

Enhanced electrokinetic dissolution of naphthalene and 2,4-DNT from contaminated soils

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Abstract

Electrokinetic soil remediation has been proven to remove heavy metals and polar organics from low hydraulic conductivity subsurface environment. In this study, carboxymethyl- β -cyclodextrin (CMCD) was used as a carrier to assist electrokinetic treatment for removal of low polarity organic contaminants from soils (2.2% organic carbon content). Naphthalene and 2,4-dinitrotoluene (2,4-DNT) were selected as the test compounds. The results from columns experiments showed that 46 and 43% of naphthalene and 2,4-DNT, respectively, were removed using 0.01N NaNO₃ flushing solution with 40 V electrical potential while 70 and 72% of naphthalene and 2,4-DNT were removed using 2 g/L CMCD solution. Naphthalene and 2,4-DNT removal was enhanced to 83 and 89%, respectively, by using 2 g/L CMCD with 40 V electrical potential. Findings from this study also demonstrated that cyclodextrin assisted electrokinetics can enhance the removal rate of naphthalene and 2,4-DNT. Electric potential applied has more influence on the contaminant removal than the amount of CMCD used. Higher voltage application caused increase in the removal rate of naphthalene and 2,4-DNT, and appeared to be one of the critical factors in obtaining higher contaminant removal while increasing CMCD solution concentration above 2 g/L appeared to have little effect on the contaminant removal.

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1. Introduction

Improper disposal of hazardous wastes into the environment, such as solvents, volatile organics, dioxins, dibenzofurans, pesticides, PCBs, heavy metals, and arsenic compounds can contaminate groundwater resources. Thus, the elimination of toxic and hazardous wastes from the surface and subsurface environments is critical to safeguard public health and safety. The long-term remediation efforts, such as groundwater pump and treat, are often ineffective for the removal of low polarity organic contaminants which are strongly adsorbed to the soils. This poor performance is mainly due to low water solubility of these contaminants, their rate limited dissolution from the sorbed phases, and limited capability of hydraulic pressure to remove contaminants from soils into the groundwater and to the collection point [1]. Furthermore, treatment methods, such as in situ bioremediation or in situ chemical treatment also face the same problem of transport of nutrients and treatment chemicals through the soil

to the contaminants using hydraulic pressure [2]. Hence, there is a need to investigate technologies that incorporate contaminant transport enhancement through physicochemical methods [3].

Enhanced in situ flushing technique has shown great potential to remediate contaminated sites. The addition of a solubility enhancement agent to the flushing fluid increases the apparent solubility of organic pollutants [4]. There is a tremendous interest in using agents, such as carboxymethyl- β -cyclodextrin (CMCD) for enhanced removal of pollutants from the contaminated soils by pump and treat remediation [5,6]. Successful examples of CMCD enhanced remediation has been reported for low polarity organic compounds including, polycyclic aromatic hydrocarbons (PAHs), trichlorobenzene, and heavy metals including Cd and Pb [5–9]. However, the conventional remediation methods are ineffective in low to moderate permeability soils, because it is difficult to introduce the cyclodextrin or other reagents into the sub-surface, and to move their complexes with contaminants due to the low hydraulic conductivity of the soils [10].

To enhance the transport of the contaminant complexes, the electrokinetic process has the potential to remove pollutants, such as PAHs from the soil by improving flow and soil-

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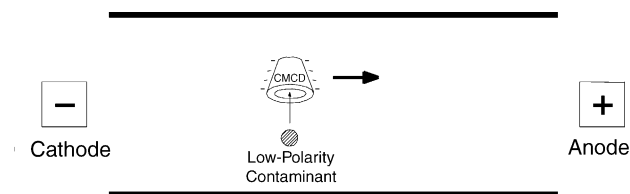


Fig. 1. Schematic of CDEK process.

solution–contaminant interaction in limited permeability soils [11]. The removal of low polarity compounds using cyclodextrin as a contaminant carrier in the electrokinetic process has not been investigated for the remediation of contaminated soil.

The approach involves combination of the two concepts of enhanced solubility of low polarity organic contaminants by cyclodextrin and enhanced electrophoretic mobility by the electrokinetic process into a remediation process called cyclodextrin-electrokinetic process (CDEK).

The main concept of CDEK deals with electrokinetic removal of low polarity and non-polar organics using cyclodextrins as carrier agents. The hydrophobic cavity of the cyclodextrin serves as the binding site for the low polarity contaminant, and the hydrophilic shell with its charged group facilitates movement through the soil toward the electrode well under electrokinetic conditions (Fig. 1). This also relies upon the diffusion of the contaminant, and the partition between cyclodextrin and the soil [12].

