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Remediation of TCE contaminated soils by in situ EK-Fenton process

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Abstract

The treatment performance and cost analysis of in situ electrokinetic (EK)-Fenton process for oxidation of trichloroethylene (TCE) in soils were evaluated in this work. In all experiments, an electric gradient of 1 V/cm, de-ionized water as the cathode reservoir fluid and a treatment time of 10 days were employed. Treatment efficiencies of TCE were evaluated in terms of the electrode material, soil type, catalyst type, and catalyst dosage and granular size if applicable. Test results show that graphite electrodes are superior to stainless steel electrodes. It was found that the soil with a higher content of organic matter would result in a lower treatment efficiency (e.g. a sandy loam is less efficient than a loamy sand). Experimental results show that the type of catalyst and its dosage would markedly affect the reaction mechanisms (i.e. “destruction” and “removal”) and the treatment efficiency. Aside from FeSO₄, scrap iron powder (SIP) in the form of a permeable reactive wall was also found to be an effective catalyst for Fenton reaction to oxidize TCE. In general, the smaller the granular size of SIP, the lower the overall treatment efficiency and the greater the destruction efficiency. When a greater quantity of SIP was used, a decrease of the overall treatment efficiency and an increase of percent destruction of TCE were found. Experimental results have shown that the quantity of electro-osmotic (EO) flow decreased as the quantity of SIP increased. It has been verified that the treatment performances are closely related to the corresponding EO permeability. Results of the cost analysis have indicated that the EK-Fenton process employed in this work is very cost-effective with respect to TCE destruction. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Contaminated soil; Trichloroethylene; Electrokinetic; Fenton; Scrap iron powder; Permeable reactive wall

1. Introduction

Various chlorinated organic compounds, including trichloroethylene (TCE), are widely used as solvents in various industries. When entering the subsurface environment, they

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generally would pose great threats to the environment and human health. For example, TCE is harmful to the respiratory system, the circulatory system, and the central nervous system of human bodies.

Among various advanced oxidation processes, the Fenton process has received much interest in destruction of various organic pollutants in various media. Normally, the Fenton reaction involves two steps [1,2]: firstly, decomposition of H_2O_2 catalyzed by Fe(II) or other transition elements resulting in generation of hydroxyl radicals and secondly, degradation of organic pollutants by hydroxyl radicals via oxidation. Since the hydroxyl radical is well-known for its nonspecific and strong oxidizing capability, the Fenton process is widely used for destruction of biorefractory organic pollutants (e.g. phenol, chlorophenols, nitrophenols, PAHs, PCE, and nitrobenzene) [3–5]. Watts and his research group, among others, have conducted extensive studies on treating soils contaminated by various organic compounds using the Fenton process [3,6,7]. Through this advanced oxidation process, various organic compounds in the soils were degraded and destroyed. Nonetheless, an employment of the Fenton process for soil remediation is in general limited to *ex situ* in-tank reactions.

Electrokinetic (EK) remediation is another innovative technology that has been extensively investigated in the laboratory and demonstrated in the field during the past decade [8–14]. Several unique advantages have been reported for this *in situ* remediation technology [15]. In general, the EK process is suitable for treating various contaminants (e.g. heavy metals, organic pollutants, and radionuclides) in all kinds of soils. Additionally, it can be used for treatment of contaminants in both the vadose zone and the saturated zone at a relatively low cost. However, contaminants removed by EK alone need further treatment in most cases.

To overcome the limitations associated with each treatment technology, soil and groundwater remediation using the treatment train concept have become a common practice nowadays. Yang and his research group have successfully combined the EK process and the Fenton process for *in situ* treatment of various organic compounds (e.g. phenol, 4-chlorophenol, and diesel fuel) in soils [16–19]. These researchers even further incorporated biodegradation in the EK-Fenton process for treating pentachlorophenol (PCP) contaminated soils. It was found that 100% PCP destruction could be obtained within a reasonable treatment time by combining these three technologies [20].

The objectives of this investigation were to evaluate the performance and cost-effectiveness of using EK-Fenton process for remediation of soils contaminated by TCE. To this end, a treatment system coupling the EK process with the Fenton process was employed to treat two types of soil spiked with TCE. In this study, the destruction efficiency and removal efficiency were determined, respectively for each test based on the mass balance of TCE. In addition, the operating costs of the EK-Fenton process under different operating conditions were determined based on their respective unit costs of electricity and chemicals/material.

