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A study on the effect of *in situ* purification on coal mine drainage by loess

Yunfeng Li[a], Yaoguo Wu[b,*], Sihai Hu[b], Jingtao Liu[c], Cong Lu[b], Maosheng Zhang[d]

[a]*School of Environmental Science and Engineering, Chang'an University, Xi'an 710054, Shaanxi, China*
[b]*Department of Applied Chemistry, Northwestern Ploytechnical University, Xi'an 710072, Shaanxi, China*
Tel: 86 29 88488018; email: wuygal@nwpu.edu.cn
[c]*The Institute of Hydrogeology and Environmental Geology, CAGS, Shijiazhuang 050061, Hebei, China*
[d]*Xi'an Institutes of Geology and Mineral Resources, Xi'an 710054, Shaanxi, China*

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ABSTRACT

Two *in situ* tests, in an unsaturated loess zone and an unconfined aquifer (northern Shaanxi Loess Plateau, Shaanxi, China), were conducted to investigate the potential of loess to purify coal mine drainage water. The first test involved the analysis of loess samples that were collected at the start of the test and at 20 days after the termination of the test. Results indicated general declines in the loess of two heavy metals: Cd declined from ∼3 to <1.5 mg/kg and Pb from ∼4 to <1.0 mg/kg. This demonstrated the capacity for removal of Cd and Pb through the irrigation of unsaturated loess. A second test indicated that, although the concentrations of a number of water quality variables remained high in the groundwater of the unconfined aquifer, after irrigation of loess there was a steady decline in the concentrations of Cd and petroleum, as well as a decline in electrical conductivity (EC). From the drainage source to a lower elevation site (of 5 m), the concentration of Cd and petroleum declined from 1.835 to 0.808 μg/L and 1.20 to 0.82 mg/L, respectively, while EC declined from 3.41 to 1.89 ms. We concluded that the unconfined loess aquifer had the potential to purify the infiltrating coal mine drainage water and to protect groundwater quality.

Keywords: Coal mine drainage water; *In situ* test; Unconfined aquifer; Loess; Purification

1. Introduction

The effectiveness of land for the *in situ* treatment of wastewater from industrial and mining activities is dependent on the geological characteristics of the site, including the thicknesses of the unsaturated and saturated soil, and the physical, chemical, and biological processes associated with such sites [1]. Soil characteristics, such as lithology, thickness and structure, and the composition of the discharge water have been extensively studied, with the purpose of finding ways to treat coal mining drainage [2]. Loess is a special type of soil that is widely distributed throughout northwestern China, Middle Asia, Russia, the Middle East, and North America [3,4]. In China, this soil is abundant in certain regions, mainly in the northwest, and covers an area of approximately 640,000 km^2. This loess region is also rich in resources, including coal, oil, and salt, thus attracting mining activity. Nevertheless, there is very little awareness of the potential of loess for treating coal mining drainage

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*Corresponding author.

[5,6]. The northern Shaanxi area (also known as Shaanbei), which is an important provider of chemical energy to the Shaanxi Province, was selected as a case study area. In the present paper, we explore the effectiveness of loess for the treatment of wastewaters discharged from coal mining activities and to provide the scientific basis for investigating locally available geological resources for mitigation and control of environmental impacts associated with wastewater discharge from coal mines in the study area.

2. Background conditions

The Shaanbei Energy Chemical Base extends across the Fugu, Shenmu, and Yuyang Counties (districts) of Yulin City and part of Jiaxian and Hengshan County in Shaanxi Province (Fig. 1), covering an area of about 22,604 km^2 with a population of approximately 1,210,400.

This is a low-rainfall region in a fragile ecological environment with a shortage of water resources. Under natural conditions, the insufficient water resource severely restricts the development and functioning of the Northern Shaanxi Energy Chemical Base, including mining and processing of minerals resources. There is thus a need to find ways to protect this scarce water resource from pollution due to human activities, including the mining and processing of minerals.