The development of CDEK or similar process will become a significant advancement in subsurface remediation since it provides a method for the removal of both polar and low polarity contaminants. Without CDEK or similar process, electrokinetics would essentially be restricted to separation of just ionized compounds. In this study, the impact of CDEK on the removal of low polarity pollutants, such as naphthalene and 2,4-DNT from the soil was investigated.

2. Materials and methods

2.1. Materials

In this study, naphthalene and 2,4-DNT were selected as model compounds because their physicochemical properties are different from each other, and their molecular volume size can fit into the cavity of CMCD (cavity size = 0.346 nm^3) [13]. Molecular volume of naphthalene and 2,4-DNT was calculated from their density and were found to be 0.186 and 0.229 nm^3 , respectively [14].

Naphthalene and 2,4-dinitrotoluene (2,4-DNT) were purchased from Sigma Chemical Company and used as received. Carboxymethyl- β -cyclodextrin (CMCD) ($MW_{\text{ave}} = 1480 \text{ g/mol}$) was supplied by American Maize-Products Company (Hammond, IN). CMCD is the derivative of β -cyclodextrin which is chemically modified to enhance its water solubility. The CMCD used in this research has 7 glucose units and an average of 14 carboxyl groups, with seven located at one end of the molecule and seven at the other end. It has been reported that the solubilization capacity of CMCD is significantly higher than

Table 1
Characteristic properties of soil

Parameter	Value
pH	7.2
Organic matter content	4.9%
Organic carbon content	2.2%
Specific gravity	2.46
Clay content	7.4%
Silt content	17.4%
Sand content	75.2%
pH_{zpc}	7.0
Hydraulic conductivity	$6.3 \times 10^{-4} \text{ cm/s}$
Soil type	Sandy loam

the other cyclodextrin forms in the removal of pentachlorophenol [15]. The soil used in these experiments was collected from a local site in an urban area in Illinois. The soil samples were taken up to depths of 12 in. after clearing the top 2 in. of debris and grass. The properties of the soil were determined according to standard methods [16] and are shown in Table 1. The typical parameters for the soil samples tested were summarized as follows: organic matter of 4.9%, hydraulic conductivity of $6.3 \times 10^{-4} \text{ cm/s}$ at moderate permeability and soil type of sandy loam.

The soil samples were sieved, and fraction passing a No. 10 was air dried and stored at room temperature in glass bottles. Due to high buffering capacity of the soil, the soil was repeatedly washed with 0.01N HNO_3 or 0.01 NaOH solutions to pre-equilibrate the soil to the desired pH. The samples were centrifuged between washes for 10 min at 5000 rpm. The soils were then dried in the oven at 60°C for 48 h.

2.2. Column experiments

The experiments were conducted to investigate the removal efficiency of naphthalene and 2,4-DNT in continuous flow polycarbonate columns. The polycarbonate column was 2.54 cm in diameter and 4-cm long, connected on each end to a 2.5-cm long electrode well containing a carbon graphite electrode. The columns were packed in incremental steps with dry soils to establish uniform bulk density. The final porosity of the soil in the column was determined to be 0.4, with a total pore volume of 8.1 cm^3 .

The soil is prevented from entering the electrode wells by $0.45 \mu\text{m}$ nylon membrane filter supported on stainless steel screen. The electrode wells were connected to the flushing solution tank and for collecting effluents from flushing.

After packing, the columns were slowly wetted from the bottom by pumping 0.01N NaNO_3 and synthetically prepared contaminant solution of known strength for 14 days at a rate of 0.08 mL/min with a 0.04 cm/min pore water velocity to obtain equal influent and effluent concentrations of naphthalene and 2,4-DNT through the soil columns. During this procedure the effluent from the columns was collected and analyzed for the residual concentration of the contaminant. Dissolution experiments were conducted after the soil columns were saturated with contaminant solutions. The effluent solution was analyzed

Table 2
Testing procedure for dissolution experiments

Dissolution	Application condition(s)
NaNO ₃	DW containing 0.01N NaNO ₃
NaNO ₃	DW containing 0.01N NaNO ₃ + electrokinetics (20, 30, 40 V)
CMCD	2 and 5 g/L CMCD
NaNO ₃ + CMCD	DW containing 0.01N NaNO ₃ + 2 g/L or 5 g/L CMCD
NaNO ₃ + CMCD	DW containing 0.01N NaNO ₃ + 2 g/L or 5 g/L CMCD + electrokinetics (20, 30, 40 V)

everyday to determine the amount of naphthalene and 2,4-DNT concentration by Perkin-Elmer Lambda 3A UV–vis spectrophotometer at wavelengths 276 and 250 nm, respectively.

