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Review on the Application Research of Covers with Capillary Barrier Effects

Qiuling Xiong, Lu Zhang*, Ailing Xun, Jianghong Du

College of Construction Engineering, Jilin University, Changchun 130026, China
**Correspondence Author, lu_zhang@jlu.edu.cn*

Abstract: ***The capillary barrier effects arise from the difference in hydraulic properties of unsaturated coarse and fine grain layers. Covers with capillary barrier effects (CCBE) can effectively prevent seepage, oxygen infiltration, and capillary rise. This paper provides an overview of CCBE applications in landfills, tailings ponds, slope protection, nuclear waste disposal, roadbed treatment, and other fields. Furthermore, it compares the similarities and differences of CCBE in different fields. Finally, this paper comprehensively discusses the factors affecting the performance of CCBE including their structural design, material properties, climatic conditions, geological characteristics as well as vegetation cover. It offers a more comprehensive knowledge system for engineers and researchers in related fields, serving as a foundation for the further expansion of CCBE.***

Keywords: Capillary barrier, Landfills, Infiltration, Acid mine drainage, Slope stability, Unsaturated water flow.

1. Introduction

Covers are often used to contain all kinds of wastes to prevent them from polluting the surrounding environment. Traditional cover systems typically include soil covers, compacted clay covers, and geosynthetic liners. However, these conventional cover layers often face challenges such as soil desiccation, cracking, and geomembrane ruptures due to factors like climatic conditions, which may hinder their long-term effectiveness in waste containment projects (Morris & Stormont, 1997). However, the use of covers with capillary barrier effects (CCBE) has attracted people's attention.

In the early days, scholars mainly applied the CCBE to the landfill capping for solid and radioactive waste, so as to minimize rainfall or surface water entering the waste to form leachate and pollute the groundwater and surrounding environment (Wing & Gee, 1994). Nyhan et al. (1997) compared landfill designs with and without CCBE using the principle of water balance. Their findings demonstrated that incorporating CCBE significantly reduced leakage. Recognizing that salt-contaminated soil serves as a persistent pollution source for surface and groundwater, Rooney et al. (1998) investigated the impact of capillary barriers on water and salt migration. They discovered that capillary barriers effectively controlled both upward and downward salt migration, facilitated normal vegetation growth, and mitigated groundwater contamination. Similarly, Rahardjo et al. (2004) explored the potential of capillary barriers to prevent rainfall-induced landslides. Through slope testing and numerical simulations, they concluded that the CCBE is an effective solution for enhancing slope stability. Molson et al. (2004) used MIN3P finite volume model to simulate the evolution process of acid mine drainage (AMD) in mine active waste. The simulation results were consistent with the actual measurement data, which verified the effectiveness of CCBE in preventing sulfide oxidation and AMD generation. Anne-Marie et al. (2005) investigated the method of evaluating the efficiency of CCBE and the practical application of the CCBE at LTA mine site, Lorraine mine site, Goldstrike mine site, and other mine sites. In agriculture, Ityel et al. (2011) investigated the effect of the capillary barrier on root conditions of horticultural crops and found that the capillary barrier increased the water content in the root zone and improved the water utilization efficiency of the plant. At the same time, this approach reduced the utilization of water and fertilizer and then reduced the pollution below the root zone. Facing the problem of subgrade instability and even uneven settlement caused by rainfall infiltration, Yan et al. (2018) conducted a study on the application of CCBE in the loess subgrade. The results showed that CCBE can reduce water movement, reduce capillary water rise as well as rainfall infiltration, ensure the stability of the subgrade, and reduce the occurrence of uneven settlement. In order to improve the stability of fine-grained soil retaining walls, Y. Chen et al. (2020) put forward a new backfilled retaining wall using the basic principle of capillary barrier to reduce rainfall infiltration and analyzed the effectiveness of this water retention system using the finite element method.

From the above, it can be seen that the CCBE has been applied to the design of impermeable cover of landfills (G. Li et al., 2022), the design of covers for nuclear waste repositories (Qian et al., 2010), the control of water and salt migration, the treatment of slope instability caused by rainfall (Tami et al., 2004), the study of oxygen barrier of acid tailings ponds (Borghetti Soares et al., 2009), the utilization of water resources in crop root zone, the control of uneven settlement of subgrade, and the construction of fine-grained soil retaining wall. Although the CCBE has achieved good results in these fields, the application information related to capillary barrier covers is generally scattered. Recent research findings have not been systematically reviewed, making it difficult and time-consuming to retrieve relevant information, which poses a significant challenge for researchers who seek a comprehensive understanding of CCBE.

Therefore, the purpose of this article is to summarize the current research status of CCBE in various fields at home and abroad, analyze the influence of different factors on CCBE, and discuss the current problems and challenges of CCBE. This will provide a reference for researchers in related fields to solve engineering problems in designing CCBE and also provide a direction for the application of CCBE in more fields.

2. Basic Properties of CCBE

2.1 Mechanism of CCBE

When the fine-grained soil is covered with coarse-grained soil (Figure 1a), due to the obvious differences in the properties and structures of the two soil layers, there will be a capillary barrier effect occurs at the interface between the two (Abdolahzadeh et al., 2011; Solanki et al., 2016; Stormont & Anderson, 1999). When the infiltrated water reaches the interface between the two soil layers, the capillary force at the interface will restrict the downward flow of water, and the water is mainly stored in the fine-grained layer (Figure 1b) (Mancarella & Simeone, 2012).

In arid and semi-arid areas, soil is often unsaturated because of more evaporation and less rainfall. According to the theory of unsaturated soil mechanical seepage, there is a great difference between the unsaturated hydraulic conductivity of coarse-grained and fine-grained soils. It can be seen from Figure 1c that there is an intersection point in the hydraulic conductivity curve of the two soil layers, and the hydraulic conductivity of the two soil layers is equal at this point. Before this point, the soil moisture content is high, approaching saturation, with low matrix suction. The hydraulic conductivity of the coarse-grained layer is larger than that of the fine-grained layer.