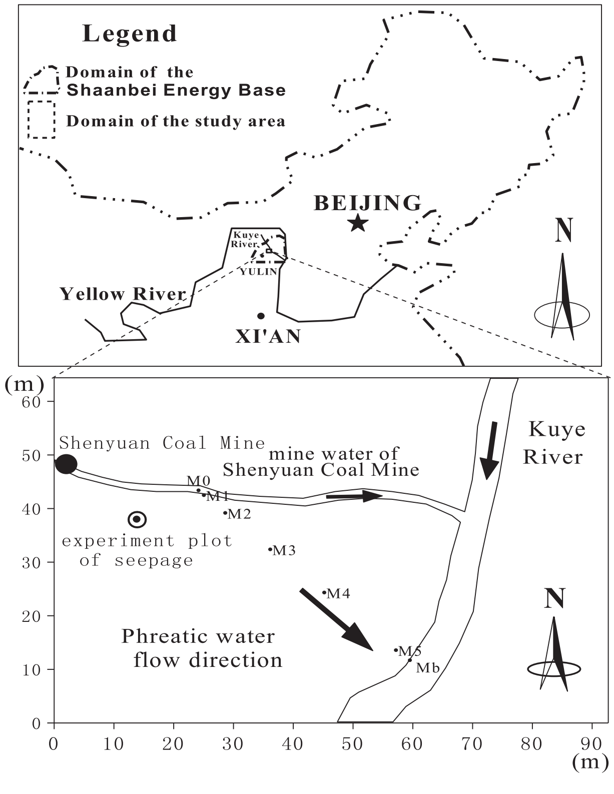

Fig. 1. Location of *in situ* tests.

We conducted an *in situ* experiment near the Shenyuan coal mining drainage outfall (Fig. 1) where the thickness of the loess is approximately 1.5 m and the phreatic water table is more than 1.5 m depth. The effluent from the Shenyuan coal mine was assumed to be representative of typical mining wastewaters, with water quality parameters similar to those listed in Table 1, with the exception of four parameters (N-NH$_4$, hydroxybenzene, Cr^{+6}, As, and Hg); the concentrations of these in the Shenyuan drainage were lower than the detection limits of these compounds.

3. Test processes and analytical methods

3.1. Tests

The experimental field work consisted of four steps, described below.

Step 1: Collection of background loess samples: representative samples were collected and their chemical composition determined so as to obtain the background values.

Step 2: Infiltration of production effluent from the coal mine: the production wastewater was irrigated continuously toward the wind-blown loess until the infiltration front moved to a depth of 1.5 m.

Step 3: Collection of loess samples at the end of infiltration: loess samples were collected immediately

Table 1
Water quality of production effluent from Shenyuan power plant

Parameters	Concentration
N–NH$_4$ (mg/L)	<0.05
P (mg/L)	0.045
Hydroxybenzene (mg/L)	<0.002
Cr^{+6} (mg/L)	<0.005
As (mg/L)	<0.002
Suspended solids (mg/L)	117.5
pH	7.89
Hg (mg/L)	<0.0005
Cd (μg/L)	1.651
Pb (μg/L)	9.483
Chemical oxygen demand (COD) (mg/L)	3
Electrical conductivity (ms)	3.48
Eh (mV)	427.5
Temperature (℃)	11.5
Petroleum (mg/L)	1.22

after the cessation of irrigation. Analytical results from this batch of sand samples are representative of the pollutants that were retained in the loess.

Step 4: Collection of loess samples 20 days after the end of irrigation: a third batch of loess samples was collected 20 days after the irrigation. The results provided information on the residual concentrations of the pollutants.

Step 2 of the field test (the infiltration test) was comprised of two loops, the inner loops and the outer loop [2]. The area of the inner loop was approximately 0.1 m^2. The production effluent was applied uniformly to the area until the infiltration front moved to a depth of 1.5 m, as observed on the pit walls of the collection pit. During the experiment, the water level of the outer loop was constantly adjusted to ensure that it did not fall below the water level in the inner loop. The flow and time taken for infiltration were recorded frequently. The wastewater was injected into the inner and outer loops at the same time. The injection lasted 333 min with a total of 565 L wastewater injected, including 185 L of wastewater, which passed through the inner loops. The initial infiltration rate of the inner loops was 0.83 L/min but gradually stabilized at 0.71 L/min.