After dissolution experiments, the contaminated soils were extracted by methanol as an extraction solvent because it has been reported that methanol extraction is the most efficient and robust method for recovering spiked VOCs [17]. After 14 days of dissolution, the contaminated soils were extracted by placing the contaminated soil in glass container that contained methanol (1%, v/v) for 1 day to measure the removal percentage of contaminants by dissolution experiments. It has been also reported that the extraction efficiencies of methanol depends on the octanol–water partition of VOCs, soil organic carbon content as well as duration of methanol extraction. Although, elevated temperatures speed up the release of VOCs especially high octanol–water partitioning compounds from soil with high organic content, 1 day MeOH extraction was long enough to get maximum release of tested compounds used in this study and was much longer than that of hot MeOH extraction at 40 °C in an ultrasonic water bath for 30 min [18].

The effectiveness of CDEK to solubilize and extract organic pollutants from soils was investigated by conducting three types of dissolution experiments as follows: (1) dissolution with CMCD; (2) dissolution with 0.01N NaNO₃ solution; (3) dissolution under electrokinetic conditions (20, 30, and 40 V potential). The experiments were performed step by step to determine the impact of each dissolution technique on the removal of naphthalene and 2,4-DNT removal. Several combinations of each application were investigated, and the details of these elutants are given in Table 2.

3. Results and discussion

Column tests were performed to evaluate the applicability and effectiveness of CDEK process as an alternative technology for remediation of soils contaminated with low polarity pollutants, such as naphthalene and 2,4-dinitrotoluene (2,4-DNT). The removal of naphthalene and 2,4-DNT from soils were determined by using three remediation approaches, NaNO₃ solution (0.01N) as a flushing agent, CMCD for solubility enhancement and electrokinetics for increasing contaminant mobility. As shown in Table 2, first, impact of NaNO₃ solution on the removal of naphthalene and 2,4-DNT from soil was determined. Then, combined effect of NaNO₃ solution coupled with CMCD or electrokinetics was investigated. Finally, the combined effect

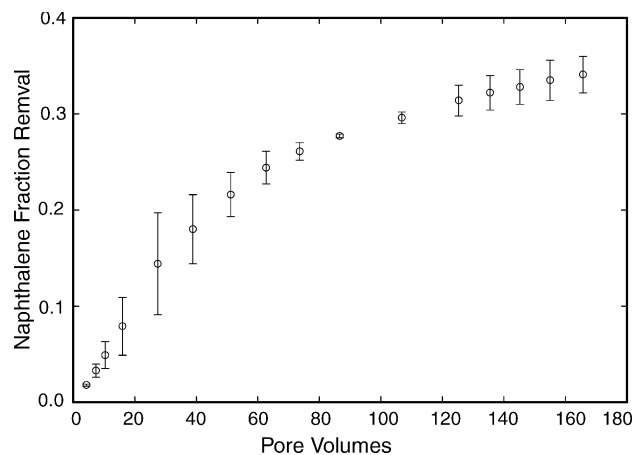


Fig. 2. Dissolution of soil contaminated with naphthalene using 0.01N NaNO₃.

of three approaches on the removal of naphthalene and 2,4-DNT from soil was investigated. The performance of each treatment method was evaluated by comparing percentage removal of naphthalene and 2,4-DNT from the soil.

3.1. Dissolution with 0.01N NaNO₃ solution

The contaminated soil was washed with distilled water (DW) containing 0.01N NaNO₃ in continuous flow columns. The results were quantified by the contaminant removal as a function of pore volumes of the packed column. Naphthalene and 2,4-DNT removals are shown in Figs. 2 and 3, respectively, and the error bars represent one standard deviation of at least four-column runs. Approximately 32% of the naphthalene was removed by 0.01N NaNO₃ after 160 pore volumes of flushing which is in agreement with the removal percentage values reported in the literature [15]. At 140 pore volumes of 0.01N NaNO₃ flushing, about 40% of the initial 2,4-DNT was removed. From the results, it can be seen that NaNO₃ solution has a limited ability to remove low polarity organic contaminants due to the low affinity of naphthalene and 2,4-DNT to water. It is well known that aged contaminated soils do not release the contaminants as easily as non-aged lab contaminated soils, but these