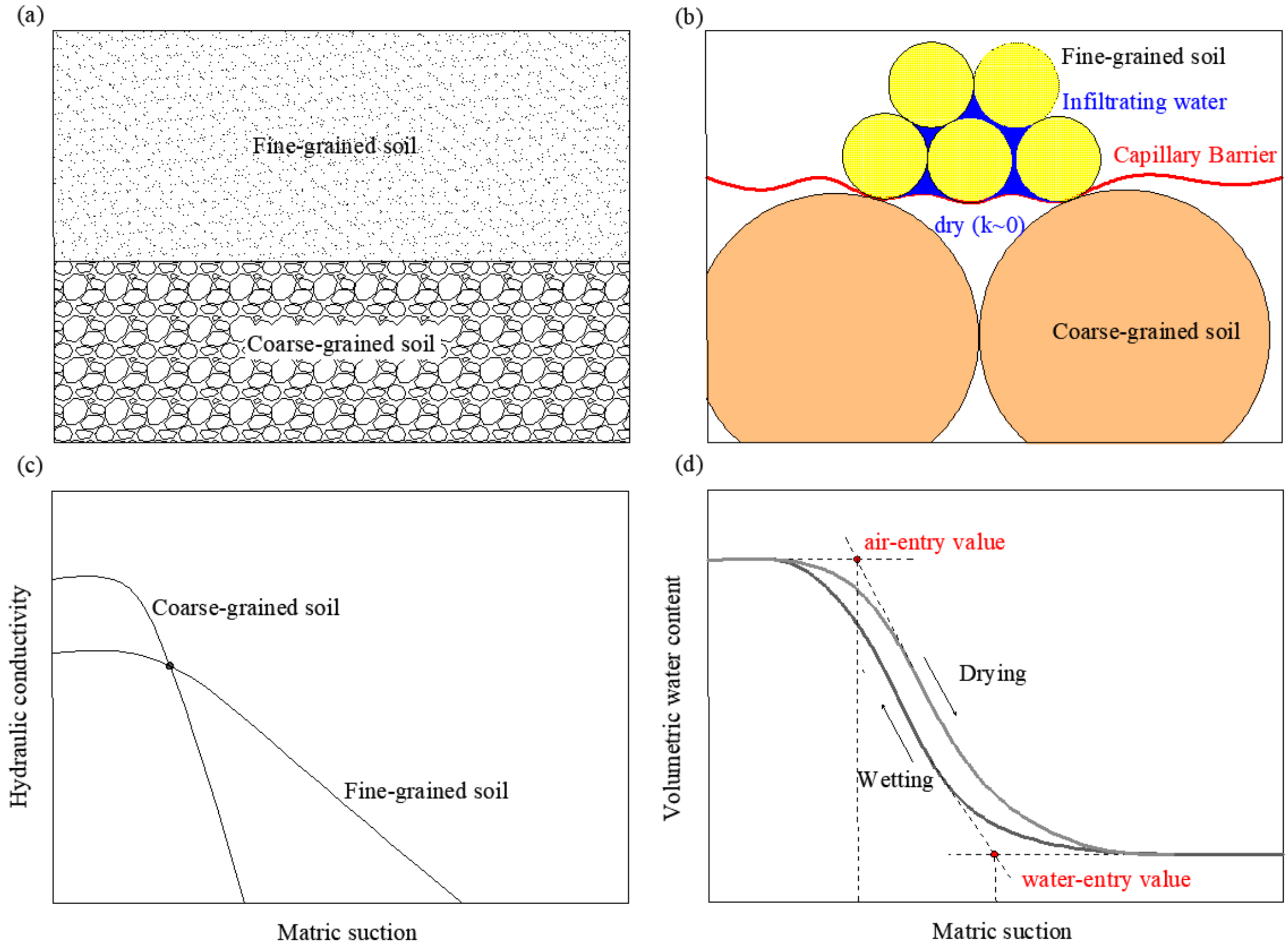

Figure 1: (a) Basic structure of the capillary barrier; (b) Capillary barrier at the interface between soils with different conductivity; (c) Hydraulic conductivity of coarse-and fine-grained soils in capillary barrier structures; (d) Soil-water characteristic curve for coarse grains

After this point, the soil moisture content decreases, entering a dry state, and the matrix suction increases. In this state, the hydraulic conductivity of the coarse-grained layer is much smaller than that of the fine-grained layer. The capillary barrier formed by the contrast in their hydraulic conductivity prevents water flow from the fine-grain layer to the coarse-grain layer. As a result, water is mainly stored in the upper soil layer, with the fine-grained layer acting as a moisture-retaining layer (MRL), and the underlying coarse-grained layer known as the capillary break layer (CBL). Therefore, during the application of CCBE, on the one hand, the strong water retention of the fine-grained layer can be utilized to store more water and reduce rainfall and surface water infiltration. Additionally, since the diffusion rate of oxygen in air is approximately four orders of magnitude faster than in water (Nicholson et al., 1989), the fine-grained layer, with its high saturation, also mitigates oxygen migration. On the other hand, the water barrier properties of the coarse-grained layer can be used to reduce the hydraulic connection between the upper and lower layers and maintain the natural state of the system.

There are two main views about capillary barrier failure. When a large amount of water accumulates above the contact surface between coarse and fine particles, J. C. Stormont & Morris (1998) believed that when the hydraulic conductivity of fine and coarse particles is completely equal, water quickly enters the coarse-grained layer, and the capillary barrier fails at this time. Benson et al. (1999) concluded that when the matrix suction at the interface between fine and coarse particles decreases to the water-entry value of the coarse-grained layer, water breaks through the interface and enters the coarse-grained layer, at which point the capillary barrier fails. The water-entry value refers to the matrix suction value corresponding to the intersection of the steeper curve tangent line and the horizontal tangent line where the residual water content is located in the hygroscopic soil-water characteristic curve (Figure 1d) (Khire et al., 2000; J. H. Li et al., 2013). However, even when the capillary barrier effect fails, excess water can be discharged through subsequent land evaporation and plant transpiration, which may restore the original function of the capillary barrier.

2.2 Structural Type of CCBE

The configuration of the CCBE can be categorized as either horizontal or inclined. In the case of horizontal CCBE, the primary focus is on the vertical movement of water when it reaches the fine-grained layer. In contrast, the inclined CCBE not only considers the infiltration of water in the vertical direction but also considers lateral diversion (T. L. T. Zhan et al., 2014). In general, the performance and efficiency of inclined CCBE are assessed based on the lateral diversion length (DL) (Gao et al., 2022; Smesrud & Selker, 2001). The lateral DL is defined as the distance from the top of the slope to the down-dip limit point, where breakthrough occurs (Aubertin et al., 2009), as illustrated in Figure 2. Lateral diversion reduces the rate of water infiltration and contributes to the long-term stability of the CCBE. Therefore, the inclined CCBE is more widely used.

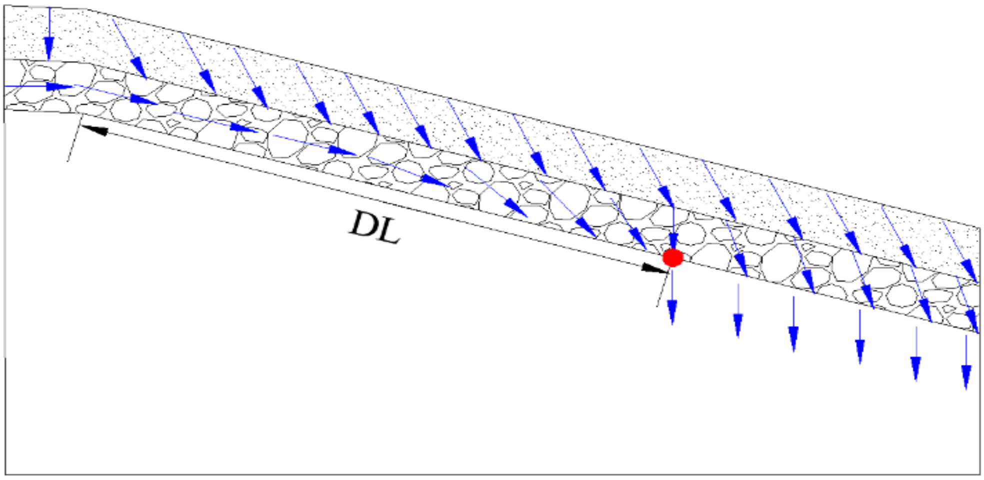

Figure 2: Schematic representation of water movement in an inclined capillary barrier

