The Application and Properties of Impermeable Materials in Solid Waste Treatment at Red Mud Yard

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Abstract: Red muds pose a significant risk of environmental contamination, particularly through soil and groundwater pollution during their storage. While sodium bentonite geosynthetic clay liners (NaB GCL) have traditionally been employed extensively in red mud storage facilities, their inherent chemical sensitivity has constrained their longevity and effectiveness as a reliable barrier. This review zeroes in on the application and performance of polymer-modified bentonite geosynthetic clay liners (BPC GCL) within the context of red mud storage. The polymer modification process endows BPC GCL with a significantly reduced permeability coefficient and bolsters its chemical resistance. By subjecting BPC GCL to rigorous testing for chemical compatibility and permeability, we have been able to evaluate its efficacy in terms of impermeable and anti-fouling properties within red mud storage environments.
***Keywords*:** bauxite leachates, red mud yard, impermeability materials, impermeability mechanism

1. Introduction

Originating from the alumina production process, the substantial accumulation of red mud not only consumes valuable land resources but also poses a significant risk of environmental contamination through the leakage of red mud leachate. The high alkalinity of this leachate can interact with the clay layer of the storage yard's foundation, leading to alterations in soil structure and chemical composition, which in turn compromise the stability and safety of the storage facility. While traditional impermeable materials, such as sodium bentonite geosynthetic clay liners (NaB GCL), have seen extensive application in red mud storage sites, their high chemical sensitivity has limited their long-term effectiveness in preventing seepage. To address this challenge, researchers have turned to polymer modification as a means to enhance the properties of bentonite. Consequently, the polymer-modified bentonite geosynthetic clay liner (BPC GCL) has been developed, offering not only a significantly reduced permeability coefficient but also improved chemical resistance.

The objective of this review is to assess the potential application of BPC GCL in the treatment of solid waste within red mud storage yards. We aim to evaluate its chemical compatibility and permeability characteristics, as well as to elucidate the interaction mechanisms between polymers and bentonite. Through these comprehensive studies, we aspire to establish a scientific foundation for the selection of impermeable materials in red mud storage yards. Our goal is to facilitate the adoption of safer and more environmentally friendly approaches to the management of red mud solid waste, thereby contributing to the advancement of sustainable waste management practices in the context of industrial solid waste.

2. Impermeable materials in solid waste treatment of red mud yard

BPC GCL has been engineered to enhance the impermeability of NaB GCL. In recent years, the incorporation of polymers and other organic compounds has been employed to modify the properties of bentonite, thereby improving the chemical compatibility and permeability coefficient of waterproof pads when exposed to highly permeable solutions[1, 2]. The polymer intercalated within montmorillonite or the bentonite-polymer composite, when dry mixed with bentonite, maintains a low permeability coefficient ($k < 10^{-10}$ m/s) even in conditions of high ionic strength, the presence of numerous polyvalent cations, and extremely high pH levels. Building on research into the enhancement of permeation expansion capacity, further studies aim to elucidate the mechanisms that govern the permeability coefficient of BPC GCL[3, 4].

3. Properties of Impermeable Materials in Solid Waste Treatment at Red Mud Yard

3.1 Chemical Properties of Leachate Affecting the Permeability Coefficient of BPC GCL

The chemical properties of red mud leachate within storage facilities are influenced not only by the composition and chemical characteristics of the red mud itself but also by the degree of compaction during construction. Additionally, the geological and hydrological conditions of the storage sites, as well as the service life of the impermeable materials, can sig-

nificantly impact the leachate's chemical properties. The primary chemical factors affecting the permeability coefficient of the impermeable layer include cation exchange, high ionic strength, and extreme pH conditions[5].

Cation exchange reactions involve the replacement of sodium (Na^+) ions bound between montmorillonite layers with divalent cations such as calcium (Ca^{2+}) and magnesium (Mg^{2+}). Due to the smaller hydration radius of divalent cations compared to Na^+, their ability to bind free water is diminished, which in turn significantly increases the permeability coefficient of bentonite[6].

Research indicates that the key parameters of the osmotic solution affecting the permeability coefficient of BPC GCL are cationic valence, the ratio of monovalent to polyvalent cations, ion concentration, and pH value[7].

Koldstad et al.[8] examined the impermeable effectiveness of NaB GCL under non-pre-hydration conditions and discovered that the impermeable performance of NaB GCL was influenced not only by the presence of various inorganic salt permeation solutions but also by the permeability coefficient of the waterproof pad due to the permeation expansion characteristics of bentonite. The ionic strength of the osmotic solution directly affects the permeability coefficient, with the retention capacity (RMD) being inversely related to the permeability coefficient. Jo[7] and Scalia[9] also observed that solutions with higher ionic strength or lower RMD could inhibit the permeability expansion of bentonite, thereby reducing the permeability expansion, increasing the permeability coefficient, and consequently diminishing the impermeable effectiveness of NaB GCL.