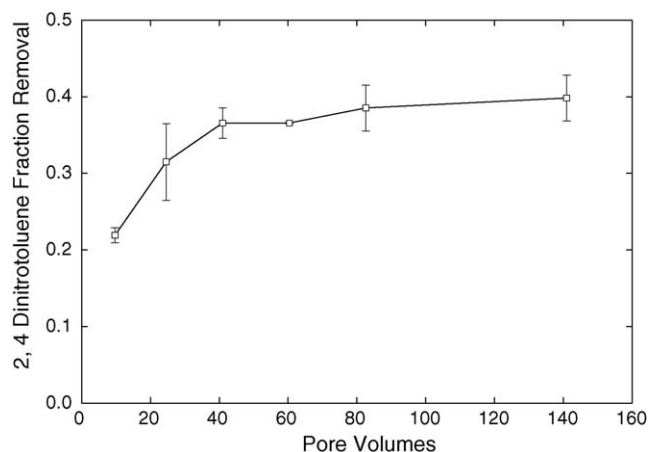


Fig. 3. Dissolution of soil contaminated with 2,4 DNT using 0.01N NaNO₃.

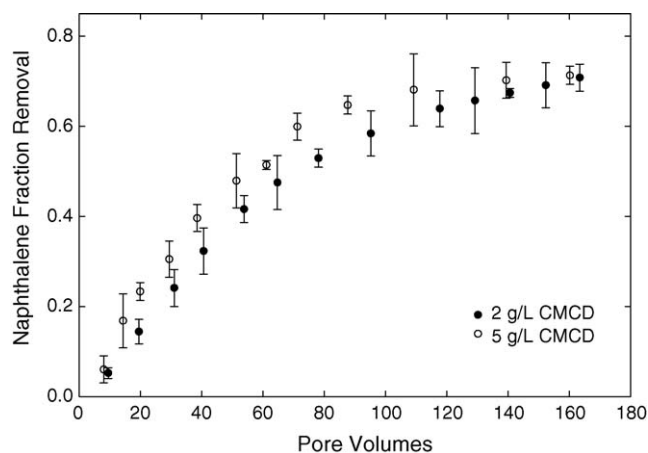


Fig. 4. Dissolution of soil contaminated with naphthalene using CMCD and NaNO₃ solutions.

results do demonstrate the difficulty in removing aromatic contaminants from soil by flushing alone.

3.2. Dissolution with CMCD and 0.01N NaNO₃ solution

Cyclodextrins can solubilize low polarity organic compounds by inclusion complexation, wherein the solute partitions into the cyclodextrin cavity. It has been reported that cyclodextrins can enhance solubility of pentachlorophenol, nonaqueous-phase organic liquids (NAPL), and phenanthrene and naphthalene up to 20–20,000-fold depending on the compound and ionic strength of the medium [4,15,19]. Hence, this increased solubility results in reduction of NAPL soil-phase concentration by 41% at the field scale [4] and results in increase of 64 and 80% phenanthrene and naphthalene removal, respectively [19]. The experiments were conducted to remove naphthalene and 2,4-DNT from the soil by using 2 and 5 g/L CMCD with 0.01N NaNO₃ as the flushing agent. The results are plotted as pore volumes of elutant versus the contaminant fraction removed. Dissolution curves for naphthalene and 2,4-DNT removal from the soil are shown in Figs. 4 and 5, respectively. Clearly, CMCD signifi-

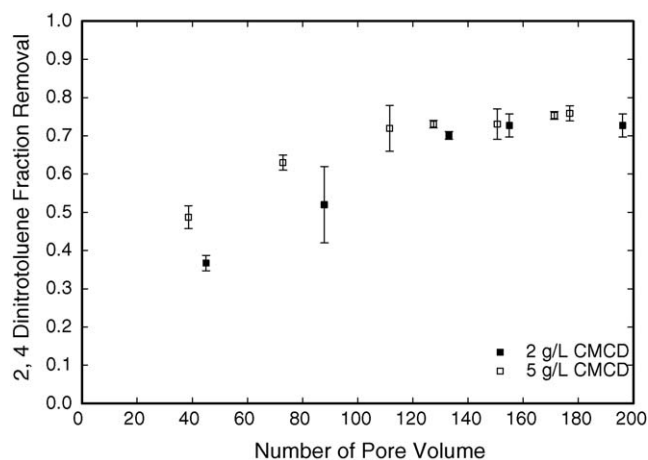


Fig. 5. Dissolution of soil contaminated with 2,4-DNT using CMCD and NaNO₃ solutions.