2. Experimental

2.1. Soils

Two topsoils (10–30 cm below ground surface) were collected from two local farmlands. Tree roots and debris were first removed from the soil samples. After they were dried in

Table 1
Characteristics of two soils used in this work

Item determined	Soil no. 1	Soil no. 2
Texture ^a	Loamy sand	Sandy loam
Particle size analysis ^b (wt.%)		
<2 μm	2.87	6.03
2–50 μm	21.06	45.24
>50 μm	76.07	48.73
Density ^c (g/cm^3)	2.44	2.55
pH ^d	4.40	7.64
Water content ^e (%)	1.05	2.64
Loss on ignition ^f (%)	3.78	6.83
Organic content ^g (%)	1.56	3.53
BET surface area ^h (m^2/g)	16.91	38.29
Cation exchange capacity ⁱ (meq/100 g)	19.93	40.95
Total iron content ^j (mg/kg)	2546	5279

^a The general soil classification of US Department of Agriculture.

^b By sieving and Coulter LS100.

^c ASTM D854-83.

^d ROC EPA NIEA S410.60T.

^e ROC EPA NIEA S280.60T.

^f Manual of Soil Laboratory Testing (by K.H. Head, 1980).

^g Handbook of Soil Mechanics (by D.W. Nelson and L.E. Sommers, 1980).

^h By Micromeritics ASAP-2010.

ⁱ ROC EPA NIEA S202.60A.

^j Ph.D. dissertation, North Carolina State University at Raleigh (by S. Kota, 1998).

the air, the soil samples were sieved to pass through a 10 mesh sieve. The fraction finer than 2 mm was properly stored for later analyses and experiments. These two soils were categorized as loamy sand and sandy loam with various characteristics listed in Table 1. The analyzing methods for these characteristics are also given in the footnotes of Table 1. Each artificially contaminated soil was prepared by mixing the pretreated soil with a TCE stock solution of 1100 mg/l at 200 rpm for 3 h. Then it was placed in the soil cell of the treatment system (Fig. 1). Before each test run, a fraction of the contaminated soil was obtained to determine its initial TCE concentration.

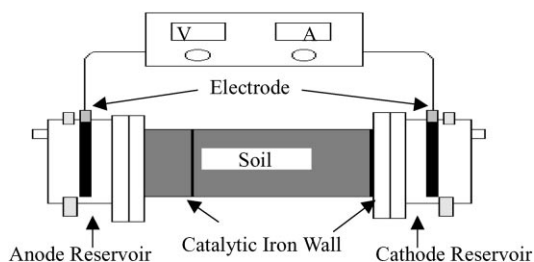


Fig. 1. An experimental set-up for treating contaminated soils by the EK-Fenton process.

2.2. Catalysts for the Fenton reaction

Aside from FeSO_4 , two types of scrap iron powder (SIP) were also used as the catalyst for the Fenton reaction. In this work, SIP was used in the form of a permeable reactive wall in the soil cell.

1. *Type I SIP*: This type of scrap iron powder was obtained from a local iron processing plant. It was the residue due to the elongation of iron wires. The only mineral species identified by X-ray diffraction is magnetite (Fe_3O_4). The particle size distribution of Type I SIP is ranging from 50 to 150 mesh (297–106 μm). Its BET surface area was determined to be 1.03 m^2/g .
2. *Type II SIP (UPF series)*: The UPF series of scrap iron powder is a commercial product. It originated from iron pieces adhering to the blast furnace slag. The iron pieces were magnetically separated, then ground and sieved to desired granular sizes. The mineral species identified by X-ray diffraction include magnetite (Fe_3O_4), hematite (Fe_2O_3), and maghemite (Fe_2O_3). The iron content of Type II SIP was determined to be 93–95 wt.%. UPF-030 represents the particle sizes of SIP are in the range of 10–30 mesh (2000–590 μm). Its BET surface area was determined to be 1.13 m^2/g . The particle sizes of UPF-050 SIP range from 30 to 50 mesh (590–297 μm) and the corresponding BET surface area was 1.02 m^2/g . For UPF-100 SIP, it consists of particle sizes in the range of 50–100 mesh (297–149 μm) having a BET surface area of 0.71 m^2/g . The particle sizes of UPF-150 SIP range from 100 to 200 mesh (149–74 μm). Its BET surface area was determined to be 1.37 m^2/g .