Pollutant components from coal mine drainage entered the phreatic water section. The quality of water from the sewage drain of the coal mine drainage was used in both of the vertical infiltration test and the horizontal migrating test.

3.2. Sample collection

Three batches of loess samples were collected. The first batch was collected prior to infiltration from a locality next to the experimental site. This ensured that the sampling activities did not damage the structure of the loess formation but were close enough to have the same lithological characteristics. The infiltration pit was then divided into two halves, to facilitate the collection of the second and third batches of samples. In each batch, the loess samples were collected at five discrete depths: 0.2, 0.4, 0.6, 1.0, and 1.5 m from the surface. The sampling pits were backfilled after sample collection.

Vertical infiltration test: The solution for this test was made up in the following proportions: two parts original sample, two parts acidulated sample, and one part alkalified sample, making up a total volume of 6,500 mL for water samples.

Horizontal migration test: Five bottles of samples were also taken from each sampling pit, each one comprising two bottles of original sample, two bottles of acidulated sample, and one bottle of alkalified sample. At this stage, a total of 35 water samples had been taken from seven sample sites.

The water samples were preserved with NaOH, HNO_3, or H_2SO_4 and sent to a laboratory for further analysis.

3.3. Analytical methods

We made use of atomic fluorescence spectrometry to determine the As concentration, using an XGY-1011A spectrometer. Fluorescence intensity is positively correlated with the content of As in the solution. Nessler's reagent photometry was adopted to determine N-NH_4 concentration, by means of a 721 spectrophotometer, set at a measure wavelength of 410–425 nm. A Thermo Electron X-7 ICP-MS (inductively coupled plasma-mass spectrometer) was used to determine Cd and Pb concentrations, and an infrared spectrophotometer was used to determine petroleum concentrations.

4. Analysis of field test results

4.1. Analysis of vertical infiltration test results

Hydroxybenzene, Cr^{6+}, and Hg were all lower than the detected limits of 0.002, 0.005, and 0.0005 (mg/kg), respectively; therefore no further tests were done on these compounds.

Figs. 2 and 3 show the concentration profiles for Cd and Pb, respectively. Fig. 2 indicates that the loess appears to have a high capacity to purify Cd. The concentration of 1 mg/kg is regarded as a background level in loess samples. Since the concentration of the infiltration wastewater was 1.651 μg/L, it can be expected that the concentration of Cd in the loess would rise. As the infiltration interface reached 1.5 m, the concentration of Cd rose above 3 mg/kg at both depths of 0.2 and 0.4 m. From 0.6 to 1.5 m, the concentration of Cd gradually declined to levels of about 1.5 mg/kg. Twenty days after the infiltration test, the concentration of Cd in all the loess samples stabilized at concentrations of approximately 2 mg/kg, indicating a broad reduction in Cd concentration. This illustrates the physical, chemical, and biological effect of loess on Cd, the overall result being a mitigation of the pollution threat to underground water.

Fig. 3 shows that the loess appears to have high capacity to purify Pb. The background concentration of Pb in loess was 1 mg/kg, which is below the detection limit. As the wastewater, with a concentration of 9.483 μg/L, was applied to the test area, the concentration of Pb in the loess initially showed an obvious change. When the infiltration interface just reaches at the depth of 1.5 m, the concentration of Pb

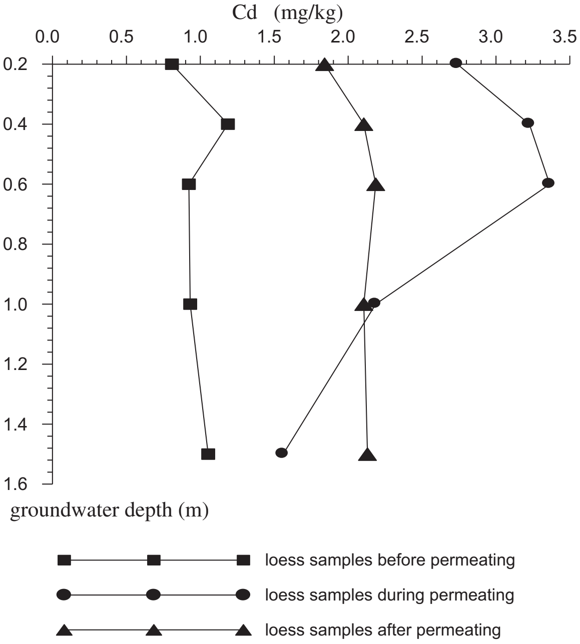

Fig. 2. Concentration profiles of Cd in loess samples.

