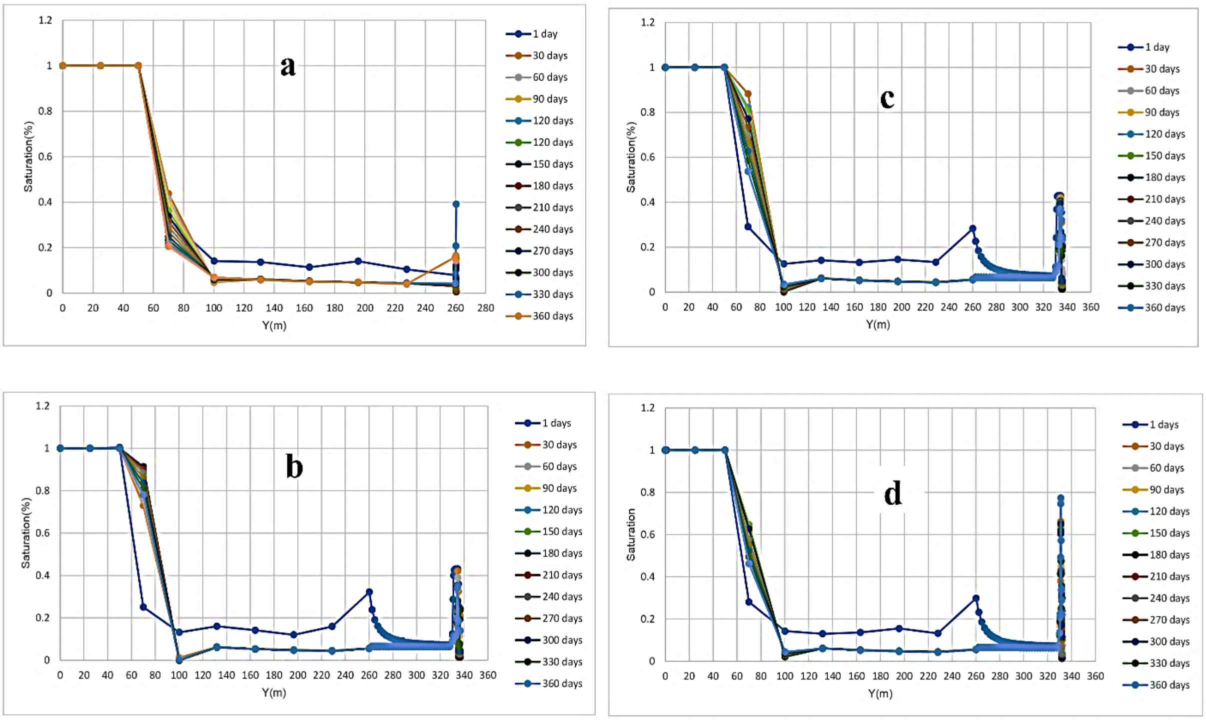


Figure 7. Saturation degree diagrams for the uncovered (a), store and release cover system (b), optimized store and release cover system (c), and capillary barrier cover system (d)