cantly enhanced the removal of naphthalene and 2,4-DNT from soil as compared to the NaNO₃ solution. Adding more CMCD did not significantly improve the total naphthalene removal. For example, 70% of the initial naphthalene was removed by 2 g/L CMCD solution and 72% was removed by 5 g/L of CMCD solution after 160 pore volumes of flushing as compared to 32% using NaNO₃ solution alone. It may be that the diffusion of the contaminants from the soils to the bulk liquid was rate limited. However, it increased the removal rate of naphthalene. The impact of CMCD concentrations on the removal rate of naphthalene was statistically analyzed, and *t*-test results showed that the impact of CMCD concentration on naphthalene removal is statistically significant at the 95% confidence interval with $P \leq 0.005$.

At 50 pore volumes of CMCD flushing, naphthalene removed was increased from 38 to 49% of initial naphthalene when CMCD solution concentration was increased from 2 to 5 g/L. Furthermore, 73 and 75% of the initial 2,4-DNT was removed after 140 pore volumes of 2 and 5 g/L CMCD solution flushing, respectively, while only 40% was removed by the NaNO₃ solution. Adding more CMCD also did not significantly improve the total 2,4-DNT removal but, it increased the removal rate of 2,4-DNT. The impact of CMCD concentrations on the removal rate of 2,4-DNT is statistically significant at 95% confidence interval with $P \leq 0.001$.

Naphthalene and 2,4-DNT could not be completely removed from the soils as desorption of these contaminants by the soil organic matter domain is slow and only partially reversible [20]. Furthermore, it has been reported that there is a competitive hydrophobic interactions between CMCD and organic matter which can be inhibit solubilization, and hence, desorption of pollutants from the soil [15].

3.3. Dissolution with 0.01N NaNO₃ solution under electrokinetic conditions

Dissolution experiments with NaNO₃ and electrokinetics were conducted to determine the effect of electrokinetics on naphthalene and 2,4-DNT removal. The DC power supplies were adjusted to 30 V (7.5 V/cm) and 40 V (10 V/cm) across 4.0 cm soil columns, and 0.01N NaNO₃ was used as the flushing solution. The solution was fed from the cathode wells through the columns and samples were collected at the anode wells. The results from these experiments are plotted between pore volumes of flushing and contaminant removal at each electrical potential. The plots of naphthalene and 2,4-DNT removal are shown in Figs. 6 and 7, respectively. These results show that electrokinetics made a small improvement in the removal of naphthalene and 2,4-DNT compared to NaNO₃ alone. Approximately 36 and 46% of the initial naphthalene was removed after 160 pore volumes flushing at electric potentials of 30 and 40 V as compared to 32% using NaNO₃. At 140 pore volumes of NaNO₃ flushing coupled with applied electric potential of 30 and 40 V, approximately 38 and 43% of the initial 2,4-DNT was removed, respectively. In fact, only marginal increase in removal with electrokinetics further confirms that partition behavior is independent of pH, as seen in batch sorption studies [21]. Furthermore, it can be seen from Figs. 4 and 6, that only 36–46%

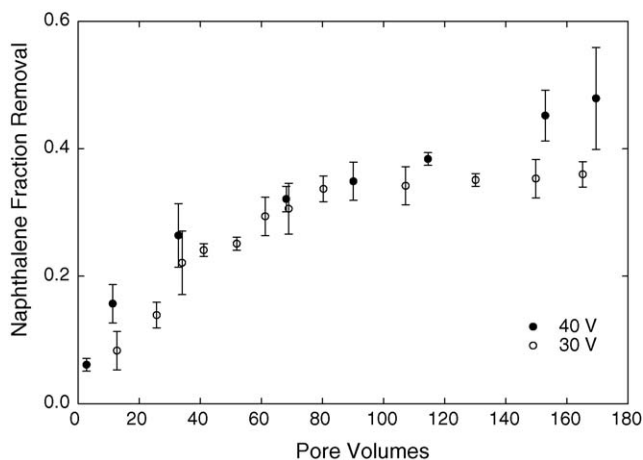


Fig. 6. Dissolution of soil contaminated with naphthalene using 0.01N NaNO_3 solution and electrokinetics.

of the total naphthalene was removed by electrokinetics alone, while 70% of the total naphthalene was removed by CMCD. The results for 2,4-DNT were found to be similar to that of naphthalene. These observations indicate that electrokinetics alone is less effective than CMCD since naphthalene and 2,4-DNT are not polar compounds.

