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The Role of Diffusion in Fluoride Containment using Compacted Clay Liner in Landfills

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1 Introduction

Fluoride contamination associated with municipal solid waste landfills has emerged as an increasingly recognized geohazard, particularly across regions where both geogenic and industrial sources contribute to elevated fluorine concentrations in leachate. Excess fluoride poses significant risks to groundwater quality due to its high mobility, weak retardation in conventional soil barriers, and long-term accumulation potential (Ahmad et al., 2022). From an engineering geology perspective, such contamination constitutes a geohazard by inducing progressive deterioration of subsurface hydrogeochemical conditions, expanding the spatial extent of impacted zones, and threatening the safety of water supplies.

Compacted clay liners (CCLs) are widely used as the barrier layer in landfill systems, usually mixed with bentonite to improve its permeability and diffusion performance in engineering practice. However, their ability to attenuate fluoride through diffusion, permeation and sorption remains insufficiently understood, as shown in **Fig. 1**. While previous studies have investigated the fluoride sorption behavior of clay minerals, diffusion behavior evaluation of fluoride in bentonite-amended CCLs is still limited. As a result, current CCLs design often rely on conservative assumptions without meaningful insights into the diffusion behavior of fluoride.

In this study, column diffusion tests were conducted to experimentally qualify the effective diffusion coefficients of fluoride in CCLs with varying bentonite contents. Findings provide an improved understanding of how clay barriers respond to fluoride diffusion.

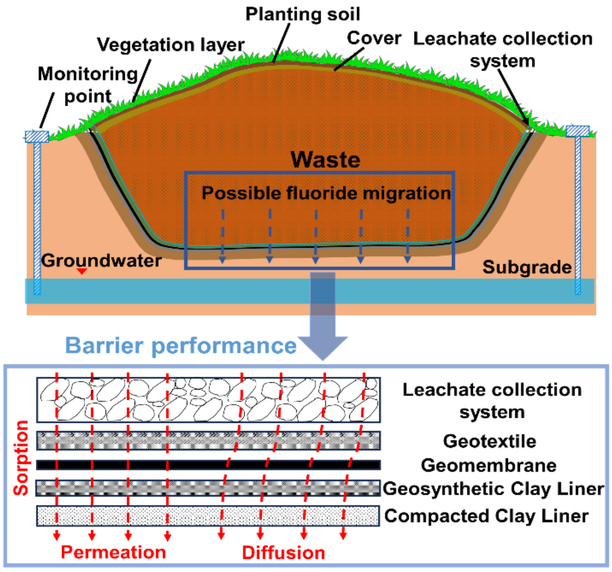

Fig. 1 Research background of this study

2 Methodology

A column diffusion apparatus comprising a flow-circulation system and a rigid-wall cell was employed (**Fig. 2**). The circulation system included two variable-flow peristaltic pumps, while the rigid-wall cell consisted of a top cap, two porous stones, a 100-mm-diameter rigid ring, and a base pedestal. The compacted clay specimen was confined tightly within the ring between the cap and pedestal.

Kasaoka clay and Kunigel V1 bentonite were used as raw materials in this study. All specimens were compacted to achieve the compaction degree of 90%, and their key properties are summarized in **Table 1**. The diffusion tests followed procedures of assembly, saturation, and diffusion, consistent with Tang et al. (2015). The influent fluorine concentration was fixed at 33 mg/L, representing the upper bound of F^- levels reported in Asian landfill leachates. During testing, the pump flow rate was maintained at approximately 0.025 mL/min.

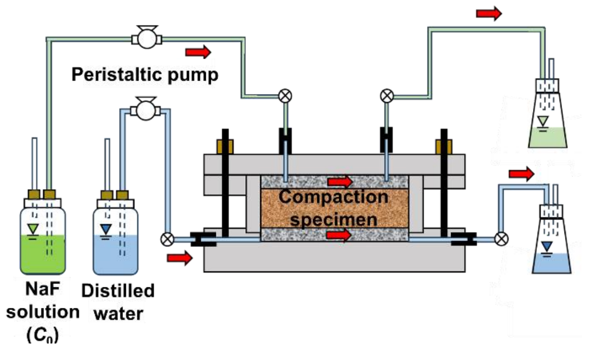

Fig. 2 Schematic drawing of column diffusion test

Table 1 Basic parameters of the compacted clay

Parameter	Sodium bentonite content (%)				
	KK-0	KK-1	KK-2	KK-3	KK-4
Bentonite content, w (%)	0	2.5	5.0	7.5	10
Water content, w (%)	19.1	19.2	19.4	19.5	20.2
Dry density (g/cm^3)	1.45	1.43	1.42	1.41	1.41
Porosity, n	0.46	0.47	0.47	0.48	0.48