2.3. Apparatus

Fig. 1 shows a schematic diagram of the experimental set-up for the EK-Fenton process used in this study. It consists of three components: anode reservoir, soil cell (or soil column) and cathode reservoir. Three components are made of Pyrex glass. The soil column is 20 cm long and 5.5 cm in diameter, whereas the electrode reservoir is 5 cm long and 7.5 cm in diameter. A set of filter media was placed between the soil column and each electrode reservoir to separate the processing fluid and soil. A power supply was connected to the electrodes to provide direct current for EK treatment. An uninterrupted power system was also used to prevent power failure during the test period.

2.4. Operating conditions

In this work treatment runs, control runs, and blank runs were all conducted for a period of 10 days. De-ionized water was used as the cathode reservoir fluid for all tests. When EK was involved, an electric gradient of 1 V/cm was applied across the soil cell. Detailed experimental conditions are given in Table 2.

1. *Treatment runs (Tests 1–13)*: When 1.5 g SIP in each wall was used as the catalyst, H_2O_2 (<4000 mg/l) was put in and added to the anode reservoir for the entire treatment period. In the case of one wall, SIP was embedded at a position 5 cm from the anode reservoir in the soil column. In the case of two SIP walls, one wall was installed at a distance

Table 2
Summary of the test program for remediation of TCE by the EK-Fenton process

Type of experiment	Test no. ^a	Soil no.	Electrode material	Catalyst type and amount/concentration
Treatment runs	1	1	Graphite	One-wall UPF-030 SIP
	2	1	Graphite	One-wall UPF-050 SIP
	3	1	Graphite	One-wall UPF-100 SIP
	4	1	Graphite	One-wall UPF-150 SIP
	5	1	Graphite	One-wall Type I SIP
	6	1	Graphite	Two-wall UPF-030 SIP
	7	1	Graphite	Two-wall UPF-150 SIP
	8	1	Graphite	Two-wall Type I SIP
	9	2	Graphite	One-wall UPF-030 SIP
	10	2	Graphite	One-wall Type I SIP
	11	1	SUS 304 Stainless steel	One-wall UPF-030 SIP
	12	1	Graphite	0.098M FeSO ₄
	13	1	Graphite	0.0196M FeSO ₄
Control runs	14	1	Graphite	Nil
	15	2	Graphite	Nil
	16	1	Graphite	Two-wall UPF-030 SIP
Blank runs	17	1	Nil	Nil
	18	2	Nil	Nil

^a In Test nos. 14 and 15, neither FeSO₄ nor SIP was used; in Test nos. 17 and 18, neither an electric field nor a catalyst was applied.

5 cm from the anode reservoir and the other wall was installed right next to the cathode reservoir. When FeSO₄(aq) was used as the catalyst, it was put in the anode reservoir for the first 3 days and then replaced by H₂O₂ for the rest of treatment period.

2. *Control runs (Tests 14–16)*: Control runs were carried out for evaluating the treatment performance of using H₂O₂ or SIP alone.
3. *Blank runs (Tests 17 and 18)*: A blank run accompanying each treatment run was simultaneously conducted to determine the TCE mass loss due to evaporation during the test period. The mass loss due to evaporation must be taken into account when the TCE mass balance is determined.

2.5. Determination of TCE concentrations in soil specimens

Each soil specimen was first subjected to extraction by methylene chloride. Then a Varian Star 3400CX gas chromatography with a flame ionization detector (GC/FID) and a capillary column (J&W P/N DB-5; 0.53 μm in diameter and 30 m in length) was used for the determination of TCE concentration. The chromatographic conditions included the injector port temperature, 270°C; detector temperature, 300°C; and initial oven temperature, 60°C programmed at the rate of 10°C/min to a temperature of 80°C; then programmed at the rate of 50°C/min to a final temperature of 200°C and kept for 4 min.

3. Results and discussion

3.1. Effect of the type of SIP on TCE treatment

In this work, the Type II SIP was studied to determine its effects of the granular size and number of wall(s) on TCE treatment. Test results were also compared with that of the Type I SIP whenever applicable.

3.1.1. Effects of the granular size of the Type II SIP

Four size fractions of the Type II SIP (i.e. UPF-30, UPF-50, UPF-100, and UPF-150) were tested to evaluate their respective performance on remediation of TCE contaminated soil by the EK-Fenton process.