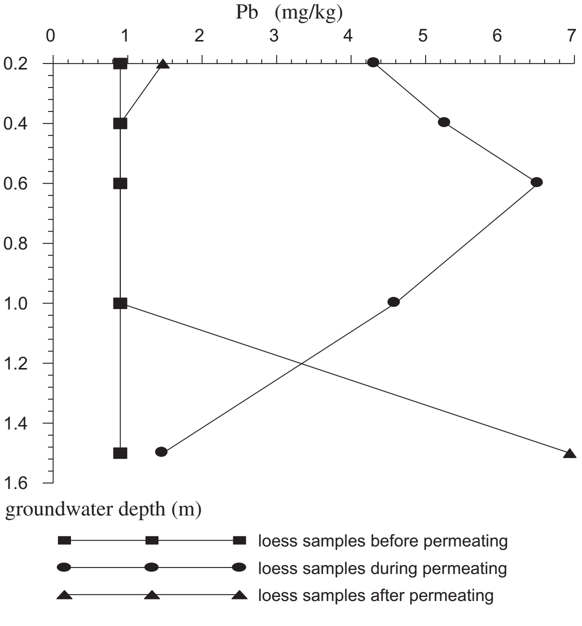

Fig. 3. Concentration profiles of Pb in loess samples.

is more than 4 mg/kg at depths of 0.2, 0.4, 0.6, and 1.0 m, with a maximum at 0.6 m. The concentration of Pb decreases after 1.0 m, to just above 1 mg/kg at 1.6 m. This shows that Pb has the high ability of transportation under the studied conditions. Twenty days after the infiltration test, the concentration of Pb in all the loess samples was below the detection limit. This indicates that, on the one hand, Pb can decline during the first 20 days after infiltration, but on the other hand, the concentration of Pb showed a broad reduction during the course of infiltration. The concentration reduction was interpreted to be a result of physical, chemical, and biological degradation in the loess. This similarity indicates that the loess also has strong self-purification ability for Pb.

4.2. Analysis of horizontal migration test results

Results of the horizontal migrating test (Figs. 4–6) indicate that the contents of Cd, petroleum, and electrical conductivity (EC) in five phreatic water sampling sites along the horizontal section of 47 m all rise and fall irregularly, and the deterioration effect of these pollutant components on this section is not obvious.

Fig. 4 shows that, as the distance of horizontal migration increases from the upstream to the downstream areas of the section, the content of Cd in phreatic water tends to gradually decrease, from 1.835 μg/L at M1 to 0.701 μg/L at M5. Within the short distance of 5 m between M1 and M2, it declined from 1.83 to 0.808 μg/L. This suggests that the phreatic aquifer along the studied section has the ability to remove Cd from the groundwater.

Fig. 5 shows that as the distance of horizontal migration increases from the upstream to the downstream section, the content of petroleum in phreatic water tends to decrease gradually, from 1.22 mg/L at M0, to 0.45 mg/L at M5. In the short distance of 5 m between M1 and M2, it declined from 1.20 to 0.82 mg/L. This suggests that the phreatic aquifer has the potential to degrade petroleum and purify the groundwater.