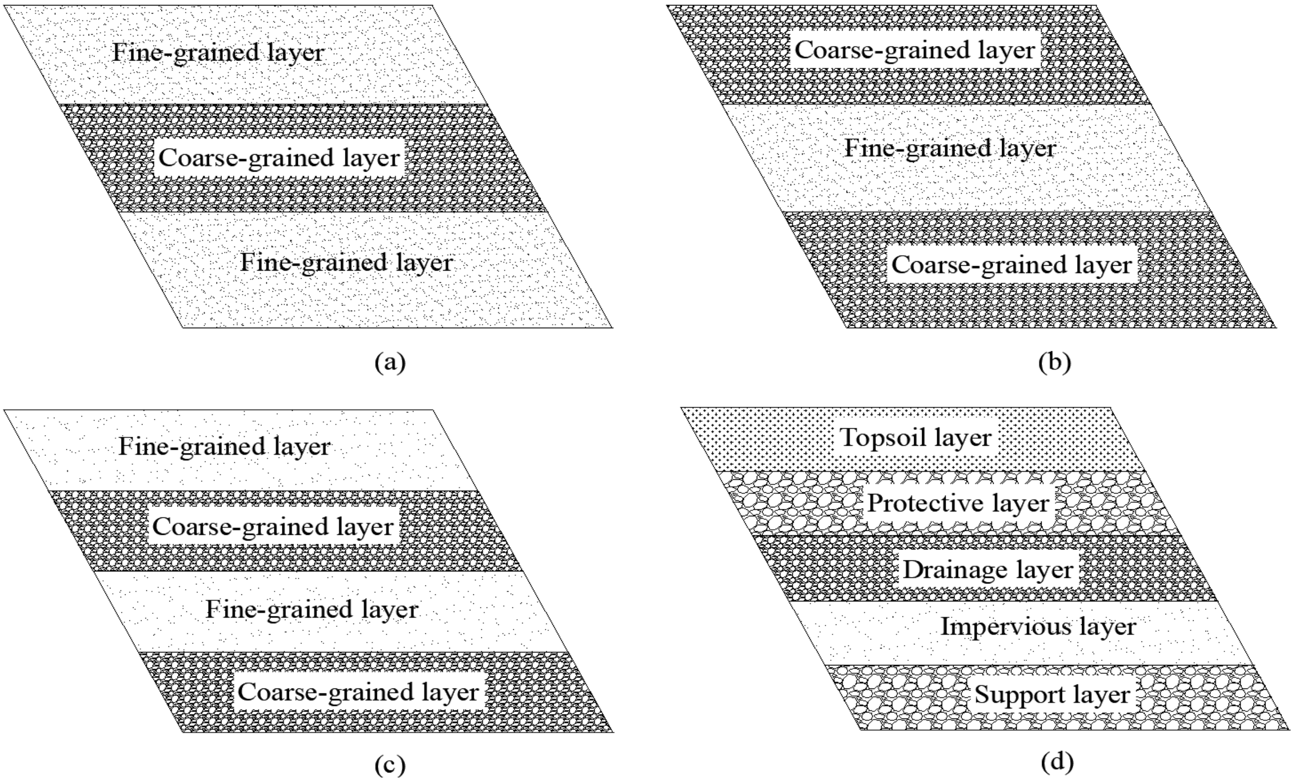

Figure 3: Covers with capillary barrier effects structure (a) three layers of fine-coarse-fine; (b) three layers of coarse-fine-coarse; (c) four layers; (d) five layers

In terms of the number of layers in the CCBE, common configurations include two, three, four, and five layers. A two-layer cover system consists of a fine-grained material layer placed over a coarse-grained material layer. A three-layer cover system can be divided into two types. The first type involves adding low-permeability material beneath the two-layer system (Figure 3a) (Ng, 2015; Ng et al., 2016). According to R. Chen et al. (2022), compared to single-layer systems, both two-layer and three-layer CCBE are more effective in preventing water percolation and maximizing water retention in the fine-grained layer. Additionally, the three-layer system further reduces gas diffusion by incorporating a low-permeability material layer. The second type of three-layer cover system adds a coarse-grained layer above the two-layer system (Figure 3b). This coarse-grained layer serves as a protective layer, preventing the fine-grained layer from desaturation and is commonly used for treating acidic tailings reservoirs. In addition to the single capillary barrier, some scholars have investigated the performance of double CCBEs (Harnas et al., 2014; Rahardjo et al., 2016). The double CCBEs consist of four layers: a fine layer, a coarse layer, another fine layer, and a final coarse layer (Figure 3c). Research has shown that, compared to the single capillary barrier, the double CCBEs exhibit superior impermeability, although they come with a higher economic cost. The five-layer cover system typically comprises a topsoil layer (organic soil to promote vegetation establishment), a protective layer (coarse-grained material with pebbles to stabilize the site and prevent biological invasion), a drainage layer (sand or gravel to manage water flow), an impervious layer (fine-grained material), and a support layer (coarse-grained material) (Figure 3d). In most cases, the protective layer can be combined with the drainage layer, with the coarse-grained material serving as a water barrier to prevent soil moisture evaporation and maintain the high saturation of the fine-grained layer (Bussière et al., 2003). The specific design of the cover system, including the number of layers, should be combined with the site's conditions and other relevant factors.

3. Research Scheme of CCBE

In the study of CCBE, two main methods are commonly employed: experiments and numerical simulations. Experimental methods include laboratory tests and field tests. Laboratory tests involve investigating the performance of CCBE by constructing physical models, such as one-dimensional soil columns or two-dimensional slopes, under controlled climatic conditions. In field experiments, a study area is established to record data on soil water content, matrix suction, and leakage of the CCBE under natural conditions, thereby assessing its performance in situ. Numerical simulation, on the other hand, typically combines measured data to construct a numerical model at a given scale. By applying appropriate boundary conditions, the efficiency of the CCBE under specific conditions can be studied. The specific applications of these methods are summarized in Table 1.

In general, field experiments are of great practical significance. Due to the influence of topography and landforms, experimental sites are mostly set up as inclined CCBEs. When field conditions are complex and experimental operations are difficult to complete, laboratory experiments can provide representative results. Laboratory experiments are characterized by small scale and ease of operation. In comparison, numerical simulations are simple to perform and possess strong predictive capabilities, making them suitable for long-term performance evaluation of CCBE under complex geological conditions and extreme weather. Both field and laboratory experiments require measurements of volumetric water content and matric suction at certain points, often using soil moisture sensors such as ECH_2O-10HS, 5TE, EC-5, and TDR sensors, as well as tensiometers or matric potential sensors like MPS-2, Teros 21, and Watermark sensors. Common numerical simulation software includes SVFlux, SEEP/W, COMSOL, and CODE_BRIGHT.