3.4. Dissolution with CMCD and 0.01N NaNO_3 solutions under electrokinetic conditions

To investigate the effect of electrokinetics on the removal of naphthalene and 2,4-DNT with CMCD, the DC power supplies were adjusted to 20 V (5 V/cm), 30 V (7.5 V/cm), and 40 V (10 V/cm) across the 4.0 cm soil columns. Solutions containing either 2 g/L CMCD (with 0.01N NaNO_3) or 5 g/L CMCD (with 0.01N NaNO_3) were used as flushing solutions. Figs. 8 and 9 show plots of naphthalene removal and plots of 2,4-DNT removal, respectively. Using both CMCD and electrokinetics increased the total removal efficiency of naphthalene and 2,4-DNT (Fig. 8). For example, 58 and 83% of the initial mass of naphthalene were removed by 2 g/L CMCD solution and

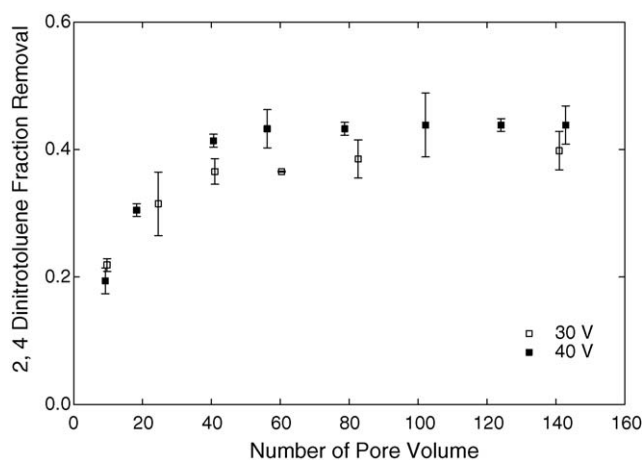


Fig. 7. Dissolution of soil contaminated with 2,4-DNT using 0.01N NaNO_3 solution and electrokinetics.

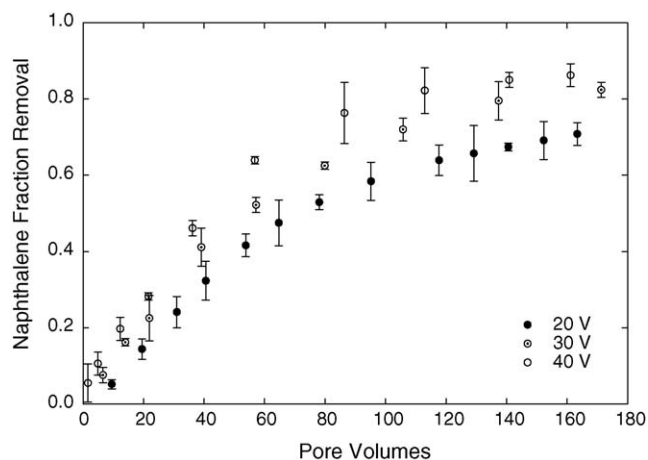


Fig. 8. Dissolution of soil contaminated with naphthalene using 2 g/L CMCD and electrokinetics.

electrokinetics (40 V) after 50 and 160 pore volumes of flushing as compared to 39 and 70% for the 2 g/L CMCD solution without electrokinetics (Fig. 4). Similar increases in 2,4-DNT removal from the soil were also observed. After 50 and 160 pore volumes of 2 g/L CMCD solution were flushed through the columns with electrokinetics (40 V), 69 and 89% of the initial 2,4-DNT were removed (Fig. 9) as compared to 38 and 73% for the 2 g/L CMCD solutions without electrokinetics (Fig. 5). The differences in removal patterns of naphthalene and 2,4-DNT could be explained due to their different physicochemical properties [14].

The increase in removal of naphthalene and 2,4-DNT could be due to increased solubilization and mass transfer rate as well as the opposite direction of the advective and electroosmotic flows resulting in longer transit times of the CMCD molecules through the column which can favor the “removal/sequestration” of the naphthalene and 2,4-DNT by CMCD. The similar results for phenanthrene removal using cyclodextrin-enhanced electrokinetic were reported by Ko et al. [22]. The phenanthrene removal increased from 56 to 75% by EK and CDEK removal, respectively.