3 Results

The Q_t-t curves for 33 mg/L F^- diffusion through compacted clays with varying bentonite contents are shown in **Fig. 3(a)**. The linear portion denotes steady-state diffusion. The corresponding slopes ($\triangle Q_t/\triangle t$) for 0, 2.5, 5.0, 7.5, and 10% bentonite were 13.6, 9.7, 7.8, 6.9, and 6.9 mg/m^2/day, respectively.

Effective diffusion coefficients were then determined using two significant digits to reduce early-stage bias. As shown in **Fig. 3(b)**, effective diffusion coefficients (D^*) values for KK-0 to KK-4 were 1.6×10^{-10}, 1.1×10^{-10}, 8.6×10^{-11}, 7.7×10^{-11} and 7.6×10^{-11} m^2/s, respectively, indicating that bentonite addition effectively reduced F^- diffusion.

4 Discussion

The results show that adding around 5% bentonite effectively reduces the effective diffusion coefficient of fluoride to below 1.0×10^{-11} m^2/s. This reduction indicates that a relatively low bentonite content is sufficient to enhance the containment capacity of compacted clay, providing a practical basis for designing environmentally safe CCLs for landfills containing low-fluoride leachates.

These findings also offer insights for managing fluoride-related geohazards. By limiting fluoride mobility through reduced diffusion pathways and enhanced retention, optimized clay barriers can help mitigate groundwater contamination risks and strengthen the resilience of waste-disposal facilities exposed to geogenic or anthropogenic fluoride sources.

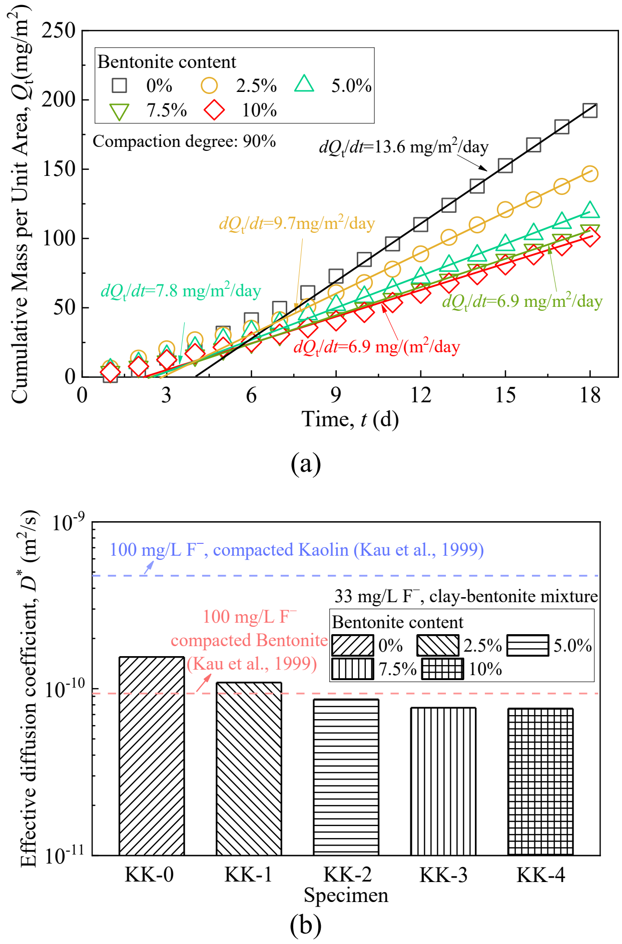

Fig. 3 Variation of **(a)** Q_t-t curve and **(b)** D^* of compacted clays with various bentonite contents

References

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