Table 1: Research Methods

Research methods	Scale Dimensions	Experimental Instruments / Simulation Software	References
Field experiment	A 2:1 side slope, with a flat portion in the bottom of 1m^2	ECH_2O-10HS sensors, MPS-2 sensors	Demers et al. (2017)
	The inclined steel box was 2.0 m long, 1 m wide, and 1.2 m high	Inclined steel box, a rainfall simulator, tensiometers	T. L. T. Zhan et al. (2014)
	The test section is 30 m long, 20 m wide, and 3H / 1 V slope	TDR probes, tensiometers, thermistors	L. Zhan et al. (2020)
	The slope angle is 3: 1, and the slope length is 30 m	Watermark sensors, TDR probes, tensiometers, thermistors	Maqsoud et al. (2011)
	Slope height 1.5 m, slope 2 %	TDR probes, tensiometers, thermistors, Watermark sensors	Bussière (2007)
	The test section is 20 m long and 30 m wide	TDR sensors, tensiometers, barometers, and temperature sensors	Jiao et al. (2019)
Soil column experiment	Base area 150mm^2, height 800mm	Organic glass column, water level indicator	Mancarella & Simeone (2012)
	The diameter of the column was 35 cm and the height was 105 cm	PVC cylinder, tensiometers, ECH_2O-10HS probes, gas chromatographer (Agilent Micro-GC)	Demers et al. (2017)
	25 cm × 25 cm for the square base and a total column height of 110 cm	Decagon Devices 5TE volumetric water content sensors, METER Environment Teros 21soil suction sensors	Hey & Simms (2021)
	Diameter 20cm, height 63cm	Transparent organic glass column, MP406 soil moisture sensor, data acquisition instrument	Li et al. (2022)
	The height and diameter of the acrylic column were 1000 and 190 mm	2100F small tip tensiometer, TRASE system, ICT data recorder, pressure sensor	Harnas et al. (2014)
	Diameter 30 cm, height 160 cm	Transparent acrylic column, EC-5 moisture sensor, tensiometer, gas pressure sensor, gas flow meter	Chen et al. (2022)
	Diameter 20cm, height 63cm	MP406 humidity sensor, CR1000 data recorder, electronic balance	X. Li et al. (2022)
Numerical simulation	25 cm × 25 cm for the square base and a total column height of 110 cm	SVFlux software	Hey & Simms (2021)
	The slope is 60 m long, 20 m high, and 3H:1V slope angle	SVFlux software	T. L. T. Zhan et al. (2014)
	Slope length 10m, slope 1: 1, 1:2, 1:3, 1:4	SEEP/W and Slope/W	Wang & Xu (2021)
	Slope 35 °, slope height 6m / 10m	CODE_BRIGHT and LimitState software	Scarfone et al. (2023)
	The slope length is 24m and the slope angle is 16.4 °	COMSOL Multiphysics V5.1	G. Li et al. (2022)
	The model is 125 m long	SEEP/W	Hotton et al. (2020)
	The slope length is 360 m	CODE_BRIGHT software	Ng (2015)
	The diameter of the soil column is 0.5 m and the height is 3 m	CODE_BRIGHT software	Sepe et al. (2021)

4. Widespread Applications of CCBE

The CCBE has been widely applied in various fields due to its strong water retention properties in MRL and water insulation performance in CBL. Among them, acid tailings ponds and agricultural crop cultivation mainly use the water retention function of MRL, while the rest are applied to the water insulation properties of the CBL. Although the performance in different fields is similar, the focus of the research varies across disciplines.

In acidic tailings dams, the water retention ability of MRL is used to maintain a high saturation level, which helps reduce oxygen intrusion, slows down sulfide oxidation, and minimizes the generation of AMD. Typically, the CCBE for acid tailings ponds is composed of coarse, fine, and coarse particles. The additional coarse-grained layer is placed on the top of fine-grained layer to create a secondary capillary barrier effect, preventing moisture evaporation from the fine-grained layer. In agricultural crop cultivation, the water retention capacity of the fine-grained layer ensures that crops' root zones receive adequate moisture, thereby enhancing water resource absorption efficiency. This ensures crops can grow even in arid regions or with minimal irrigation.

The water insulation properties of CBL are widely used in landfills, nuclear waste disposal facilities, slope engineering, embankment construction, and other projects. In landfills and nuclear waste disposal facilities, the CCBE prevents water leakage at the interface and minimizes leachate contamination risk. In slope engineering, the CBL helps prevent changes in pore water pressure due to rainfall infiltration, thereby maintaining slope strength and stability. For problems like unsaturated subgrade wetting and uneven settlement caused by rainfall infiltration, or instability due to capillary rise in the subgrade, the CBL effectively blocks water from entering the subgrade, reducing the impact of pore water pressure distribution and ensuring stability. The new landfill retaining walls also make use of the water insulation performance of the CBL to block rainwater infiltration into low permeability soils, thus maintaining high suction values. Furthermore, the CCBE can effectively reduce the migration of salts in saline soils to the surface and groundwater. The following section will provide a detailed overview of the historical development and current research status of capillary barrier covers in various fields.

4.1 Application of CCBE in Landfills

Common methods for the disposal of domestic waste include incineration, landfill, and composting. Currently, landfill remains the primary method for solid waste treatment. However, landfills need to occupy a large amount of land and may cause pollution of nearby groundwater and soil due to leachate. Therefore, it is crucial to implement effective final covers to prevent water from infiltrating the waste, generating leachate, and contaminating the environment. Traditional final covers are typically made of compacted clay, which has limited durability and is prone to cracking (Morris & Stormont, 1997). Based on the permeability characteristics of unsaturated soils and the typical characteristics of the capillary barrier effects, many researchers have explored the application of CCBE in landfills. For example, Abdolahzadeh et al. (2011) established an experimental area at the Saint-Tite-des-Caps landfill to evaluate the effectiveness of CCBE in controlling water infiltration. In arid and semi-arid regions, capillary barrier evapotranspiration covers have been proposed (Scanlon et al., 2005; W. Zhang et al., 2016; Z. F. Zhang, 2016). These covers typically consist of a vegetation layer, a fine-grained layer, and a coarse-grained layer (Figure 4a). By utilizing the capillary barrier effects, water is primarily stored in the fine-grained layer during rainfall, which reduces vertical water infiltration. The stored water is later released through land evaporation and plant transpiration (Zhao, 2014). Experimental results have shown that in arid and semi-arid regions, capillary barrier evapotranspiration covers exhibit excellent resistance to seepage and effectively prevent water percolation (Oldecop et al., 2017; Scanlon et al., 2005).

In humid regions, abundant rainfall can hinder the timely discharge of water, making it prone to breakthrough at the interface, which can lead to the failure of the CCBE. As a result, the application of CCBE in humid areas remains controversial. To address this, many scholars have investigated the performance of CCBE in humid and semi-humid regions (L. Zhan et al., 2020). J. H. Li et al. (2013) conducted a numerical simulation to study the performance of CCBE in southern China, a region with heavy rainfall. Their findings indicated that the CCBE composed of clayed sand and silty sand with gravel performed well under long-term light rain, but was susceptible to breakthrough during short-term heavy rainfall. Ng et al. (2016) proposed a new three-layer CCBE, which consists of a fine-grained layer, a coarse-grained layer, and a low-permeability material (compacted clay) (Figure 4b). The capillary barrier formed between the fine-grained and coarse-grained layers prevents downward water movement, and the low-permeability clay layer beneath resists drying and cracking. Even if water breakthrough occurs, the hydraulic conductivity of the low-permeability clay is minimal under low suction conditions, further preventing water infiltration. Therefore, this new three-layer CCBE is well-suited for humid areas (R. Chen et al., 2019).