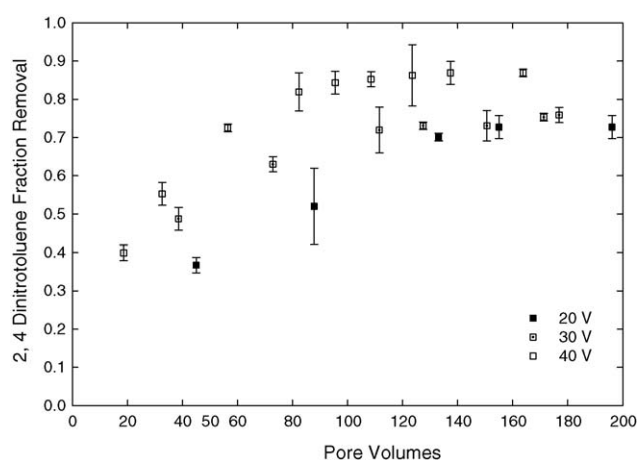


Fig. 9. Dissolution of soil contaminated with 2,4 DNT using 2 g/L CMCD and electrokinetics.

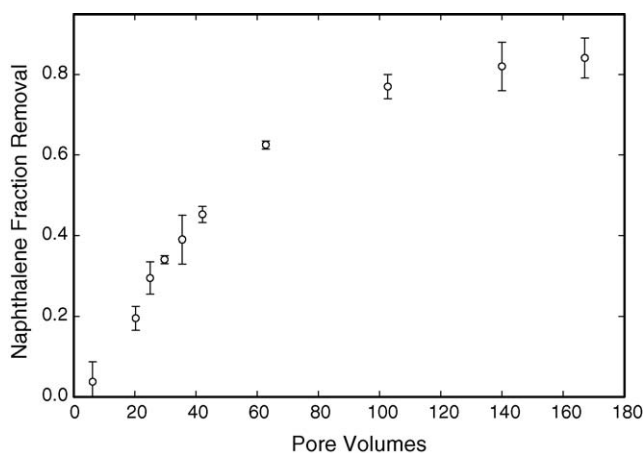


Fig. 10. Dissolution of soil contaminated with naphthalene using 5 g/L CMCD and electrokinetics.

Furthermore, increase in the removal rate of naphthalene and 2,4-DNT was observed when the applied voltage was increased. After 50 pore volumes of flushing with 2 g/L CMCD solution, 62, 50, and 48% of the initial naphthalene were removed at 40, 30, and 20 V, respectively (Fig. 8). 2,4-DNT was removed by 69 and 53% after 50 pore volumes of 2 g/L CMCD solution was flushed through the columns at 40 and 20 V, respectively (Fig. 9). The increase in the total removal and removal rate was caused by electrophoresis and electrolysis during electrokinetic washing [11]. Only marginal increase in total removal efficiency when the voltage was increased without CMCD, and a significant improvement with increased voltage and CMCD confirms the transport of contaminant-laden CMCD molecules through the soil by electrokinetics. Higher voltage application contributed to the increase in the removal rate of naphthalene and 2,4-DNT in the presence of CMCD, and appeared to be one of the critical factors in obtaining higher contaminant removal. This could be due to application of high voltage resulted dissolution and migration of some of the metals “opening up” the soil structure, and hence, facilitating and the removal of the target compounds.

Under the same applied voltage (30 V), the removal rate of naphthalene did not increase much when CMCD concentration in the solution was increased to 5 g/L (Fig. 10). For example, 50% of the initial mass was removed by 2 g/L CMCD after 50 pore volumes of flushing as compared to 52% for the 5 g/L CMCD solution.

The results indicate that for CDEK, the amount of the electric potential applied has more influence on the contaminant removal than the amount of CMCD used. Increasing CMCD solution strength appeared to have little effect on the complex formation. This could be due to the fixed ratio of the inclusion complexes between CMCD and the contaminant, hence, less increase in percentage removal of naphthalene and 2,4-DNT from the soil.