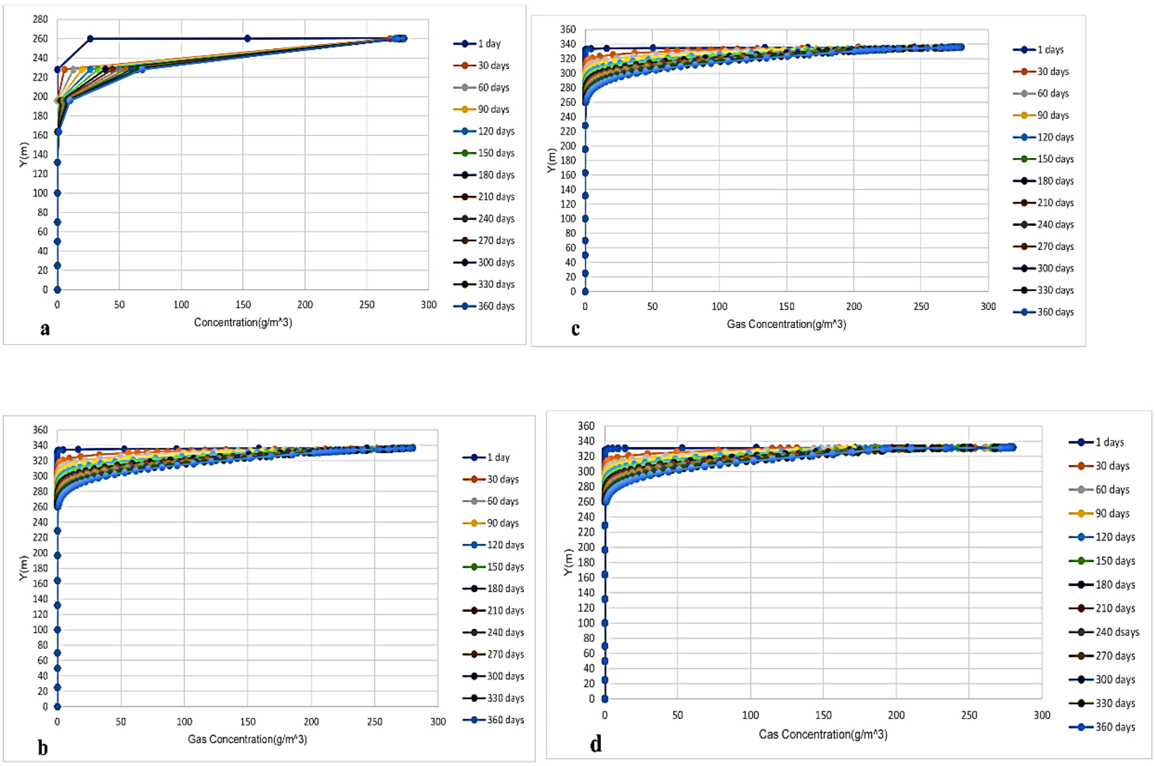


Figure 8. Oxygen concentration diagrams for the uncovered position (a), store and release cover system (b), optimized store and release cover system (c), and capillary barrier cover system (d)