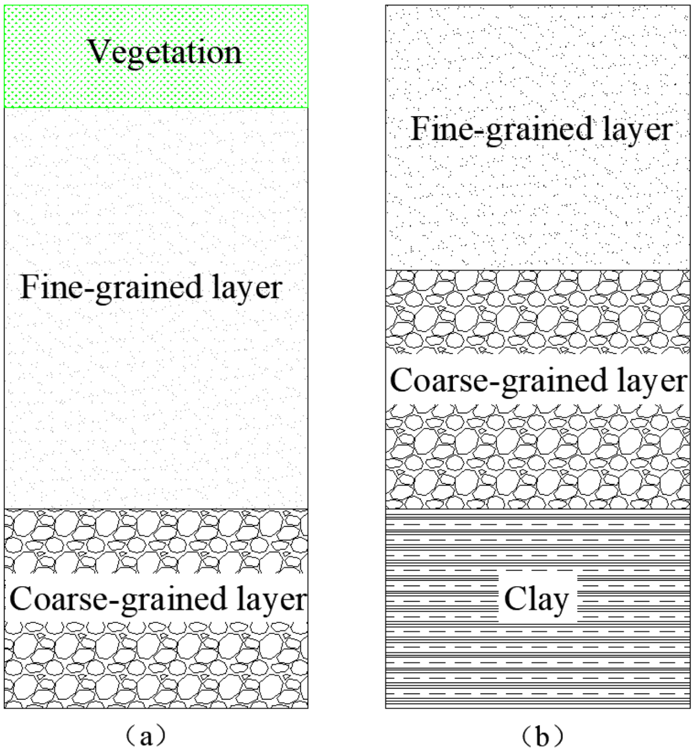

Figure 4: (a) Capillary barrier evapotranspiration covers; (b) New three-layer landfill cover system

Common cover materials for CCBE include silt, sand, and gravel (Parent & Cabral, 2012). As natural resources gradually deplete, geosynthetics have been increasingly explored as a coarse-grained layer for CCBE (Krisdani et al., 2010; McCartney & Zornberg, 2010; K. Park & Fleming, 2006; Trpkosova & Mls, 2010; Zornberg et al., 2010). However, geosynthetics are prone to damage and have high costs, necessitating the search for more economical and practical materials. Jiao et al. (2019) demonstrated the feasibility of using loess as a fine-grained layer in CCBE by measuring and analyzing the water storage performance of loess-gravel CCBE (Yan et al., 2018; T. L. T. Zhan et al., 2014). In line with the concept of "treating waste with waste", Harnas et al. (2014) applied recycled asphalt pavement materials to the construction of CCBE and achieved good test results. Wang & Xu (2021) used construction waste as CCBE's material and verified the feasibility of construction waste by comprehensively analyzing the water retention, anti-seepage and anti-sliding properties of the established CCBE. Additionally, biochar has been shown to modify soil permeability (R. Chen et al., 2022; Yang, 2016), and Xu et al. (2020) found that biochar-modified clay can serve as a fine-grained layer in CCBE.

4.2 Application of CCBE in Nuclear Waste Disposal

Nuclear energy is a type of clean energy primarily used for electricity generation. The cost of nuclear fuel is lower than that of fossil fuels and the energy output is significantly higher, making nuclear energy a promising sustainable resource. However, the byproduct of nuclear energy, nuclear waste, is highly radioactive. Improper disposal of this waste can lead to nuclear leakage, which not only threatens the surrounding ecosystem but also poses significant risks to human health and safety (Huo et al., 2009). Consequently, the safe disposal of radioactive waste has been a critical global concern. Geological disposal is commonly employed for nuclear waste, with multiple barrier covers used to prevent water infiltration and the migration of radionuclides (Huo et al., 2014). Commonly used multiple barrier covers involve placing a fine sand or pebble layer beneath the MRL. The capillary barrier effects, resulting from the hydraulic property differences between the coarse and fine-grained layers under unsaturated conditions, allow water to accumulate in the fine-grained layer, thereby reducing water infiltration and mitigating the leaching of radioactive waste. Bentonite is frequently used for the fine-grained layer due to its high montmorillonite content, which enables it to swell upon water absorption, blocking voids in the surrounding medium and reducing porosity. Additionally, bentonite exhibits low hydraulic conductivity, high cation exchange capacity, and a large specific surface area (Ma & Han, 2014). Nuclear waste landfill disposal is a special case of landfill disposal, so the application of CCBE can be learned from landfills.

4.3 Application of CCBE in Acid Tailings Ponds

Common acid tailings ponds include sulfur-rich mines, waste rock piles (Fala et al., 2005), tailings dams, and underground mines. When exposed to air over long periods, the pyrite and other sulfide minerals within these materials are highly susceptible to oxidation, reacting with oxygen and water to produce AMD (Bussière et al., 2004). AMD is highly acidic (pH < 3) and can dissolve significant amounts of harmful heavy metal ions, such as Fe, Cu, Zn, Pb, As, and Cr, posing serious environmental risks (G. Chen et al., 2021). To address AMD, both treatment and prevention technologies are commonly employed. While treatment technologies can effectively mitigate the environmental impact of AMD, they are often complicated to operate, time-consuming, and costly (I. Park et al., 2019). In contrast, more attention is being given to economically sustainable prevention methods. Since the oxidation of pyrite is driven by the presence of oxygen, water, and microorganisms, limiting the exposure to oxygen and water can help reduce the production of AMD.

The oxygen barrier is an effective preventive measure for managing AMD. Oxygen barriers can be implemented in two main forms: water cover and dry cover. The water cover works by taking advantage of the significantly lower diffusion rate of oxygen in water compared to air. The diffusion coefficient of oxygen in water is approximately $1.90\times10^{-9} m^2/s$, which is about 1/10000 of its diffusion rate in air ($1.98\times10^{-5} m^2/s$) (Schmitz et al., 2013). As a result, the existence of oxygen can be ignored in a saturated state. However, water covers require specific topographical and hydraulic conditions, making them unsuitable for arid and semi-arid regions. In contrast, dry covers primarily utilize the capillary barrier effects, which are created between a layer of impermeable material and a relatively coarse-grained soil layer. Under unsaturated conditions, water is stored in the fine-grained material due to the difference in hydraulic conductivity between fine-grained and coarse-grained soils, which reduces water infiltration and mitigates oxygen diffusion (Anne-Marie et al., 2005). To ensure the long-term effectiveness of the CCBE, it is crucial to maintain a consistently high degree of saturation in the fine-grained layer. Therefore, the final covers of acidic tailings ponds typically include a coarse-grained protective layer placed on top of the two CCBE layers (Figure 5). This protective layer serves two key functions: first, it reduces plant root invasion and disturbances caused by humans and animals, and second, it minimizes the direct evaporation of water from the fine-grained layer, thereby preserving its high saturation and reducing oxygen diffusion. Bussière et al. (2003) investigated the performance of inclined covers as oxygen barriers and observed variations in the saturation levels of the covers at different positions along the slope. After 60 days of drought, the saturation of the MRL near the bottom of the slope remained above 90%, while that near the top dropped below 80%. Compared to horizontal covers, inclined covers experienced an increased local oxygen flux through the barrier.