Table 3 shows the treatment efficiencies of TCE by using different granular sizes of the Type II SIP (i.e. Tests 1–4) and the Type I SIP (i.e. Test 5). For the Type II SIP, a lower percentage of TCE removal would be obtained when a smaller granular size of SIP was used. It is ascribed to the fact that for the weight of SIP used, the smaller the granular size is, the greater the total surface area will be. A greater total surface area might result in more $\text{Fe}(\text{OH})_3$ precipitates forming on the iron wall and a lower electro-osmotic (EO) permeability. This speculation can be verified by the EO permeability calculated. The values of EO permeability for the Type II SIP are given as follows: UPF-30 SIP, $6.76 \times 10^{-6} \text{ cm}^2/\text{V s}$; UPF-50 SIP, $6.36 \times 10^{-6} \text{ cm}^2/\text{V s}$; UPF-100 SIP, $5.69 \times 10^{-6} \text{ cm}^2/\text{V s}$; and UPF-150 SIP, $5.82 \times 10^{-6} \text{ cm}^2/\text{V s}$. Table 3 also shows that the residual TCE concentration in the soil cell is lower for the case of using a larger granular size of the Type II SIP. Fig. 2 is an example of the TCE treatment pattern in the soil cell by the EK-Fenton process for soil no. 1. On the other hand, a greater destruction efficiency of TCE would be obtained when a smaller granular size of the Type II SIP was used (Table 3). This can also be explained by the differences in total surface areas for different sizes of the Type II SIP used. Apparently, a greater total surface area of SIP would help to generate more hydroxyl radicals, which in

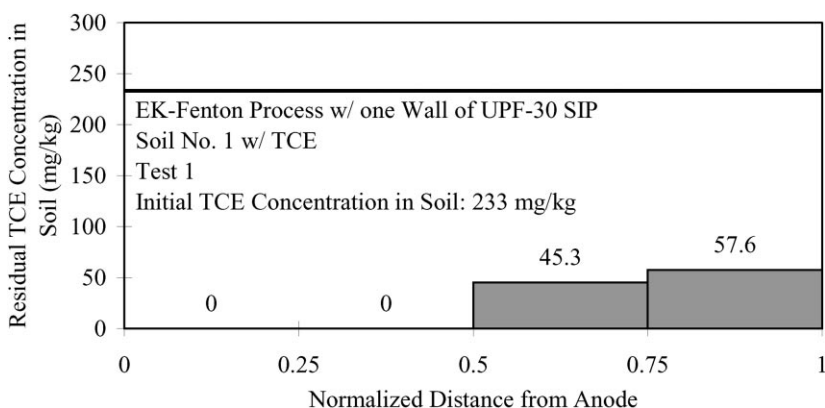


Fig. 2. Residual TCE concentration in soil no. 1 treated by the EK-Fenton process using one wall of UPF-30 SIP.

Table 3
TCE mass balances for Tests 1–16

Test no.	Initial TCE mass in the soil cell (mg)	Residual TCE mass in the soil cell (mg)	Cumulative, increased TCE mass in the cathode reservoir (mg)	TCE mass loss due to vaporization (mg) ^a	Residual TCE fraction in soil (%) ^b	Percent removal (%) ^c	Percent destruction (%) ^d	Percent removal and destruction (%) ^e
1	177.00	19.50	78.66	1.15	11.09	44.73	44.18	88.91
2	192.73	32.42	63.58	1.13	16.92	33.19	49.89	83.08
3	203.78	39.56	55.17	1.20	19.53	27.24	53.23	80.47
4	188.59	49.69	35.54	1.18	26.51	18.96	54.52	73.49
5	159.93	60.91	23.28	1.22	32.28	12.34	55.38	67.72
6	204.46	31.25	61.83	1.22	15.37	30.42	54.20	86.63
7	209.82	52.44	38.85	1.21	25.14	18.62	56.24	74.86
8	200.24	62.78	18.01	1.23	31.55	9.05	59.41	68.45
9	140.05	67.00	46.40	0.88	48.14	33.34	18.52	51.86
10	146.31	73.16	37.22	0.85	50.29	25.59	24.12	49.71
11	212.05	47.80	67.65	1.21	22.67	32.09	45.24	77.33
12	172.01	44.99	95.93	1.11	26.33	56.13	17.54	73.67
13	186.14	41.80	117.73	1.15	22.59	63.64	13.77	77.41
14	190.53	90.42	88.69	1.19	47.75	46.84	5.41	52.25
15	165.01	67.55	66.58	1.05	41.20	40.61	18.20	58.80
16	215.90	129.77	40.38	1.22	60.45	18.81	20.74	39.55

^a Based on the TCE mass vaporized in the blank run, each treatment run must take into account this mass loss accordingly.

^b Residual TCE fraction in soil = (residual TCE mass in the soil cell/(initial TCE mass in the soil cell) – (TCE mass loss due to vaporization)) × 100%.

^c Percent removal = (cumulative, increased TCE mass in the cathode reservoir/(initial TCE mass in the soil cell – TCE mass loss due to vaporization)) × 100%.