Results illustrated in Fig. 6 indicate that, as the distance of horizontal migration increases from the

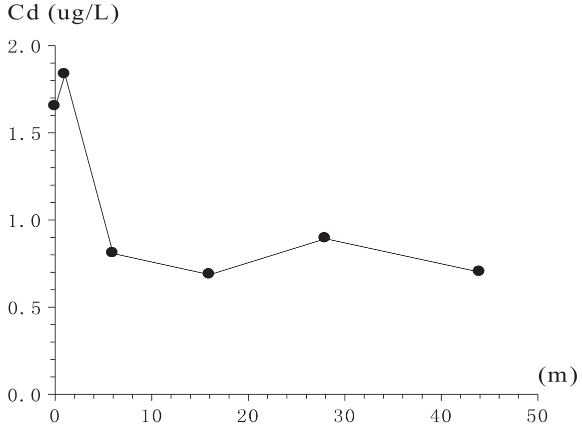

Fig. 4. Analysis curve of the horizontal migration of Cd as a drainage pollutant component in Shenyuan coal mine.

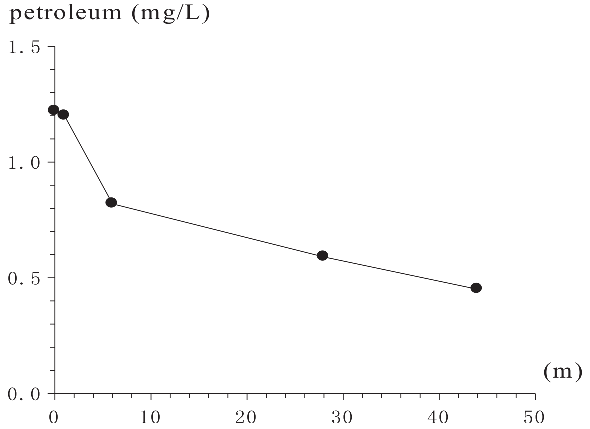

Fig. 5. Analysis curve of the horizontal migration of petroleum as a drainage pollutant component in Shenyuan coal mine.

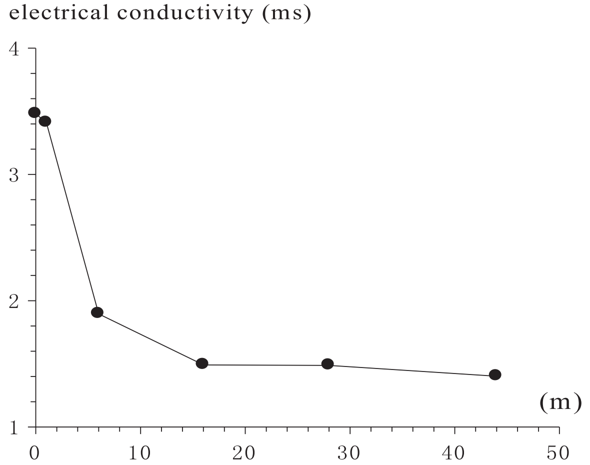

Fig. 6. Analysis curve of the horizontal migration of EC as a result of drainage pollutant components in Shenyuan coal mine.

upstream to the downstream section, the content of EC in phreatic water tends to decrease gradually, from 3.48 ms at M0 to 1.401 ms at M5. In the short distance of 5 m between M1 and M2, it has declined from 3.41 to 1.895 ms. EC reflects the level of electrolytes in the solution and is regarded as an indication of the total mineral salts dissolved in the water. The EC of aqueous solutions is in direct proportion to the dissolved solid content. As indicated in Fig. 6, the content of EC in phreatic water tends to decrease gradually as the distance of horizontal migration increases. This suggests that the phreatic aquifer has a strong potential to purify the infiltrating water.

5. Conclusions

In the vertical infiltration test, within 20 days of cessation of sewage irrigation, Pb and Cd migrated downwards. This indicates that the loess unsaturated zone has the ability to remove Pb and Cd.

In the horizontal migration test, the polluted drainage water from the Shenyuan coal mine had a high content of P, Cd, Pb, COD, EC, and petroleum. The concentrations of Cd, petroleum, and EC declined steadily in the phreatic water section of the coal mine drainage outfall. Within 5 m of the sewage drain, the Cd concentration declined from 1.835 to 0.808 μg/L; petroleum from 1.20 to 0.82 mg/L, and EC from 3.41 to 1.895 ms. This suggests that the unconfined groundwater system has the potential to purify the infiltrating coal mine drainage water.

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