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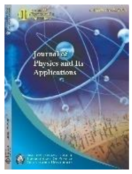

Electrokinetic Remediation Treatment of Chromium (Cr) Concentration and Distribution in Soil from the PT Semen Baturaja Cement Factory Environment

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A B S T R A C T

PT Semen Baturaja, a cement production company in South Sumatra, Indonesia, holds a Mining Business License of 103.4 hectares, of which 64.23% was reclaimed during 2017–2021. However, the revegetation success rate remains low at only 9%, potentially due to excessive soil chromium (Cr) accumulation. This study investigates the application of electrokinetic remediation to reduce Cr concentrations and improve soil conditions for revegetation. The experiment was conducted on soil samples collected from Disposal Area 4 of PT Semen Baturaja, using a laboratory-scale setup with copper electrodes powered by a 20 V direct current, applied continuously for 48 hours. The results showed that Cr ions tend to migrate toward the anode due to electromigration, while redox reactions influence Cr distribution over time. The highest treatment efficiency was observed in segment one (11.123%), and the lowest in segment three (1.651%). These findings demonstrate the potential of electrokinetic remediation as a viable method for enhancing revegetation in Cr-contaminated post-mining soils.

1. Introduction

Mining activities in forest areas are often driven by the presence of valuable mineral resources such as coal, nickel, silica, and other industrial minerals [1]. In Indonesia, these resources are frequently located within designated forest zones. According to a 2021 report from the Coordinating Ministry for Economic Affairs, approximately 5.2 million hectares of forest land have been utilized for mining operations under Mining Business Licenses, contributing up to 13% to national economic growth. Despite their financial benefits, mining activities in forest ecosystems also pose significant environmental risks, primarily due to the release of industrial waste and the accumulation of toxic heavy metals in topsoil, including chromium (Cr), lead (Pb), cadmium (Cd), and mercury (Hg) [2][3].

To mitigate the environmental impact of mining, the Indonesian government mandates post-mining land reclamation under Government Regulation No. 78 of 2010. This regulation obligates holders of Business Licenses for the Utilization of Land for Mining Activities to restore disturbed lands through structured reclamation and revegetation programs [4]. PT Semen Baturaja, a cement production company operating in South Sumatra, holds a mining business license covering 103.4 hectares for limestone and clay extraction [5]. As of 2021, the company had reclaimed 64.23% of its concession area. However, the success of revegetation remains low, with an index of only 9% [6].

Previous reclamation efforts at PT Semen Baturaja have included phytoremediation using marginal-land-tolerant species such as acacia *(Acacia mangium)*, sengon *(Falcataria moluccana)*, and pine *(Casuarina equisetifolia).* While environmentally friendly, these methods have shown limited effectiveness in improving soil conditions and heavy metal uptake [7]. The persistently low revegetation index suggests chromium accumulation may be a primary limiting factor in soil recovery.

Electrokinetic remediation is proposed as a complementary technique for soil restoration to address this issue. Electrokinetic remediation involves the application of a low-voltage direct current across soil using electrode pairs, promoting the movement of charged contaminants through electromigration, electroosmosis, and electrophoresis [8][9]. Electrokinetic remediation offers advantages over other soil remediation methods, as it can reduce heavy metal concentrations more rapidly and apply to various soil types, making it a more flexible approach. This method is particularly effective in fine-grained soils. It has been successfully applied in international case studies, such as the 2009 railway bed rehabilitation project in London, where pollutant levels were reduced by up to 75% [10].

This study aims to observe changes in chromium (Cr) concentration during electrokinetic treatment, as well as the mobility and reduction of Cr in soil collected from the mining site of PT Semen Baturaja. An ex-situ, laboratory-scale experiment was conducted using soil from Disposal Area 4. Copper electrodes were applied at 20 V for 48 hours, and changes in chromium distribution, pH, and treatment-related parameters were monitored. The outcomes of this study are expected to contribute to improved strategies for post-mining land restoration and revegetation success in contaminated forest areas.

2. Methods

This study was conducted through several sequential stages, including soil sample preparation, characterization, and electrokinetic remediation treatment. Each stage involved specific procedures and equipment to ensure the accuracy and reliability of the data. Below is a detailed explanation of the experimental steps, tools, and materials. The research flow in this study is shown in Fig. 1.