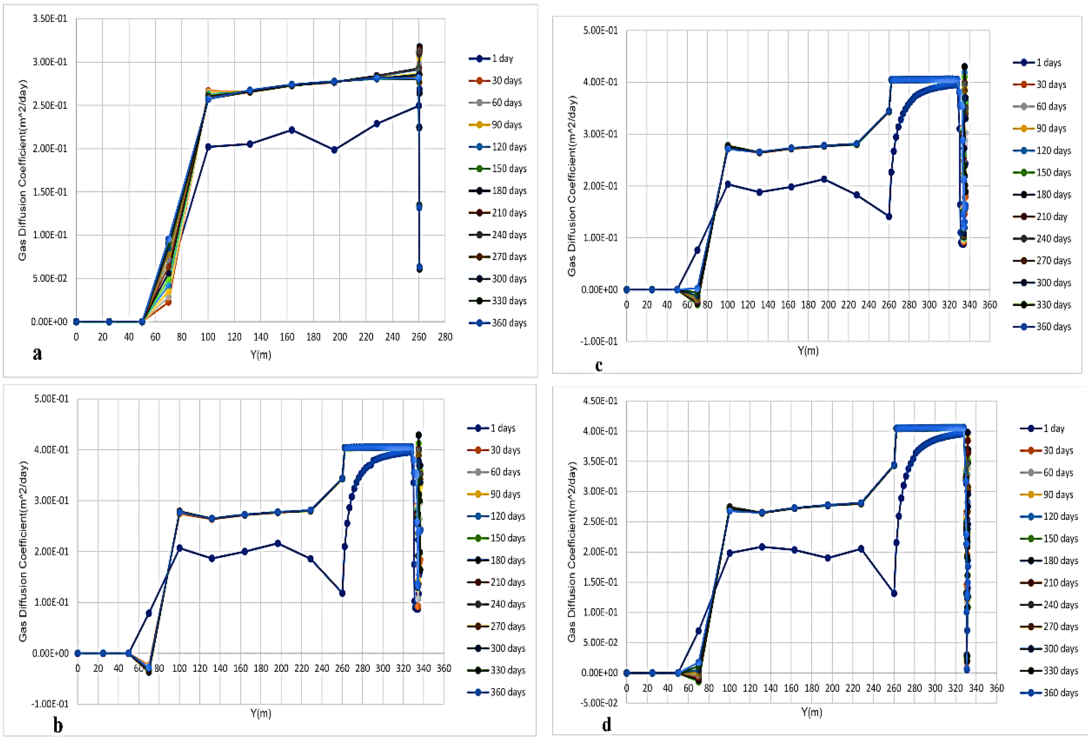


Figure 9. Oxygen diffusion coefficient diagrams for uncovered (a), store and release cover system (b), optimized store and release cover system (c), and capillary barrier cover system (d)

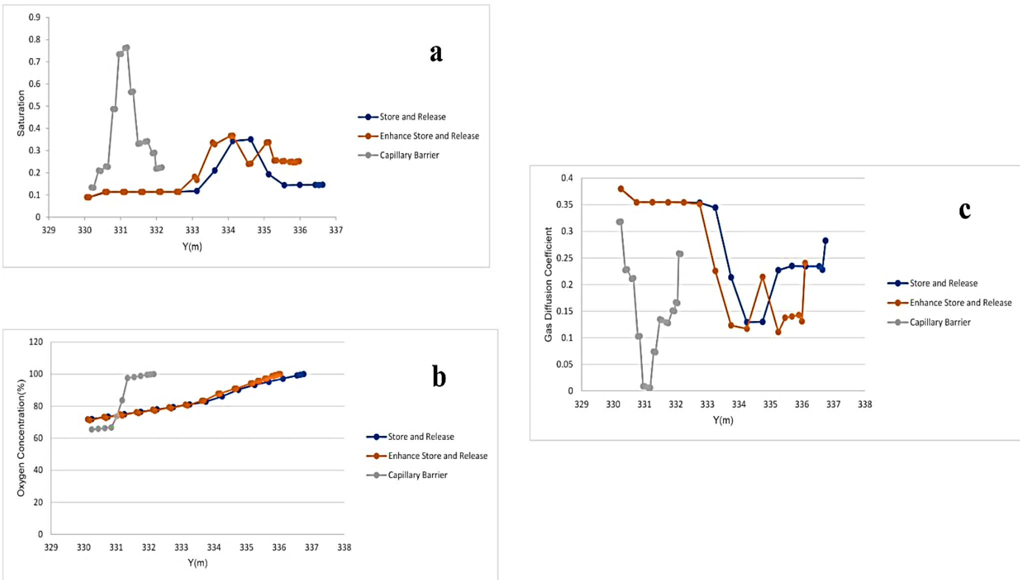


Figure 10. Graphs of saturation degree (a), oxygen concentration (b), and oxygen diffusion coefficient (c) of the store layer in three different cover systems

most important factor in regulating oxygen concentration. According to the diagram in Figure 10c, the oxygen diffusion coefficient for the capillary barrier system is close to zero due to the high degree of saturation of the storage layer and the complementary performance of the different layers in this system. In comparison with other scenarios, the oxygen diffusion coefficient in the store layer is about (m^2/day) 0.12, reflecting the superiority of the capillary barrier cover system.

4. CONCLUSION

In the current study, using VADOSE / W software, the behavior of the multi-layer cover system in regulating the penetration of oxygen gas was evaluated. Four scenarios were defined for modeling: store and release, optimized store and release, capillary barrier, and uncovered cover systems. The most significant results obtained are as follows:

1. Saturation graphs were used to predict the potentiality of oxygen diffusion into the tailings. In-store and release cover systems and optimized ones, the expected saturation in the storage layer is not achieved, while the capillary barrier has a high ability to keep the store layer close to saturation.
2. In this study, the lowest possible water level during the year is considered the most critical condition to evaluate the performance of each of the proposed cover systems in preventing the oxidation process (in the most critical conditions).
3. In the designed cover systems, the main factor controlling oxygen penetration into the tailings is the granulation of the cover system materials, the high degree of saturation in the storage layer, and the cover system layering.
4. In all cover systems, it is recommended that tailings with lower sulfide content be stored on tailings with higher sulfide content. This creates a situation in which low-sulfide materials act as an oxygen-consuming system, reducing oxygen infiltration into the higher-sulfide materials and thus limiting AMD production.
5. The capillary barrier cover system was particularly designed and evaluated for the arid climate of Songun mine area (and applicable to similar conditions). According to the results, this cover system can maintain the store layer in a state close to saturation of 85%, so the diffusion coefficient of near zero was obtained in the storage layer.
6. In the proposed cover systems, by considering different layers, an attempt was made to keep the store layer close to the saturation level above 85%. The modeling results revealed that with increasing degree of saturation, oxygen penetration depth, and oxygen diffusion in the engineered cover system drop.
7. Only capillary barrier cover system with suitable performance for use on the tailings dam of Songun copper mine limits the production of AMD and its environmental consequences and, in the long run, significantly reduces AMD production. In addition, considering that the cover system is implemented after completing the capacity of tailings dams, it is necessary to take measures to improve the performance despite the proper functioning of the capillary barrier system. AMD may be prevented from infiltrating into waste rock and groundwater by employing impermeable layers such as geosynthetics in the subsoil of tailings. Additionally, AMD produced can be collected and treated in isolated pools by implementing drains. This will minimize the possibility of environmental damage.

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Persian Abstract

چکیده

در صنعت معدن، سیستم های پوششی برای باطله ها وسیله ای موثر برای کاهش زهکشی اسید معدن است. سیستم های پوششی چند لایه در آب و هوای خشک که میزان تبخیر سالانه بیشتر از بارندگی سالانه است کارآمد هستند. تحقیق حاضر مناسب برای کاربران و طراحان سدهای باطله معدن میباشد که با هدف شناسایی سیستم پوششی بهینه برای سدهای باطله معدنی و همچنین بررسی پارامترهای ژئوتکنیکی موثر در کنترل گاز اکسیژن ورودی به محل دفع باطله های معدنی جهت کاهش و مدیریت تولید زهاب اسیدی انجام شده است. در این تحقیق پس از بررسی دقیق متون علمی و گردآوری داده ها، ابتدا کارایی و صحت نتایج نرم افزار با استفاده از مدلسازی عددی به روش المان محدود (FEM) در نرم افزار VADOSE/W اعتبارسنجی شده و سپس بر اساس داده های جمع آوری شده مدلسازی صورت می گیرد. در مطالعات پیشین در ارزیابی سیستم های پوششی اغلب از مدل سازی یک بعدی استفاده شده است، اما در این تحقیق کارایی سیستم های پوششی با استفاده از مدلسازی دو بعدی مورد ارزیابی قرار گرفته شده است. نکته کلیدی جهت عملکرد موفقیت آمیز سیستم های پوششی، حفظ لایه ذخیره سازی در سطح اشباع حدود ۸۵ درصد در طول سال است. دو سیستم پوششی «ذخیره و رهاسازی» و «ذخیره سازی و رهاسازی بهینه» در حفظ لایه ذخیره سازی در حدود ۸۵ درصد اشباع ناموفق عمل کرده اند،در حالیکه، سیستم پوششی مانع موئینگی عملکرد موفقیت آمیزی داشته و قادر بوده است که لایه ذخیره را در تمام طول سال در درجه اشباعی در حدود ۸۰٪ نگه دارد. با توجه به استفاده از مواد ضایعات کم سولفید به عنوان یک لایه مصرف کننده اکسیژن، عملکرد هر سه سیستم پوششی در کنترل دسترسی و نفوذ اکسیژن به باطله های پرسولفید قابل قبول بوده نشاندهنده کارایی این ایده منحصربفرد میباشد، البته شایان ذکر است که سیستم پوشش مانع موبینگی به دلیل اشباع بالای لایه ذخیره‌سازی توانسته است بلافاصله دیفیوژن اکسیژن را بصورت پلکانی کاهش دهد، در حالی که در دو سیستم پوششی دیگر این کاهش در دیفیوژن و غلظت اکسیژن را بصورت تدریجی ایجاد کرده اند، بنابراین سیستم پوشش سد مویرگی با توجه به شرایط آب و هوایی و نوع مواد زائد به عنوان بهینه ترین سیستم پوششی در منطقه مورد مطالعه پیشنهاد می شود.