^d Percent destruction = 100% – residual TCE fraction in soil – percent removal.

^e Percent removal and destruction = percent removal + percent destruction.

turn would result in a higher percentage of TCE destruction. It is worth pointing out that the acid front generated during the EK remediation would move from the anode end, passing through the iron wall, toward the cathode end. Inevitably, in the course of EK treatment SIP particles would be subjected to acid washing as well. It has been reported that acid washing would increase the surface area of zero-valent iron [21]. Moreover, acid washing of zero-valent iron would create more reactive sites for oxidation [22]. Therefore, during the EK-Fenton process the iron particles in the reactive wall might play at least two roles in this study. First, SIP acted as a catalyst for generating hydroxyl radicals to oxidize TCE and its daughter products. Second, SIP provided new reactive sites for oxidation of TCE and other organic pollutants.

In comparison with Type II SIP, in general, a greater TCE destruction efficiency and a smaller percent removal were obtained by using Type I SIP (Table 3). Type I SIP consists of particles ranging from 50 to 150 mesh and having a BET surface area of 1.03 m²/g. These characteristics are somewhat similar to that of UPF-150 SIP. It is understandable why these two types of scrap iron powder have a similar percentage of TCE destruction. Although Test 5 (i.e. one-wall Type I SIP) had an EO permeability of 6.31×10^{-6} cm²/V s, close to that of Test 2 (i.e. one-wall UPF-50 SIP), it yielded only 12.34% of TCE removal. The reason for a rather low percent removal of TCE is not clear at present.

3.1.2. Effect of the amount of SIP on TCE treatment

From Table 3, it is evident that an increase of total amount (i.e. an increase in wall number) of SIP used would enhance the TCE destruction, but lower the removal efficiency regardless of the type of SIP used. Comparing the performances of one wall and two walls of Type I SIP, its TCE destruction efficiency increased from 55.38 to 59.41% and its removal efficiency decreased from 12.34 to 9.05%. For UPF-150 SIP, its TCE destruction efficiency increased from 54.52 to 56.24% and its removal efficiency slightly decreased from 18.96 to 18.62% (i.e. Test 4 versus Test 7). Again, a greater total surface area and likely more Fe(OH)₃ precipitates formed due to a greater amount of SIP used might explain the above experimental findings. The determined EO permeability also supports this speculation. For example, the EO permeability for Tests 1 and 6 were determined to be 6.76×10^{-6} and 5.19×10^{-6} cm²/V s, respectively. Thereby, 44.73 and 30.42% TCE removal for the cases of one wall and two walls of UPF-30 SIP, respectively become self-explanatory.

If comparisons were made among the same type of SIP in two walls, a decreased overall treatment efficiency and an increased destruction efficiency of TCE were found for a smaller size of SIP. For example, two walls of UPF-30 SIP yielded an overall treatment efficiency of 84.62% and a destruction efficiency of 54.20% for TCE. Two walls of UPF-150 SIP, however, yielded an overall treatment efficiency of 74.86% and a destruction efficiency of 56.24% for TCE. The effect of the amount of SIP on TCE treatment found in this work is in very good agreement with previous investigations on phenol [16,17], 4-chlorophenol [16], and diesel [19].

3.2. Effect of the soil type on TCE treatment

From Table 3, it is evident that a lower destruction efficiency and overall treatment efficiency were found for soil no. 2 in comparison with soil no. 1. This is ascribed to the fact

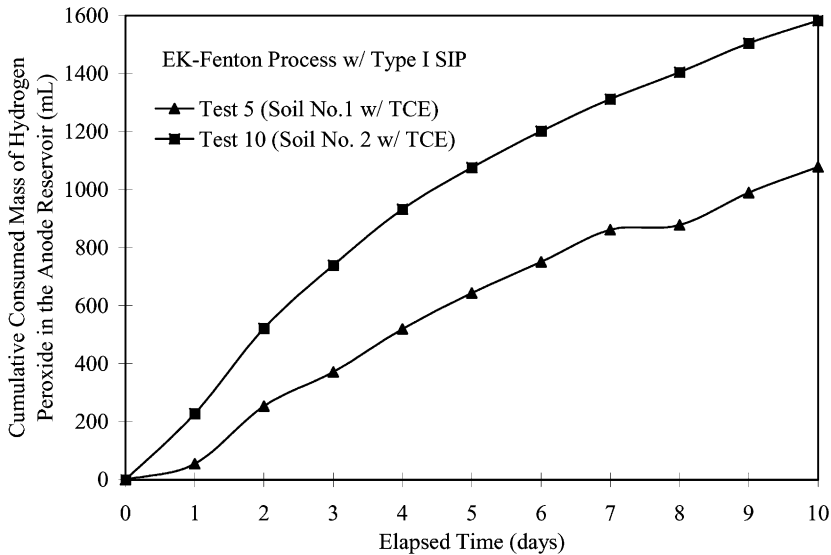


Fig. 3. Cumulative consumed masses of H_2O_2 in the anode reservoir vs. time for Tests 5 and 10.

