Evaporation of Volatile Chlorinated Hydrocarbons in Soils

Junho Lee[†] · Kapsong Park

Department of Environmental Science, Hankuk University of Foreign Studies

토양의 휘발성 염화 탄화수소 화합물 증발

이준호[†] · 박갑성

한국외국어대학교 자연과학대학 환경학과

Abstract

Evaporation of selected toxic volatile chlorinated hydrocarbons was studied in laboratory soil columns. The evaporation values were obtained for the ten volatile chlorinated hydrocarbons at two different temperatures (12°C and 21°C) from columns filled with silty clay loam and sandy loam soils. 1,1,1-Trichloroethane, trichloroethylene and chloroform evaporated considerably (36.7~54.6% removal), carbon tetrachloride, 1,2-dichlorobenzene, tetrachloroethylene, 1,3-dichlorobenzene, dichlorobromethane and dibromochloromethane to a lesser extent (15.3~39.3% removal), and bromoform evaporated poorly (<10 percent removal) at both temperature. Volatile chlorinated hydrocarbons concentration did not affect evaporation, no statistically significant difference in evaporation between the soil types was found. However, temperature affected evaporation, the effect of concentration on the evaporation was not conclusive.

1. Introduction

Volatile chlorinated hydrocarbons are a specific class of the volatile organic compounds with boiling points ranging from 50~100°C to 240~260°C. They exist mainly in the gas phase within the temperature and humidity ranges encountered indoors. They are ubiquitous: several hundred of those compounds have been found in atmosphere layer on the soil ground (Roulet et al., 2002).

Volatile chlorinated hydrocarbons have been extensively used in a variety of industrial and commercial applications for specific purposes, and they are known as one of the harmful pollutants because of their toxicity, malodorous nature, and a relatively high vapor pressure. Therefore, the proper control, removal, and reduction of the emission of volatile chlorinated hydrocarbons are a crucial task for the protection of the environment (Khan and Ghoshal, 2000; Ruddy and Carroll, 1993). One of the major sources of contamination is the leakage of petroleum and diesel fuel from underground storage tanks. Other sources of contamination by volatile chlorinated hydrocarbons are man-made sources, e.g. municipal waste, traffic, petrochemicals, indus-try, plastics, solvent extraction and agricultural effluents.

The monitoring of volatile chlorinated hydrocarbons shows an increasing interest on the part of wastewater and contaminated soil treatment managers owing to the toxicity and hazards associated with these compounds. Literature sources revealed the lack of systematic studies on the effect of different types of natural soil with variable pH, organic carbon and clay mineral contents on the fate of volatile chlorinated hydrocarbons. But this kind of systematic studies will be very useful in the decision-making process to choose the most appropriate remedial technique to clean contaminated soils (Serrano and Gallego, 2006).

A common means to clean up volatile chlorinated hydro-carbons contaminated soil is surfactant-enhanced remediation. However, surfactant-enhanced remediation has caused eco-nomic problems because of enormous surfactant usage and its high cost. Various methods such as air stripping, eva-poration, solvent extraction and vacuum extraction had been suggested for the remediation of volatile chlorinated compounds from soils (Kim et al., 2007). Increased evaporation in sand soils is directly related to increased permeability. Several studies presented evaporation charac-teristics of volatile chlorine compounds from soils such as clays, which exhibit higher porosities but have pore size

[†] To whom correspondence should be addressed.
  leejh@kordi.re.kr

distributions skewed towards smaller pores, show lower evaporation rates than sand (Acher et al., 1990; Fine and Yaron, 1993; Galin et al., 1990). In fine silty clay contaminated with gasoline, at water contents approaching 90% of saturation, vapor-phase diffusion of the contaminant was reduced (Johnson and Perott, 1990). Evaporation fluxes increased with the addition of small amounts of water to dry soils due to reduced sorption (Batterman et al., 2005; Goss, 1993; Shonnar and Bell, 1993).

Relatively few results have been reported in the literature on the removal of volatile chlorinated hydrocarbons in the contaminated soil by thermal decontamination. Removal of volatile chlorinated hydrocarbons have studied how soil decomposition itself may affect thermal cleanup (Bucala et al., 1996). They have quantified the total weight loss and the yields of several volatile products from rapid pyrolysis of an U.S. EPA synthetic soil matrix. These authors presented data and kinetics models that should be useful in better understanding the contributions of soil evaporation itself during soil thermal decontamination processes performed at very high heating rates. These experiments showed that temperature can significantly modify the chemical and physical structure of the volatile chlorinated hydrocarbon in soils, strongly depending on its nature and constituents, especially when soils contain high organic matter content to be pyrolyzed (Merino et al., 2003). However studies on the evaporation of volatile chlorinated hydrocarbons from soils are largely lacking.