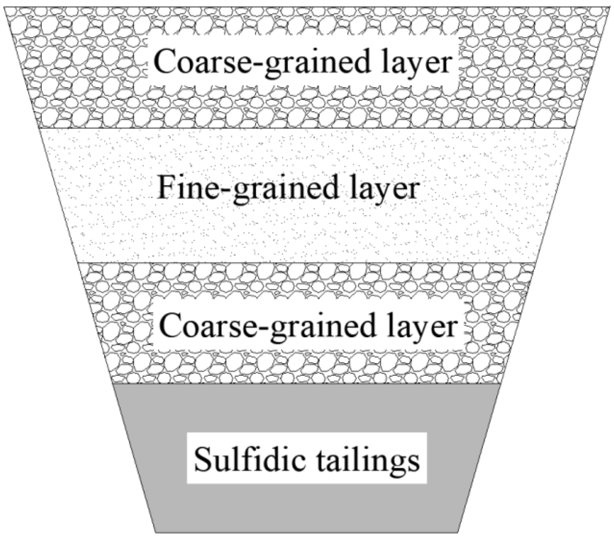

Figure 5: Covers with capillary barrier effects of acid tailings ponds

Dry cover materials include clean tailings, desulfurization tailings, industrial organic wastes (e.g., fly ash, green liquor dregs), and organic materials (Bussière, 2007; Krisdani et al., 2005; Lu et al., 2013; Mäkitalo et al., 2015, 2016; Shaikh et al., 2021). Among these, industrial organic wastes are generally alkaline and can react with acids, thereby increasing the pH and reducing the concentration of heavy metal ions. Organic materials, such as sawdust, consume large amounts of oxygen during decomposition, which helps reduce the generation of AMD. For example, Demers et al. (2017) demonstrated through laboratory research and field tests that a sludge-soil mixture could be used as the CCBE material to prevent the generation of AMD and reduce the dissolution of heavy metals. Additionally, Kalonji Kabambi et al. (2017) showed through indoor soil column experiments that truncated waste rock can be employed in the CCBE to limit oxygen migration and mitigate the generation of AMD. Larochelle et al. (2019) proposed using acid-generating waste rocks as the CBL in CCBE to reduce environmental pollution and promote resource recycling at mining sites. Hey & Simms (2021) demonstrated through laboratory experiments and numerical simulations that a mixture of anaerobically digested biosolids, combined 1:1 with leaf and yard waste, could be used as the fine-grain layer in the CCBE. Numerous studies have shown that CCBE can effectively prevent sulfide oxidation and reduce the formation of acid leachate (Hotton et al., 2020; Molson et al., 2004.)

4.4 Application of CCBE in Slope Protection

Rain-induced landslides are a common natural disaster. The primary mechanism involves rainwater infiltrating the slope, which alters the pore water pressure in the soil. As the soil transitions from an unsaturated to a saturated state, the pore water pressure increases, matrix suction decreases, and the shear strength diminishes. This process can lead to soil instability and result in landslides. Previous studies have shown that the use of CCBE can reduce rainfall infiltration (Rahardjo et al., 2004). In slope protection applications, inclined covers are typically used (Figure 6), which enhance lateral flow diversion, further reducing water infiltration and extending the breakthrough time of rainwater. Tami et al. (2004) conducted a numerical analysis and developed a physical model of the capillary barrier to investigate its mechanism for slope stabilization. When the fine-grained layer is placed above the coarse-grained layer, the difference in hydraulic conductivity between the two layers limits the downward movement of water under unsaturated conditions. Infiltrated water is retained in the fine-grained layer due to capillary forces, thereby ensuring slope stability. Rahardjo et al. (2012) compared the performance of slopes with and without CCBE in reducing rainwater infiltration and maintaining negative pore water pressure through slope experiments. The results demonstrated that the slope soil layer with CCBE effectively maintained negative pore water pressure during rainfall, particularly at the top of the slope. Erasanayagam (2021) investigated the applicability of CCBE on local slopes in Sri Lanka through laboratory physical models and 2D and 3D numerical simulations using GeoStudio 2012 SEEP/W and Midas GTS-NX software. The study found that the CCBE, consisting of a 20 cm thick layer of river sand covered with 10 cm of coarse Msand, significantly reduced rainfall infiltration into the slope, even during continuous rainfall of 20 mm/h for 5 days.

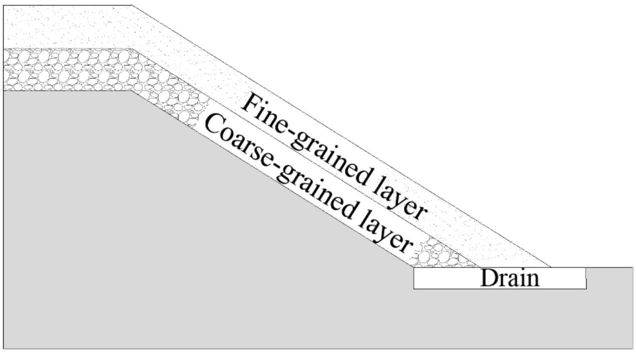

Figure 6: Slope covers with capillary barrier effects

In selecting slope cover materials, local materials can be utilized in combination with the properties of local soils to design an effective CCBE. Additionally, Krisdani et al. (2010) investigated the performance of CCBE formed using geosynthetics as the coarse-grained layer to prevent rainfall-induced slope failure. The results showed that the geosynthetics successfully created a capillary break, effectively preventing water infiltration. Tan et al. (2018) proposed a dual mechanism of biological clogging and biological reinforcement to improve soil properties and reduce permeability. The treated soil was applied as the fine-grained layer in CCBE to mitigate rainfall-induced landslides in tropical regions. Li et al. (2024) investigated the seepage control performance of bentonite clay-based CCBE, and the results showed that 4% bentonite-modified clay can be used as a fine-grained layer material, and the resulting CCBE reduces the pore water pressure response of the soil and enhances the slope stability under the condition of short-term rainstorms.

4.5 Application of CCBE in Subgrade Treatment

With the rapid development of the social economy, the demand for automobiles has been steadily increasing, leading to a growing need for expressway construction. However, several issues persist in the construction of existing expressways, particularly the flooding of unsaturated subgrades caused by rainfall infiltration. This leads to subgrade instability and uneven settlement, which, if not addressed promptly, can negatively impact driving safety. Common treatment methods, such as pile composite foundations or the use of high-strength materials as subgrade fillers, are costly and their long-term effectiveness remains uncertain. As a result, the use of CCBE has been proposed as a solution to prevent subgrade wetting and associated disasters (Huang et al., 2017). Given that coastal areas experience high rainfall and that the subgrade is significantly affected by climatic conditions such as rainfall and evaporation post-construction, Wu et al. (2022) investigated the feasibility and long-term performance of applying CCBE to sloped subgrades through numerical simulations. The results indicated that the subgrade with CCBE significantly reduced the impact of pore water pressure distribution, leading to a 94% reduction in settlement and a 15% increase in the safety factor compared to conventional subgrades. Furthermore, when silt was used as the low-subgrade material, capillary action could lead to a decrease in subgrade strength. Huo et al. (2022) investigated the influence of capillary barriers formed by eight types of geotechnical materials on the vertical migration of water in silty soils using both indoor soil column model tests and field experiments. The findings revealed that, among the eight combinations, the most effective barrier was formed by a 40 cm thick lime soil layer (cured for 45 days) combined with a composite geomembrane. These dual capillary barriers significantly hindered the upward migration of capillary water in the silt subgrade. In seasonally frozen soil zones, the moisture in highway subgrades often rises due to temperature fluctuations, resulting in subgrade frost heaving and pavement cracking. Zhao et al. (2022) found, through indoor roadbed model tests, that under freeze-thaw cycle conditions, the CCBE effectively inhibited the upward movement of water (Figure 7). This barrier prevented the upward migration of moisture in the roadbed, thereby maintaining the stability of the soil moisture field in seasonal frozen soil areas.