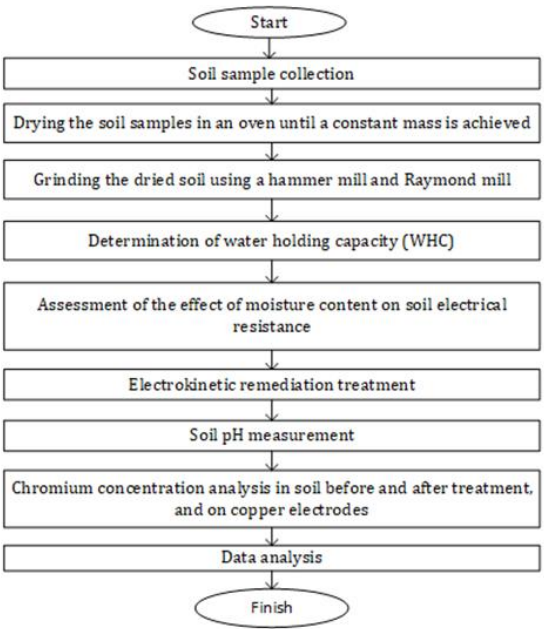

Fig. 1: Research flowchart.

This study utilized various materials and equipment to support the electrokinetic remediation process. The primary material was post-mining soil collected from Disposal Area 4 of PT Semen Baturaja, which served as the experimental sample. Additional materials included distilled water and copper electrode plates (dimensions: 10 cm × 10 cm × 1.5 mm), which functioned as electrical conductors.

The equipment used in this study included the following: WANPTEK DC Power Supply (WPS 30104H): Provided the direct current (DC) required for the electrokinetic system; Alligator clip wires: Used to connect and transmit electricity from the power supply to the electrodes; Aquarium tank (30 cm × 10 cm × 10 cm): Served as the soil container during the treatment process; ENDECOTTS Octagon 200 Sieve Shaker: Used to separate soil particles by size; Biobase Laboratory Oven: Utilized to dry soil samples to a constant weight; Aluminum trays: Functioned as containers for soil during the drying process; Digital pH meter: Used to measure the soil's pH levels before and after treatment; Raymond Mill and Hammer Mill: Employed to crush and homogenize the soil samples; X-ray Fluorescence (XRF) Analyzer: Used to determine the concentration of heavy metals, particularly chromium (Cr), in both soil and electrode samples.

The soil samples were dried at the Tropical Forest Engineering Laboratory, Sumatra Institute of Technology, using a Biobase oven until constant weight. The dried soil samples were crushed using a Hammer Mill & Raymond Mill at the Laboratory of Excavation Materials Processing, Sumatra Institute of Technology to reduce the particle size of the soil samples used. After crushing, the soil samples were sieved using a sieve shaker until the soil samples passed the 200-mesh sieve.

Water Holding Capacity (WHC) measurement was carried out using 50 gram soil sample and 50 ml of water. Tools used include filter paper, Erlenmeyer flask, and pipette. Soil measuring 200 mesh was put into a funnel-shaped filter paper on top of an Erlenmeyer and then filled with water. The amount of water that falls into the Erlenmeyer is observed and then calculated using the following equation.

$$\text{WHC} = \frac{\text{initial water volume} - \text{final water volume}}{\text{soil mass}} \times 100\%$$

where WHC is water holding capacity (%), initial water volume is volume water added to the soil sample (mL), final water volume is volume of water that passes through the soil and is collected in milliliters (mL), and soil mass is mass of the soil sample used in the test that measured in grams (g).

This stage was carried out using 1.5 kg of soil placed in an aquarium, along with a copper electrode plate, multimeter, power supply, and 1200 mL of distilled water. Distilled water was added incrementally, starting from 200 mL up to 1200 mL, in 100 mL intervals. After each addition, the resulting electric current was measured using a multimeter. This procedure aimed to determine the optimal water content. That is, the volume of water that produced the highest current and correspondingly the lowest electrical resistance under electrokinetic treatment conditions.

Soil samples passed through a 200-mesh sieve were placed into an aquarium measuring 30 cm × 10 cm × 10 cm. Two copper electrode plates were inserted into the soil and connected to a power supply, with a multimeter used to monitor the applied current and voltage. The aquarium was divided into three segments of 10 cm each to define the sampling areas for post-treatment analysis. The electrokinetic treatment was conducted under a constant voltage of 20 V and a current limit of 5 A for 48 hours. The configuration of the electrokinetic treatment setup is illustrated in Fig. 2.