that soil no. 2 per se had a much higher content of organic matter, which would consume a greater extent of hydroxyl radicals encountered. Thus, a lower concentration of hydroxyl radicals remained in the treatment system would result in a lower extent of TCE destruction. This point can also be verified by comparing the quantities of consumption of hydrogen peroxide for soil no. 1 and 2 (Fig. 3). Clearly, soil no. 2 consumed much more H_2O_2 than that of soil no. 1 for the same treatment time. Fig. 4 shows the treatment pattern of TCE for soil no. 2 by EK-Fenton process using one wall of UPF-30 SIP. From Figs. 2 and 4, evidently, a much higher residual concentration of TCE was found in soil no. 2 after 10

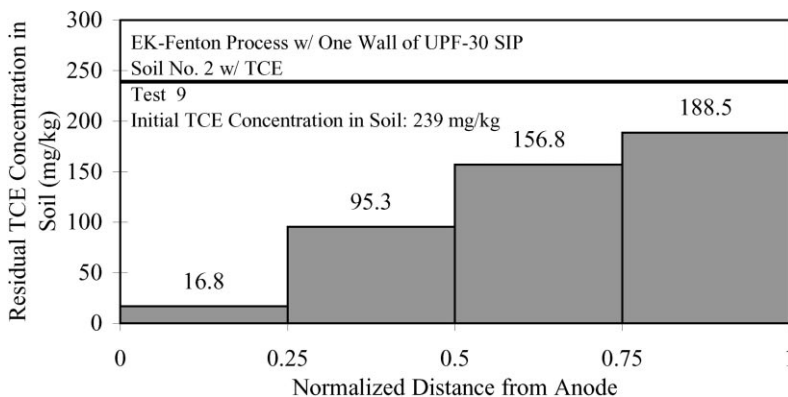


Fig. 4. Residual TCE concentration in soil no. 2 treated by the EK-Fenton process using one wall of UPF-30 SIP.

days of remediation by EK-Fenton process. The findings obtained above are supported by those reported by other researchers. It has been reported that the organic matter in soil may not only compete for hydroxyl radicals with organic contaminants but also adsorb these target organics [23,24]. Thus, a soil of higher organic content in general would result in an inferior treatment performance of organic contaminants by any process involving the Fenton reaction.

3.3. Effect of the electrode material on TCE treatment

Fig. 5 shows the treatment pattern of TCE for soil no. 1 by EK-Fenton process using one wall of UPF-30 SIP and SUS 304 stainless steel (SS) electrodes. Apparently, the treatment patterns in soil no. 1 are different when different electrode materials are used (Figs. 2 and 5). In the case of SS electrodes, a much higher residual TCE concentration was obtained. Perhaps this is due to a much smaller EO flow quantity and EO permeability in the case of SS electrodes. From Fig. 6, it is clear that the cumulative EO flow quantity is much greater for graphite electrodes than that of SS electrodes. Starting from day 4 of the test period the EO flow quantity for Test 11 (i.e. the case of SS electrodes) dramatically decreased and almost remained the same till the end of test period. Regarding the EO permeability for Test 11, it is much lower than that of Test 1 (i.e. 2.91×10^{-6} versus 6.76×10^{-6} $\text{cm}^2/\text{V s}$). Table 3 shows that Test 11 yielded a lower percent removal and overall treatment efficiency than that of Test 1 (i.e. 32.09 versus 44.73% and 77.33 versus 88.91%, respectively). Accordingly, graphite electrodes are superior to SS electrodes in terms of TCE treatment efficiency.