3.2 Permeability Coefficient and Control Mechanism of BPC GCL

Organically modified bentonite-based waterproof pads have demonstrated a significant enhancement in the impermeability of bentonite. Scalia et al.[9] utilized CaCl2 solutions with ionic strengths of 50 mmol/L, 200 mmol/L, and 500 mmol/L to test the impermeability of BPC GCL containing 20% Super Absorbent Polymer (SAP). When subjected to 1000 mmol/L HNO3 and 1000 mmol/L NaOH solutions, BPC GCL was found to maintain a permeability coefficient below 9.0×10^{-11} m/s over an extended period. This represents a reduction in permeability of up to five orders of magnitude compared to NaB GCL. The experimental results from Tian et al.[3] indicate that BPC GCL with more than 10% SAP addition can resist chemical erosion from leachate with an ionic strength of up to 755 mmol/L, with the permeability coefficient kept between 10^{-12} and 10^{-11} m/s. Moreover, a long-term low permeability coefficient was sustained throughout a two-year testing period. Dong Qinge et al.[10] analyzed the permeability effects of sand, loam, and clay treated with SAP and discovered that as the addition amount increased (0.08%-0.50%), permeability gradually decreased. Similar findings have been reported in other studies. The modification of bentonite with polymers and other organic molecules enables the waterproof pad to maintain better impermeable effects in strongly alkaline osmotic solutions[11]. Bentonite-polymer composites, whether intercalated with montmorillonite or dry mixed with bentonite, maintain low permeability coefficients ($< 10^{-10}$ m/s) in solutions with high ionic strength, numerous polyvalent cations, or very high pH values. The research team also investigated the impermeable mechanisms of BPC GCL, including increased swelling capacity, cation exchange capacity, and hole plugging efficiency[12]. However, the underlying physical and chemical mechanisms that enable BPC GCL to exhibit superior impermeability against higher concentrations of osmotic solutions require further investigation.

4. Conclusion

The use of Sodium Bentonite Waterproof Pads (NaB GCL) in red mud storage facilities is challenged by their sensitivity to high ionic strength solutions and divalent cations, which can increase permeability. To overcome this, Polymer Modified Bentonite Waterproof Pads (BPC GCL) have been developed. BPC GCLs, enhanced with organic compounds like Super Absorbent Polymer (SAP), exhibit significantly reduced permeability coefficients (down to 10^{-11} m/s) even under extreme pH and high ionic strength conditions. Studies show that BPC GCL can maintain low permeability over time, making it a viable alternative for impermeable applications in red mud storage. Further research is needed to fully understand the mechanisms behind its enhanced impermeability, particularly regarding interactions with metal-containing leachates.

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References

[1] Fehervari A, Gates W P, Turney T W, et al. Cyclic organic carbonate modification of sodium bentonite for enhanced

containment of hyper saline leachates[J]. Applied Clay ence, 2016, 134: 2-12.
[2] Cao J, Kang X, Bate B. Microscopic and physicochemical studies of polymer-modified kaolinite suspensions[J]. Colloids & Surfaces A Physicochemical & Engineering Aspects, 2018, 554: 16-26.
[3] Tian K, Benson C H. Containing Bauxite Liquor Using Bentonite-Polymer Composite Geosynthetic Clay Liners: Towards a Sustainable Geoenvironment[M]. Proceedings of the 8th International Congress on Environmental Geotechnics Volume 2. 2019: 672-678.
[4] Mazzieri F, Di Emidio G, Van Impe P O. Diffusion of calcium chloride in a modified bentonite: impact on osmotic efficiency and hydraulic conductivity[J]. Clays & Clay Minerals, 2010, 58(3): 351-363.
[5] Gholamreza, Mesri, Roy, et al. Mechanisms Controlling the Permeability of Clays[J]. Clays and Clay Minerals, 1971, 19: 151-158.
[6] Norrish K, Quirk J P. Crystalline Swelling of Montmorillonite: Use of Electrolytes to Control Swelling[J]. Nature, 1954, 173(4397): 255-256.
[7] Jo H Y, Katsumi T, Benson C H, et al. Hydraulic Conductivity and Swelling of Nonprehydrated GCLs Permeated with Single-Species Salt Solutions[J]. Journal of Geotechnical & Geoenvironmental Engineering, 2001, 127(7): 557-567.
[8] Kolstad D C, Benson C H, Edil T B. Hydraulic Conductivity and Swell of Nonprehydrated Geosynthetic Clay Liners Permeated with Multispecies Inorganic Solutions[J]. Journal of Geotechnical & Geoenvironmental Engineering, 2004a, 130(12): 962-962.
[9] Scalia IV J, Benson C H, Bohnhoff G L, et al. Long-Term Hydraulic Conductivity of a Bentonite-Polymer Composite Permeated with Aggressive Inorganic Solutions[J]. Journal of Geotechnical & Geoenvironmental Engineering, 2013, 140(3): 04013025.
[10] Dong X L. 2018, Study on migration mechanism and pollution intercepting performance of coal gangue leachate in geosynthetic clay liner [D]. Coal Research Institute.
[11] Malusis M A and Daniyarov A S. Membrane efficiency and diffusive tortuosity of a dense prehydrated geosynthetic clay liner[J]. Geotextiles and Geomembranes, 2016, 44(5):719-730.
[12] Scalia J I, Bareither C A, Shackelford C D. Advancing the use of geosynthetic clay liners as barriers[J]. Geotechnical Engineering, 2018, 49(4): 100-114.