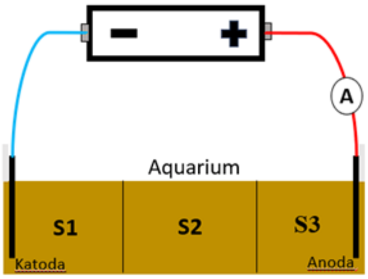

Fig. 2: Electokinetic configuration.

Soil samples were analyzed using X-ray Fluorescence (XRF) at the BRIN Tanjung Bintang Laboratory. Approximately 30 grams of soil were collected at three time points: before treatment, after 24 hours, and after 48 hours, to determine the concentration of chromium (Cr) in the soil. In addition, both copper electrodes were submitted for elemental analysis to assess potential changes in metal content resulting from the electrokinetic process.

Soil samples were taken as much as one tablespoon from each segment before, after 24 hours, and after 48 hours of treatment. Subsequently, the soil sample was mixed with 15 mL of distilled water and allowed to settle until the supernatant became clear. A digital pH meter was immersed in a clear solution to measure the soil pH. This measurement was conducted to determine the acidity level of soil.

Data analysis was conducted based on the results of soil sample testing obtained through X-ray Fluorescence (XRF). Chromium (Cr) concentrations, expressed in parts per million (ppm), were processed using Microsoft Excel to generate comparative graphs illustrating the changes in Cr levels before and after treatment. In addition, the data were used to evaluate the directional migration of Cr across different soil segments.

3. Result and discussion

WHC measurement is carried out to determine the ability of soil to bind and store water. WHC measurements on the sample showed results with a percentage of 83.16%. Based on the measurement results, water can be added as much as 1247.4 mL for electrokinetic remediation treatment. In this case, soil texture is one factor that affects the soil's ability to bind and retain water [3]. The sample used in the WHC measurement is a soil with a particle size of 200 mesh. The condition of soil samples with fine texture further increases the soil's ability to bind and distribute water, because soils with micro pore arrangement fractions have a tenuous particle structure that can facilitate the process of water entering, moving, and filling the space in the soil pores [11].

Although the WHC results showed that the soil could hold up to 1247 mL, puddles appeared after adding 1000 mL during the experiment. Therefore, the volume of water used for the electrokinetic remediation treatment set was 900 mL. This is because puddles reduces the efficiency of the electrolysis process at the electrodes, where H^+ ions should be produced at the anode and OH^- ions at the cathode to regulate soil pH. When the soil is overly saturated, a portion of the electrical current is diverted to splitting water into hydrogen and oxygen gases (water electrolysis), thereby reducing the production of H^+ or OH^- ions and preventing pH changes. As a result, the mobilization or precipitation of pollutants (heavy metal ions) is inhibited. [12].

Based on the measurement results obtained, a graph can be made, which can be seen in Fig. 3.

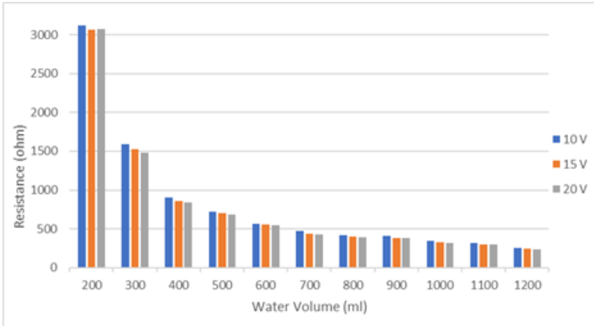

Fig. 3: Effect of water content and voltage on soil electrical resistance.

Fig. 3 shows soil electrical resistance decreases with increasing water volume. The lowest resistance was observed at the maximum water addition based on the soil's water holding capacity (WHC), specifically at 1200 mL, with resistance values of 236.7 Ω at 20 V, 241.2 Ω at 15 V, and 250 Ω at 10 V. This reduction in resistance is attributed to higher soil moisture, which fills soil pores and enhances electrical conductivity [16]. Moist soil acts as a conductor, facilitating electron migration through increased current flow due to the presence of water. As water content increases, it serves as a medium for electrical movement, thus reducing soil resistance [17].