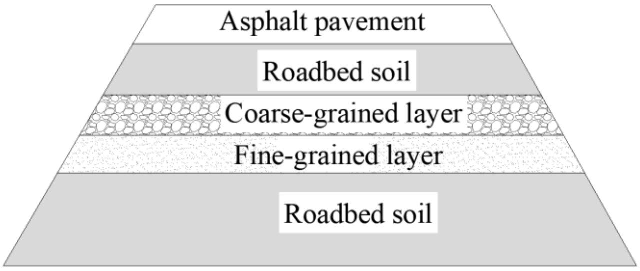

Figure 7: Covers with capillary barrier effects for subgrade

4.6 Other Applications

The CCBE has been applied in several fields with desired results. Retaining walls backfilled with fine-grained soil are particularly susceptible to the effects of rainfall, as water infiltration increases pore-water pressure and reduces matrix suction, thereby decreasing the stability of the retaining wall. Several studies have investigated the application of CCBE in retaining walls. For instance, Chen et al. (2020) used the finite element method to analyze the performance of a capillary barrier retaining system composed of silt, nonwoven geotextile, and sand. Their findings indicated that, even under heavy rainfall conditions, the silt backfill maintained a high level of suction, ensuring that the safety factor remained consistent with that of the initial support system.

As water resources become increasingly scarce, crop production is significantly impacted. Enhancing water use efficiency in crops is critical, and the use of CCBE offers a potential solution. The capillary barrier consists of a fine-grained layer overlying a coarse-grained layer, where water is primarily stored in the fine-grained layer. This arrangement utilizes the difference in unsaturated hydraulic conductivity between the coarse and fine-grained layers, enabling efficient water retention for crop root growth. Sao et al. (2021) found that irrigation methods, the amount of water applied, and the timing of irrigation all influence crop growth. By using the CCBE, water can be applied more locally to the crops, reducing the overall irrigation volume, thus preventing failure of the capillary barrier while meeting the water needs of plant roots and promoting healthy plant growth.

To address the issue of basement erosion in soil sites in arid and semi-arid regions, W. Chen et al. (2023) explored the application of CCBE for controlling soil salinization. In this configuration, with the coarse-grained layer placed above the fine-grained layer, the capillary barrier effect occurs at the interface between the coarse and fine particles. This prevents capillary water from rising into the coarse-grained layer, thereby inhibiting the upward migration of water and salts, and reducing secondary salt accumulation in the restored area.

5. Influencing Factors of CCBE

The performance of CCBE is influenced by a variety of factors, and numerous scholars have conducted in-depth research on these aspects. For example, Qian et al. (2010) investigated the effects of slope, coarse-grained layer thickness, spraying intensity, and other factors on the CCBE in nuclear waste treatment through indoor infiltration experiments. Scarfone et al. (2023) used numerical simulations to examine how material, thickness, slope height, and weather conditions affect slope stability. Ng et al. (2019) explored the influence of vegetation type on water infiltration in the cover system of a recycled concrete slope. Li et al. (2022) studied the relationship between CCBE performance in landfills and factors such as rainfall intensity, the thickness of the fine-grained soil layer, and initial moisture content. Harnas et al. (2014) compared the impermeability of single and double-layer CCBE using recycled asphalt pavement as the material. Cosset & Aubertin (2010) investigated the effects of particle size distribution, initial water content, and groundwater level on the saturation of the MRL in tailings treatment through laboratory tests and numerical simulations. Zhao et al. (2024) focused on the impact of freeze-thaw cycles on CCBE's performance in subgrade engineering. Although the functions of CCBE differ across various applications, the factors influencing its performance are largely similar. In summary, the main factors affecting CCBE can be grouped into five categories: covers' structure, material properties, meteorological conditions, geological conditions, and vegetation.

5.1 The Structure of CCBE

Experimental studies by Rahardjo et al. (2016) have shown that the performance of double CCBE is superior to that of single CCBE, although the associated economic cost is higher. The performance of CCBE is also significantly influenced by the inclination of the covers. Specifically, the slope length, slope height, and gradient of the covers play a critical role in determining CCBE performance (Anne-Marie et al., 2005; Rahardjo et al., 2012; Walter et al., 2000). According to research by Qian et al. (2010), the anti-seepage performance of CCBE improves as the slope increases, but the safety factor for slope stability decreases with steeper gradients. For steep slopes, it is recommended to incorporate multiple drainage ditches along with the diversion length of the CCBE to ensure slope stability. Additionally, the material of MRL in tailings reservoirs can maintain high saturation at the bottom of the slope; however, the top of the slope is prone to desaturation, which may hinder its ability to effectively isolate oxygen.

5.2 Material Properties

The performance of the CCBE is directly influenced by the properties of the materials used, as it consists of at least a fine-grained layer and a coarse-grained layer. These material properties include factors such as particle size, saturated hydraulic conductivity, air entry value, porosity, and initial water content. Equally important is the structural difference between the fine-grained and coarse-grained layers. For instance, Smesrud & Selker (2001) studied inclined cover layers and found that for a given infiltration rate, interfacial slope, and fine-grained material properties, the coarse-grained material beneath the fine-grained layer needed to be 2.5 times coarser than the overlying fine-grained material to achieve 80% of the maximum diversion length. To reach 90% of the maximum diversion length, the coarse-grained material had to be 5 times coarser than the fine-grained material. Generally, the greater the difference in particle structure properties between the two layers, the more effective the capillary barrier (J. Stormont & Anderson, 1999). From Table 2, it can be observed that a significant difference of at least two orders of magnitude in saturated hydraulic conductivity between the coarse- and fine-grained layers is necessary to achieve the effective capillary barrier effects. Furthermore, the thickness of the materials plays a critical role in determining the performance of the CCBE. Wang & Xu (2021) concluded through numerical simulations that the effectiveness of the CCBE improves with the increase in the thickness of the fine-grained layer. Similarly, Qian et al. (2010) found that the efficiency of the CCBE increases as the thickness of the coarse-grained layer increases. Additionally, Li et al. (2022) concluded that the performance of the CCBE improves as the initial moisture content of the fine-grained layer decreases and its thickness increases.

5.3 Meteorological Conditions

Long-term meteorological conditions shape specific climatic characteristics, such as semi-arid and humid climates. In arid and semi-arid regions, the anti-seepage performance of the CCBE is excellent, which benefits applications in landfills, nuclear waste disposal, slope engineering, and roadbed engineering. However, maintaining the high saturation of the fine-grained layer in these areas poses challenges, making it difficult to meet the oxygen isolation requirements for acid tailings. Conversely, in humid regions, the performance of the CCBE is influenced by rainfall intensity and volume. Mancarella & Simeone (2012) conducted a study where the rainfall intensity varied from 50 mm/h to 2.5 mm/h, and they found that the effective time of the CCBE under 5 mm/h rainfall intensity was 22 times longer than under 50 mm/h intensity. This suggests that short-duration, high-intensity rainstorms are more likely to cause failure of the capillary barrier compared to prolonged, low-intensity rainfall. Similarly, Li et al. (2022) concluded that the anti-seepage performance of the CCBE decreases as rainfall intensity increases. Wang & Xu (2021) also found that the safety factor for slope stability gradually decreases with the increase in rainfall intensity.

