

Field Application of Waste Sludge-Based Adsorbents for Arsenic Removal from Alkaline Mine Drainage in South Korea

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Abstract

Field pilot-scale experiments were conducted over 371 d to evaluate the applicability of coal mine drainage sludge (CMDS)-derived adsorbents for As removal from alkaline mine drainage. The study site exhibited alkaline conditions (pH 8.2) and an average dissolved As concentration of 400 µg/L. Modified CMDS materials, including polyurethane-coated and pelletized forms, showed substantially improved treatment performance compared with raw CMDS. Effluent As concentrations remained below the Korean discharge limit of 50 µg/L throughout most of the operational period. This site-specific study demonstrates the applicability of mining waste-derived adsorbents as sustainable treatment materials for alkaline mine drainage systems.

Keywords: Arsenic, alkaline mine drainage, adsorption, mine drainage sludge, pilot-scale treatment

Introduction

Mine drainage generated from abandoned mine sites can contain contaminants such as Fe, Al, Mn, Zn, and As, potentially affecting nearby agricultural areas and aquatic systems (McCarthy 2011; Lechner *et al.* 2016; Worlanyo and Jiangfeng 2021). Under natural conditions, dissolved As may be attenuated through adsorption onto Fe and Al (hydr)oxides occurring downstream of mine discharges (Campbell and Nordstrom 2014; Paikaray 2015). However, in neutral or alkaline mine drainage systems, dissolved Fe concentrations are often low, limiting natural attenuation and increasing As mobility (Johnston *et al.* 2020; Rodriguez-Freire *et al.* 2014). Consequently, site-specific treatment strategies are required for effective As control.

Adsorption using Fe-rich materials is considered an effective approach for As removal from mine drainage. Coal mine drainage sludge (CMDS), generated as a by-product during active mine water treatment, contains abundant iron hydroxides and therefore has potential as a low-cost adsorbent (Kim *et al.* 2021). Reuse of CMDS

may also reduce waste disposal requirements and treatment costs (Lee *et al.* 2022).

A detailed physicochemical characterization of the adsorbents and extended interpretation of the experimental results were previously reported by Kang *et al.* (2026). The present paper focuses primarily on field-scale operational performance and practical applicability under alkaline mine drainage conditions.

This study evaluated the As removal efficiency of several sludge-derived adsorbents using pilot-scale column reactors installed directly at an abandoned gold mine in South Korea.

Materials and Methods

The study area is located at the G mine, an abandoned gold mine in North Gyeongsang Province, South Korea. Mine drainage continuously discharges from a single adit and exhibits persistent As contamination exceeding the Korean discharge standard (Fig. 1). As summarized in Table 1, mine drainage pH ranged from 7.4 to 8.5, indicating alkaline conditions. Dissolved



Al, Fe, and Zn concentrations remained relatively low (<0.1 mg/L), whereas dissolved As averaged 400 $\mu\text{g/L}$, exceeding the Korean discharge criterion of 50 $\mu\text{g/L}$ (Ministry of Environment in Korea 2025).

Pilot-scale column reactors were installed near the mine adit using untreated mine drainage as influent (Fig. 2a). Four Fe-based adsorbents were evaluated: raw coal mine drainage sludge (CMDS), polyurethane-coated CMDS (CMDS-PU), pelletized CMDS (CMDS-PE), and commercial granular ferric hydroxide (GFH).

CMDS was obtained from an active coal mine drainage treatment facility in South Korea. To produce CMDS-PU, pulverized sludge (<0.25 mm) was mixed with polyol, water, and methylene diphenyl diisocyanate (MDI), followed by foaming and drying. Detailed preparation procedures and physicochemical characterization were described by Kang *et al.* (2026). A schematic diagram of the experimental setup and column configuration is shown in Fig. 2b.

The packed adsorbent volumes were defined as bed volume (BV): 2.5 L for CMDS, 15.2 L for CMDS-PU, 18.5 L for CMDS-PE, and 17.4 L for GFH. Experimental durations were 371 d for CMDS-PU and GFH and 292 d for CMDS and CMDS-PE.

Column performance was evaluated using effluent As concentrations and cumulative treated BV. The breakthrough point was defined as the point where effluent As concentration exceeded the Korean discharge limit of 50 $\mu\text{g/L}$. Breakthrough behavior was additionally evaluated using the C/C_0 ratio between effluent and influent As concentrations.