WHC measurements showed that the soil could retain up to 1247 mL of water. Saturation began at around 1000 mL, indicated by surface pooling. Such pooling may lead to uncontrolled pollutant mobility through water-bonded transport mechanisms [12]. Based on these observations, 900 mL of water was selected for the electrokinetic treatment using 20 V, as this condition provided high current flow without causing surface water accumulation.

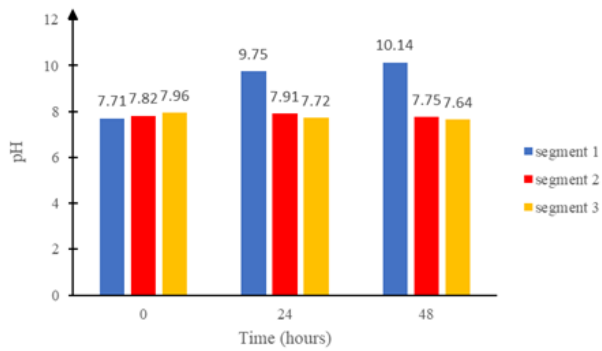

Fig. 4: Changes in the pH value of each segment

Data on pH changes in each segment can be seen in the graph in Fig. 4. The electrokinetic remediation treatment caused a shift of ions towards the electrodes, resulting in pH changes in each segment after 24 and 48 hours. Before treatment, the pH of segment 1 was 7.71, 7.82 in segment 2, and 7.96 in segment 3. After 24 hours, the pH of segment 1 rose significantly to 9.75, along with the pH of segment 2 to 7.81, while the pH value of segment 3 decreased to 7.72. After 48 hours, the pH of segment 1 continued to increase to 10.14, while segments 2 and 3 decreased to 7.75 and 7.64.

The electrolysis process occurs when two electrodes (anode & cathode) are electrified. Fig. 4 shows that the pH of the soil in segment 1 near the cathode (negative pole) increased with treatment time. The electric field causes reduction at the cathode, so that water (H_2O) is converted into OH- (hydroxide) molecules and hydrogen gas (H_2) [18]. Fig. 3 shows that the pH of segment 2, located between the anode and cathode, increased at 24 hours and decreased at 48 hours. The movement of ions, reactions at the cathode and oxidation at the anode, influence this change. Additionally, the electrophoresis process affects the movement of charged ions, contributing to this change. Segment 3, which is close to the anode, showed a decrease in pH over time. This decrease is caused by the oxidation of water (H_2O) to O_2 at the anode, so increases H+ ions and decreases pH due to the escape of electrons towards the anode rod [19].

The chromium concentration changed over the treatment period. In segment 1, it decreased from 261.6 ppm to 260.2 ppm after 24 hours, followed by a significant drop to 232.5 ppm after 48 hours. In segment 2, the concentration declined from 257 ppm to 231 ppm after 24 hours, then increased to 247.4 ppm after 48 hours. In segment 3, it increased from 218 ppm to 240.2 after 24 hours, decreasing to 214.4 ppm after 48 hours. These variations are illustrated in Fig. 5.

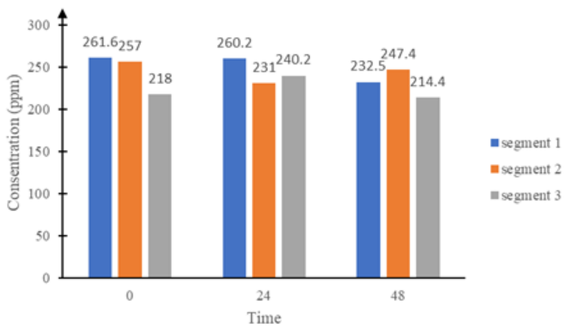

Fig. 5: Changes in Chromium (Cr) concentration in each segment.

The decrease in chromium concentration in segments 1 and 2 at the 24-hour mark can be identified as the result of changes in the chromium ion form due to the influence of soil acidity, which subsequently migrates toward segment 3 through electromigration. Based on Fig. 5, it can be observed that the soil pH in segment 1 indicates a strongly alkaline condition. During the electrolysis process, the alkaline soil condition leads to the formation of OH- ions and the removal of H+ ions, thereby promoting the formation of chromium ions with a higher oxidation state into chromate (CrO_4^{2-}) [20]. The reaction equation for the transformation of Cr ions under alkaline conditions is shown in the following equation:

$$Cr^{6+} + 4OH^{-} \rightarrow CrO_4^{2-} + 2H_2O$$

Based on the reaction, it can be identified that alkaline pH conditions influence the transformation of Cr ions into negatively charged Cr ions in segment 1, driven by an increase in pH. Due to electromigration, these negatively charged Cr ions will move toward the oppositely charged electrode, namely the anode located in segment 3 [12]. This decreases the Cr concentration in segments 1 and 2, while the Cr concentration in segments 3 increases.