3.5. Mass balance of contaminants

The mass balances for each contaminant in the soil columns were calculated to determine the amount of the contami-

Table 3
Mass balance for naphthalene in column tests

Flushing condition	Naphthalene		
	Removed (%)	Remaining (%)	Loss (%)
0.01 NaNO ₃	32 ± 2	52 ± 2	16
2 g/L CMCD	70 ± 3	16 ± 1	14
5 g/L CMCD	72 ± 2	16 ± 5	12
30 V EK	36 ± 2	44 ± 4	20
40 V EK	46 ± 8	35 ± 6	19
2 g/L CMCD + 20 V EK	81 ± 2	5 ± 10	14
2 g/L CMCD + 30 V EK	82 ± 3	8 ± 6	10
2 g/L CMCD + 40 V EK	83 ± 3	4 ± 7	13
5 g/L CMCD + 30 V EK	83 ± 5	11 ± 2	16

nants in the soils and in the solutions. In this study, mass balances were used to determine the amount of naphthalene and 2,4-DNT in the soil columns after flushing with 0.01N NaNO₃ solution, 2 and 5 g/L CMCD, 0.01 NaNO₃ solution with 30 and 40 V electrokinetics, and 2 and 5 g/L CMCD with 20, 30, and 40 V electrokinetics. Table 3 shows the percent of naphthalene removed and the percent remaining from column tests. The mass balance for 2,4-DNT is shown in Table 4.

Tables 3 and 4 show the amount of naphthalene lost is between 10 and 20% while the amount of 2,4-DNT lost is 9–30%. No biodegradation was observed or to be expected under these conditions due to nutrient limitations. Moreover, the spectrum of each treated sample was similar to the spectrum of control experiments and no partial degradation product was detected by GC–MS. Furthermore, soil is usually supplemented with mineral solution and additional carbon source for the CMCD enhanced biodegradation of similar compounds [7]. This loss is possibly due to the volatility of naphthalene and 2,4-DNT, sorption in the column, or “sequestration effect” resulting from contact between soil organic matter [23,24], and limitation in measuring the naphthalene and 2,4-DNT concentrations from the columns. The percentage of organic matter (~5%) of soil used in this study could be considered as high organic matter which favors the CMCD sorption as well as the interaction with contaminant, and hence, retention of contaminants in the soil [19]. Since the losses found both in blanks and the columns with CMCD and electrokinetic were close to each other at 95% confidence interval, the conclusions reached in this research are still valid.

Table 4
Mass balance for 2,4 DNT in column tests

Flushing condition	2,4 DNT		
	Removed (%)	Remaining (%)	Loss (%)
0.01 NaNO ₃	40 ± 3	30 ± 10	30
2 g/L CMCD	73 ± 3	12 ± 4	15
40 V EK	43 ± 3	35 ± 2	22
2 g/L CMCD + 20 V EK	73 ± 1	18 ± 1	9
2 g/L CMCD + 40 V EK	89 ± 2	12 ± 5	9

4. Conclusions

CMCD assisted dissolution of 2,4-DNT and naphthalene from soils was found to be effective approach to increase the removal of naphthalene and 2,4-DNT from contaminated soil. This study showed that using electrokinetics alone to remove naphthalene and 2,4-DNT from soil is less effective than using CMCD solution since naphthalene and 2,4-DNT are not charged molecules. However, combined use of CMCD and electrokinetics showed improvement in total removal and removal rate of naphthalene and 2,4-dinitrotoluene (2,4-DNT) from soils as compared to CMCD or electrokinetics alone. The obtained results are in agreement with the removal percentage values for the similar type of treatment approaches and model compounds reported in the literature [4,17,22].

It can be hypothesized that CDEK can increase the apparent removal of naphthalene and DNT by forming inclusion complexes and increased electroosmotic flow, hence, enhancing the removal of pollutants. From these results, it can be concluded that CDEK in principle could be an effective alternative for the removal of low polarity compounds from soil. Furthermore, this study found that under CDEK process the electric potential applied has more influence on the contaminant removal than the amount of CMCD used.

Although the work was performed with moderate permeability soil and not with low permeability soil, the overall goal is to improve polar and low polarity contaminants in soils, and in particular, low permeability soils. Since the concept of CDEK needs to be proven first and then should be extended to investigate the effect of permeability on the effectiveness of CDEK. Our work is the first step in advancement the CDEK method and it was important to minimize variables of the study. Further work is necessary to address dissolution of contaminants from low permeability soils using CDEK in the field, and to demonstrate its effectiveness in commercial applications for the remediation of actual contaminated sites. The forthcoming work should also take into account the economical aspects of the process. The magnitude of differences in mass balances caused by naphthalene and 2,4-DNT loss due to partitioning with the soil, recovery of these compounds from the soil as well as volatilization should be minimized for the use of CDEK method in the field. Improvements obtained by optimizing operating conditions should help extend the application utility of this technology to field applications.

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