3.4. Effect of FeSO_4 concentration on TCE treatment

In addition to two types of SIP, 0.0196 and 0.098 M FeSO_4 were also tested to determine their effects on TCE treatment by EK-Fenton process. From Table 3, it is clear that 0.0196 M FeSO_4 yielded a slightly greater overall treatment efficiency and removal

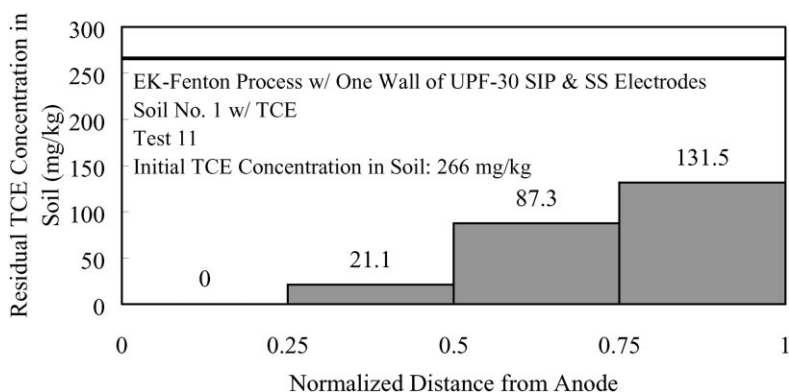


Fig. 5. Residual TCE concentration in Soil no. 1 treated by the EK-Fenton process using one wall of UPF-30 SIP and SS electrodes.

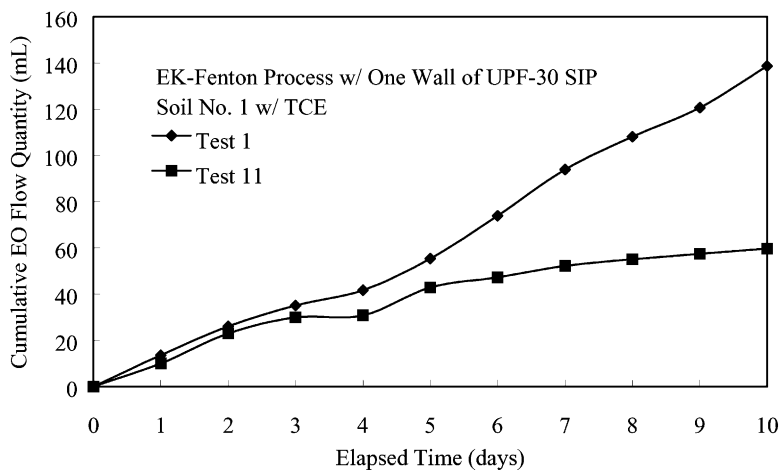


Fig. 6. Cumulative EO flow quantity vs. time for Tests 1 and 11.

efficiency than that of 0.098 M FeSO_4 . The percent removal and overall treatment efficiency of TCE were found to be in the neighborhood of 60 and 75%, respectively. Apparently, the removal mechanism dominated when 0.0196 M or 0.098 M FeSO_4 was used as the catalyst for Fenton reaction in EK-Fenton process. On the contrary, the destruction mechanism dominated when any type of SIP was used in the same treatment system. This may be ascribed to the fact that a considerable quantity of hydrogen peroxide consumed possibly turned out to be in vain in the system of soluble iron addition. In this operating system, a vigorous attack of soluble iron by hydrogen peroxide took place because about 800 mg hydrogen peroxide was consumed in the first day of H_2O_2 addition in the anode reservoir. The hydroxyl radicals thus generated would lose their oxidizing capacity before they entered the soil cell to destroy the organic contaminants within. Similar findings were also reported for treating soils contaminated by 4-chlorophenol and PCP using the same process [18,20].

3.5. Effect of the content of inherent iron in soil on TCE treatment

Remediation of TCE by EK-Fenton process without application of any foreign catalyst was also conducted for soil no.1 and 2. Under the circumstances, Fenton reaction could only take place by making use of the inherent iron minerals in soil as the catalyst. Results of Tests 14 and 15 showed that the removal mechanism dominated in the course of treatment (Table 3). By comparing the treatment performances of TCE for two soils, soil no. 2 having a greater content of inherent iron yielded a higher TCE destruction over the other soil. This finding was also supported by the fact that a greater consumption of hydrogen peroxide in the anode reservoir for the case of soil no. 2. However, a rather low percentage of TCE destruction was attributed to the lack of foreign catalysts, which would enhance the generation of hydroxyl radicals for oxidation of organic contaminants.