At 48 hours, a decrease in chromium concentration was observed in segments 1 and 3, while the chromium concentration in segment 2 increased. The decrease in chromium concentration in segment 3 may be attributed to the transformation of chromate (CrO_4^{2-}) into its gaseous form, CrO_3 [21]. During electrolysis, water (H_2O) is oxidized into O_2 and H^+, leading to an increase in H^+ ions, which in turn causes a decrease in the soil pH. The CrO_4^{2-} ions are then protonated by reacting with H^+ to form CrO_3, as represented by the following equation:

$$CrO_4^{2-} + 2H^{+} \rightarrow CrO_3 + H_2O$$

CrO_3 is a strong oxidizing agent that can induce corrosion when it reacts with metal surfaces, such as the copper plate used as the anode. The structure of the CrO_3 ion is dominated by a large number of oxygen atoms bonded to chromium. This composition enables CrO_3 to release oxygen during reactions, enhancing its powerful oxidizer capability [24]. This corresponds with the corrosion observed on the anode plate surface, as shown in Fig. 6.

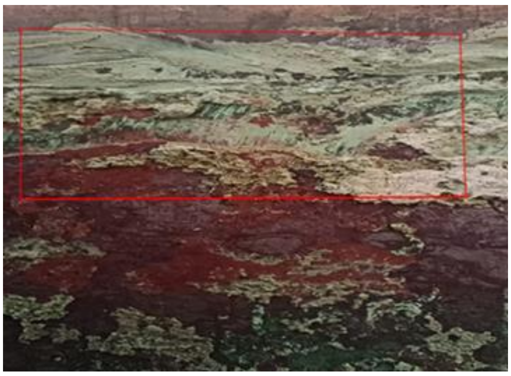

Fig. 6: Corrosion on the anode plate surface.

The copper plate used as the electrode was also tested using XRF to determine whether changes in chromium concentration in the soil were influenced by the presence of chromium on the copper plate itself. The results of the electrode plate analysis using XRF are presented in Table 1.

Table 1. Element Concentration on the Electrode Plate

Element	Concentration (ppm)		
	Before	Cathode	Anode
Chromium (Cr)	0	0	0

The results showed that chromium (Cr) was undetected on any electrode part. This indicates that the changes and shifts in chromium concentration in the soil were not influenced by chromium content in copper, which could have been ionized due to electrochemical reactions. It can be identified that the changes in ion forms and the migration of chromium in the soil occurred due to pH conditions and the influence of electric current.

The chromium concentration in the soil remains above 200 ppm, despite significantly decreasing following electrokinetic remediation treatment. Soil conditions with chromium concentrations exceeding the threshold limit (50 ppm) can lead to root tissue damage, cell division and elongation disruption, stunted growth, and reduced photosynthetic capacity in plants growing on such soil [23]. These conditions require the selection of plant species that can survive in marginal environments if revegetation efforts are to be carried out. In such cases, pioneer species such as sengon (*Albizia chinensis*) or casuarina (*Casuarina equisetifolia*) can be chosen, as they can help improve soil structure while providing shade for other plant species to be introduced later [24]. Chromium-contaminated soil is unsuitable for cultivating fruit-bearing plants such as durian, mango, matoa, or other similar species, as this could potentially spread chromium toxicity through the fruits if consumed by living organisms [25].

4. Conclusions

The findings of this study indicate that electrokinetic treatment significantly affects the concentration and mobility of chromium (Cr) in soil. Under alkaline pH conditions, chromium predominantly exists in the form of chromate ions (CrO_4^{2-}), which migrate toward the anode via electromigration. During the first 24 hours of treatment, a decrease in Cr concentration was observed in segment 1, while an accumulation occurred in segment 3. This was followed by a subsequent reduction in Cr levels, likely due to the transformation of CrO_4^{2-} into chromium trioxide (CrO_3), which reduced its mobility and availability in the soil matrix.

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