Because CMDS is classified as waste material under Korean regulations (Ministry of Environment in Korea 2024), environmental assessment was also conducted using soil and waste contamination testing standards (Ministry of Environment in Korea 2023a, 2023b).

Results and Discussion

Evaluation of As Removal Performance

The CMDS column reached breakthrough most rapidly, exceeding the Korean discharge

standard after treatment of $1,871$ BV on day 80 (Fig. 3a). During the 292 -d operational period, the column processed $12,534$ BV. In contrast, CMDS-PU maintained effluent As concentrations below 50 $\mu\text{g/L}$ until $5,242$ BV on day 364 .

The CMDS-PE and GFH columns continuously maintained effluent As concentrations below the Korean discharge criterion throughout the monitoring period. Total treated volumes were $3,353$ BV for CMDS-PE and $9,550$ BV for GFH.

The total As loads removed also differed substantially among the adsorbents. CMDS removed $1,677$ mg As before breakthrough, whereas CMDS-PU removed $31,374$ mg As. CMDS-PE and GFH removed $26,110$ mg and $66,223$ mg As, respectively, during the experimental period.

Figure 3b shows variations in C/C_0 values with cumulative treated BV. CMDS and CMDS-PU reached breakthrough at C/C_0 values of 0.24 and 0.16 , respectively. These results generally agree with typical adsorption breakthrough behavior where breakthrough occurs near $C/C_0 \approx 0.1$ (Gutierrez-Reyna *et al.* 2024). In contrast, CMDS-PE and GFH maintained C/C_0 values close to zero throughout the experiment.

Although raw CMDS exhibited relatively high Fe content and surface area, its adsorption performance declined rapidly. Field observations showed uneven wetting and preferential flow paths within the adsorbent layer. Channeling likely developed because of non-uniform packing and compaction of the sludge material, limiting effective interaction between mine drainage and the adsorbent (Haryanto *et al.* 2018).

In contrast, CMDS-PU and CMDS-PE formed more stable and permeable adsorption media, improving hydraulic distribution within the columns. Flow rates differed considerably despite identical injection pressure conditions: 67.9 mL/min for CMDS, 229.4 mL/min for CMDS-PU, and 121.5 mL/min for CMDS-PE. Corresponding empty bed contact times were 37.5 , 66.3 , and 152.0 min, respectively. These results indicate that hydraulic stability strongly influenced adsorption efficiency under field conditions.

Environmental Assessment of CMDS

The elemental composition results based on soil and waste contamination standards are summarized in Table 2. According to waste contamination testing standards, harmful substances in CMDS remained below the Korean regulatory limits.

Total content analysis showed detectable concentrations of F, Ni, and Zn, with F and Ni exceeding soil contamination criteria. However, monitoring of the column effluent showed no substantial release of harmful substances from the CMDS-based adsorbents during the experiment (Table 3). These results suggest that the adsorbents remained chemically stable under alkaline mine drainage conditions.

Conclusions

Pilot-scale field experiments demonstrated that modified CMDS materials effectively removed As from alkaline mine drainage under operational field conditions.

Raw CMDS showed relatively rapid breakthrough because of hydraulic instability and channeling within the adsorbent layer. In contrast, CMDS-PU and CMDS-PE exhibited improved hydraulic behavior and longer treatment performance.

CMDS-PU maintained effluent As concentrations below the Korean discharge standard until 5,242 BV, whereas CMDS-PE and GFH maintained stable treatment efficiency throughout the monitoring period.

Environmental assessment indicated limited leaching potential under alkaline conditions, supporting the applicability of mine drainage sludge as a sustainable adsorbent material for field-scale mine drainage treatment.

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Figure 1 (a) Overview of a site at G mine with a single adit discharging mine drainage, and (b) a detailed view of the mine drainage.