Table 2: Material properties

Experimental materials	Thickness (m)	D_{10} (μm)	D_{50} (μm)	K_{sat} (m/s)	Porosity	AEV (kPa)	Reference
Sand	0.15	141	550	1.00e-04	0.30	9	Hey & Simms (2021)
Custom Reclamation Mix	0.15	—	85	4.00e-09	0.83	388	
Pre-Oxidized Tailings	0.5	9.7	20	1.00e-06	0.42	8	
Unoxidized Tailings	0.5	61	180	5.00e-05	0.37	37	
Silty clay	15/30/40/53	15	90	7.60e-7	—	10	Li et al. (2022)
Gravel soil	0.1	2000	3000	4.48e-02	—	0.5	
Fine recycled asphalt pavement	0.75	200	1800	5.00e-03	0.34	0.79	Harnas et al. (2014)
Coarse recycled asphalt pavement	0.75	15000	18000	5.00e-01	0.38	0.02	
Silt	0.2	13	30	5.30e-06	0.47	18.2	T. L. T. Zhan et al. (2014)
Sand	0.1	100	250	3.84e-04	0.46	3	
Gravel	0.1	4000	10000	2.00e-02	0.42		
loess	0.6	—	—	5.00e-07	0.50	14.3	L. Zhan et al. (2020)
Gravel	0.3	—	—	2.40e-05	0.40	0.04	
Sand	0.3	200	—	4.00e-04	0.32	2-4	Bussière (2007)
Clean tailings	0.3/0.6/0.9	4.2	—	2.00e-06	0.42	20-40	
Natural silt	0.6	4.2	—	2.00e-07	0.42	27-35	
Sulfidic tailings	0.2	15.9	—	2.00e-05	0.43	7-11	
Recycled fine aggregate	0.3/0.6/0.9/1.2/1.5/1.8/2.1	—	1240	9.70e-05	0.386	3.72	Wang & Xu (2021)
Recycled coarse aggregate	0.3	—	12480	7.50e-02	0.455	0.23	
Solidified mud cake	0.3	—	10	1.00e-07	0.498	24.45	
Geotextile	0.02	—	—	1.50e-03	0.82	1.45	Park & Fleming (2006)
Rock Flour	—	1.5	17	6.00e-07	0.44	59.5	
Tailings	2.5	17	90	8.30e-05	0.47	8.1	
Cover Soil	1	2	23	2.40e-07	0.42	10.9	
Completely decomposed granite	1.2/1/0.6	—	—	2.00e-08	0.45	33.3	Chen et al. (2022)
Gravelly sand	0.2	—	—	1.00e-02	0.30	0.03	
Kaolin	0.4	—	—	6.00e-08	0.51	100	
Compacted waste rocks	0.5	20	3000	1.00e-07	0.19	25-30	Boulanger-Martel et al. (2021)
Loose waste rocks	0.25	300	19000	1.50e-03	0.38	0.2	

5.4 Geological Conditions

Geological conditions in the field are generally complex, and topography directly influences the design and placement of the CCBE. In field experiments, CCBE systems are typically implemented as inclined covers. Additionally, Cosset & Aubertin (2010) studied the impact of groundwater levels and found that the groundwater level significantly affects the saturation profile of tailings, thereby influencing the design of cover thicknesses.

5.5 Vegetation

Wing & Gee (1994) studied the effect of vegetation on the CCBE and found that, under vegetative cover, the water storage capacity of the MRL can be enhanced due to water absorption by the plants. Additionally, through transpiration, vegetation releases stored water into the atmosphere, which plays a critical role in the evapotranspiration process of capillary barrier covers. The growth of plant roots consumes oxygen, helping to reduce oxygen infiltration into acidic tailings. Regarding the influence of vegetation types, Proteau et al. (2020) observed that the roots of herbaceous plants in the upper 10 cm of the MRL have minimal effect on the saturation of the MRL. However, willow species, with their denser root systems, can reduce the saturation at the top of the MRL. Ng et al. (2019) found that in recycled concrete layers, the suction maintained under shrub cover is 2-12 kPa higher than that under grass cover.

6. Challenges and Prospects

Scholars both domestically and internationally have conducted extensive research on CCBE, and its application can be considered relatively mature. Researchers have employed not only numerical simulation methods but also various experimental approaches in their studies. However, several challenges remain in CCBE research. First, in terms of research methods, numerical simulations rely on models that need further development to become more comprehensive and adaptable. Future models should incorporate factors such as climate change, extreme weather conditions, vegetation, and its evolution (Hotton et al., 2020). Laboratory tests, such as column and box tests, are commonly used by researchers. While column tests focus on vertical water infiltration, box tests typically use small-scale models and are conducted under relatively ideal conditions. However, when faced with complex terrains and other real-world factors—such as erosion, biotic invasion, or water absorption by plants—the performance of CCBE requires further validation and refinement (Chen et al., 2022). Most field tests conducted so far have been relatively short-term, and the long-term performance of CCBE requires further observation (Scarfone et al., 2023). Additionally, when selecting materials for CCBE, it is essential to not only consider their permeability but also their strength characteristics, long-term stability, economic costs, and the interaction between different materials (Shaikh et al., 2021). Furthermore, the design of the CCBE should take into account factors such as the cover structure, the thickness of the coarse- and fine-grained layers, and the slope of the inclined covers. These elements must be aligned with the local topography and climatic conditions, making on-site assessments crucial. For the CCBE that is currently under construction or has already been implemented, it is important to establish comprehensive protective measures and ensure timely supervision and maintenance. Given the strong seepage control and oxygen barrier properties of CCBE, along with its simplicity, cost-effectiveness, and environmental sustainability, it is expected to see broader applications and further development across various fields.

7. Conclusions

Scholars both domestically and internationally have made significant contributions to the research and application of CCBE. Currently, the CCBE has been successfully applied in landfills, radioactive waste repositories, tailings ponds, subgrades, slopes, and other areas, yielding notable achievements. The research findings demonstrate that:

The CCBE exhibits excellent impermeability, effectively preventing surface water from infiltrating waste or radioactive materials, thereby reducing environmental pollution.

The CCBE provides robust oxygen barrier performance. The strong water retention capacity of the MRL limits oxygen intrusion into acidic tailings, thereby reducing the production of AMD.

The CCBE effectively regulates changes in pore water pressure caused by rainfall, ensuring soil strength, slope stability, and foundation integrity.

The CCBE can prevent saltwater erosion and mitigate soil pollution. Additionally, it improves water use efficiency by partially regulating water availability for plants, meeting the water requirements of plant roots, and supporting healthy crop growth.

However, to address the current challenges faced by CCBE, it is essential to create more realistic environmental conditions for testing and prediction, particularly through numerical simulations. Whenever feasible, field tests should be conducted to dynamically monitor the long-term performance of CCBE. For the rational design of on-site CCBE, it is crucial to consider factors such as the structure of the covers, material properties, climatic conditions, geological characteristics, and vegetation. Combining theoretical analysis with practical conditions is key to ensuring the effectiveness of the CCBE in real-world applications.

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