Table 4
Operating costs for TCE contaminated soils treated by the EK-Fenton process

Test no.	Soil no.	Catalyst type and amount/ concentration	Unit cost of electricity (US\$/m ³)	Unit cost of chemical(s) and/or material (US\$/m ³)	Unit operating cost (US\$/m ³)
1	1	One-wall UPF-030 SIP	1.43	0.27	1.70
2	1	One-wall UPF-050 SIP	1.50	0.26	1.76
3	1	One-wall UPF-100 SIP	1.29	0.23	1.52
4	1	One-wall UPF-150 SIP	1.43	0.23	1.66
5	1	One-wall Type I SIP	1.52	0.24	1.76
6	1	Two-wall UPF-030 SIP	1.34	0.24	1.58
7	1	Two-wall UPF-150 SIP	1.17	0.23	1.40
8	1	Two-wall Type I SIP	0.90	0.20	1.10
9	2	One-wall UPF-030 SIP	5.63	8.48	5.89
10	2	One-wall Type I SIP	5.53	0.35	5.88
11	1	One-wall UPF-030 SIP	0.95	0.25	1.20
12	1	0.098M FeSO ₄	2.07	0.55	2.62
13	1	0.0196M FeSO ₄	2.07	0.53	1.96
14	1	Nil	1.44	0.19	1.63
15	2	Nil	4.90	0.20	5.10
16	1	Two-wall UPF-030 SIP	1.13	0.03	1.16

3.6. Cost analysis of TCE contaminated soil treated by the EK-Fenton process

In this work, the energy expenditure per unit volume of soil was calculated by the equation given below [25].

$$E_u = \frac{1}{V_s} \int VI dt$$

where E_u is the energy expenditure per unit volume of soil (kWh/m³), V_s the soil volume (m³), V the electric potential difference across the electrodes (V), I the electric current (A), and t the treatment time (h). The electricity cost per unit volume of soil for each test was determined by multiplying E_u by the average electricity rate (i.e. 1.5 NT\$/kWh; US\$ 1 = 33 NT\$) for industries (Table 4).

In addition to the electricity cost, the cost of chemical(s) and material involved must be taken into account in the estimation of operating cost. The unit costs of various chemicals and material are given as follows: H₂O₂, US\$ 1.52/l; FeSO₄, US\$ 0.30/l; and SIP, US\$ 3.03/kg. The calculated unit costs of chemical(s) and/or material are presented in Table 4.

Table 4 also presents the sum of unit cost of electricity and unit cost of chemical(s) and/or material (i.e. the unit operating cost) for each treatment run. Apparently, the unit operating cost for soil no.2 is more than three times higher than that of soil no. 1. Comparing various catalyst types, the unit operating cost for FeSO₄ was found to be higher than that of any SIP. From Table 4, it is evident that the unit operating cost obtained for the EK-Fenton process is much lower than many other treatment technologies. In the literature, unit operating costs for in situ soil remediation at various sites range from US\$ 40 to 90 per cubic yard [26]. That is, US\$ 52–118 per cubic meter. Apparently, the unit operating cost for the EK-Fenton process employed in this study is much lower than those reported in the literature.

In this work, the most cost-effective test based on the greatest extent of TCE destruction was determined to be Test 8, then followed by Test 7. In other words, an employment of two walls of Type I SIP or UPF-150 SIP in soil no. 1 would be the first choice for TCE destruction. However, it is worth pointing out that the capital cost (including the installment cost for SIP walls) and maintenance cost are not considered here.

4. Conclusions

In this work, the performance and cost-effectiveness of using the EK-Fenton process for treating TCE contaminated soils were evaluated. The evaluations of treatment performance were conducted for different soil types, catalyst types, catalyst quantities/concentrations, and electrode materials. Based on the experimental findings, the following conclusions are drawn.

1. Scrap iron powder (SIP), in general, yields a higher treatment performance than that of FeSO₄.
2. For the same type of SIP, normally, the smaller the granular size is, the greater the TCE destruction will be. However, a lower percent removal and overall treatment efficiency will be obtained for the case of a smaller granular size of SIP.

3. For the same type of SIP, generally, the greater the wall number is, the greater the TCE destruction will be. As for FeSO₄, 0.0196 M in concentration would have a better treatment performance than that of 0.098 M.
4. When SIP was used in the EK-Fenton process, the destruction mechanism dominated. On the contrary, the removal mechanism would dominate when FeSO₄ was used.
5. A soil with a high content of organic matter, in general, would consume more hydrogen peroxide resulting in a lower destruction of organic contaminant.
6. Graphite electrodes were found to be superior to SUS 304 stainless steel electrodes in terms of TCE treatment performance.
7. Inherent iron content in soil alone is insufficient to give rise to a satisfactory level of TCE treatment.
8. Results of cost analysis have shown that the EK-Fenton process is very low in operating cost. Furthermore, this process is cost-effective if appropriate operating conditions are adopted.

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