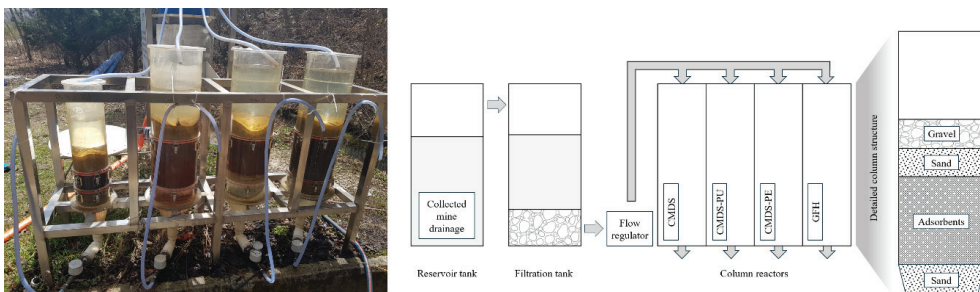


Figure 2 The overall experimental setup installed at the G mine site and Schematic diagram of experiments and detailed structure of columns.

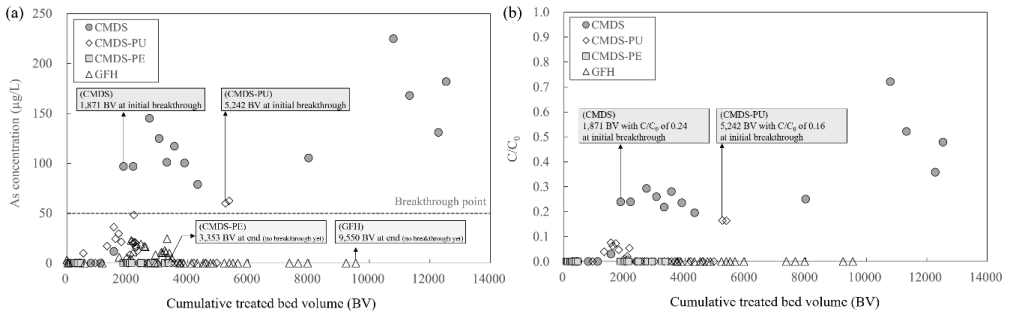


Figure 3 Variation of (a) As concentration and (b) the ratio of the As concentration in effluent (C) to the initial As concentration in the influent (C₀) with cumulative treated bed volume (BV).

Table 1 Flow rate and chemical properties of mine drainage monitored over a period of three years.

Parameter	Average	Maximum	Minimum	Note (standard) ¹
Flow rate (m ³ /d)	240	890	110	–
pH	8.2	8.5	7.4	5.8–8.6
Alkalinity (mg/L as CaCO ₃)	248	390	167	–
EC (µS/cm)	756	1217	366	–
ORP (mV)	142.6	275.9	-65.4	–
As (mg/L)	0.40	0.50	0.31	0.05
Fe (mg/L)	0.07	0.26	0.02	2
Mn (mg/L)	0.03	0.08	0.01	2
Zn (mg/L)	0.002	0.005	N.D.	1

¹Permissible discharge limit according to Korean Ministry of Environment (2025)

Table 2 Analysis results of elemental composition of CMDS before and after drying based on Soil Contamination Testing Standard and Waste Contamination Testing Standard

Elements	Soil Contamination Testing Standard (Korean Ministry of Environment, 2023a)		Waste Contamination Testing Standard (Korean Ministry of Environment, 2023b)			
	Standard ¹	CMDS (before drying)	CMDS (after drying)	Standard ²	CMDS (before drying)	CMDS (after drying)
Pb	200	4.1	4.8	3	ND	ND
Cu	150	ND ³	ND	3	ND	ND
As	25	3.57	4.00	1.5	ND	ND
Hg	4	ND	ND	0.005	ND	ND
F	400	236	439	–	–	–
Cd	4	ND	ND	0.3	ND	ND
Zn	300	211.3	229.0	–	–	–
Ni	100	122.7	134.4	–	–	–
Cr6+	5	ND ³	ND	1.5	ND	ND

¹Standards according to Ministry of Environment in Korea (2022); ²Standards according to Ministry of Environment in Korea (2024); ³ND: Not detected



Table 3 Comparison of concentrations of F, Zn, and Ni in influent (mine drainage) and effluent from CMDS-based columns.

Elements	Average concentration (mg/L)				Note (Permissible discharge standard ¹)
	Influent	Effluent			
	Mine drainage	CMDS	CMDS-PU	CMDS-PE	
F	0.134	0.130	0.052	0.159	3.0
Zn	0.004	0.016	0.012	0.012	1.0
Ni	ND ²)	ND	ND	ND	0.1

¹Permissible discharge limit according to Korean Ministry of Environment (2024); ²ND: Not detected

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