In the present work, the thermal treatment of a whole soil (i.e., not an isolated soil fraction) contaminated with volatile chlorinated hydrocarbons was studied. The pure chemical instead of a fraction of volatile chlorinated hydrocarbons to keep track of the contaminant more accurately. The objective of this study was to evaluate the evaporation of volatile chlorinated hydrocarbons in contaminated samples following surface application to laboratory soil columns at two temperatures from silty clay loam and sandy loam soils and two concentrations (12°C and 21°C).
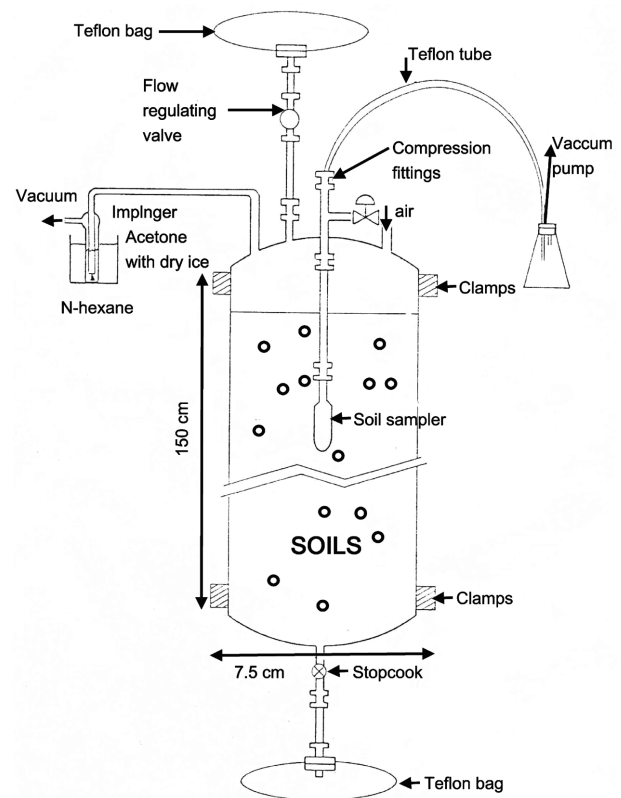

Fig. 1. Experimental apparatus used in the column study.

2. Materials and Methods

2.1. Soils

Two unsaturated soil types, silty clay loam (Porosity 0.49, Moisture retention 31.8%) and sandy loam (Porosity 0.48, Moisture retention 25.1%) add $HgCl_2$ soils, were used in the column study. These soils were chosen on the basis of physical and chemical characteristics.

Soils were collected with a soil core tube. The soil core tube is a steel pipe 150 cm long with an inside diameter of 7.5 cm. Soil cores collected were sectioned according to horizonation, air dried, crushed, and sieved (U.S. Standard Sieve mesh number 3.5; particle size 5.6 mm).

Each horizon of each soil was characterized in terms of

Table 1. Characteristics of soil samples

Soil texture	Horizon	pH	ECe[a] mmhos/cm	Nitrogen				P ppm	K ppm	CEC meq/100g	Organic carbon %
				T-N	NO₃-N	NO₂-N	NH₄-N				
				ppm							
Silty clay loam	A	8.2	0.6	841.0	11.7	0.2	0.3	26.7	344.0	18.1	0.9
	B	8.4	0.7	449.0	13.0	0.2	0.2	4.1	258.0	14.0	0.7
	C	8.4	1.0	263.0	7.4	0.3	0.2	3.4	255.0	15.6	0.3
Sandy loam	A	8.3	0.5	706.0	6.0	0.1	0.4	23.8	312.0	8.7	0.8
	B	8.8	0.6	436.0	6.1	0.3	0.3	16.7	381.0	10.5	0.4
	C	9.3	0.6	116.0	3.4	0.3	0.1	3.4	209.0	4.8	0.2

[a]Mean electrical conductivity of soil

pH, electrical conductivity, phosphorus, potassium, lime, cation exchange capacity, organic matter, texture, and nitrogen (Table 1).

2.2. Volatile chlorinated hydrocarbons

Ten volatile chlorinated hydrocarbons were used for laboratory experiments. The compounds used were reagent grade chloroform, trichloroethylene (Mallinckrodt Chemical Co., New York, NY), 1,1,1-trichloroethane, tetrachloroethylene, 1,2-dichlorobenzene, carbon tetrachloride, bromoform (Baker Chemical Co., Fair Lawn, NJ), dichlorobromomethane, dibromochloromethane, and 1,3-dichlorobenaene (Aldrich Chemical Co., Milwaukee, WI). These hydrocarbons were selected based on the toxicological characteristics of the compounds, the occurrence frequency and concentrations detected in soil and water environments.

2.3. Experimental design and procedure

Columns (150 cm in length and 7.5 cm in diameter) were packed with the sieved soil mimic to the original soil profile. The columns were made of borosilicate glass, and all materials contacting the feed solution, soil, and column effluent were made of either borosilicate glass, stainless or Teflon to minimize sorption of applied compounds or leaching of contaminants from the column and associated plumbing. The experimental configuration is presented in Fig. 1.

The feed solution, stored in a Teflon gas-sampling bag (All tech Assoc., Arlington Heights, I L), was added to the soil column through a Teflon tube with a flow regulating valve. The bottom of the column had a single port cap that was packed with Pyrex glass wool. Effluent from the column was also collected in the Teflon gas-sampling bag. The Teflon bags had minimal headspace and prevented the loss of volatile compounds in both the feed and the effluent.

Laboratory column studies were performed at 12°C and 21°C. For each temperature, 14 soil columns, seven columns for each soil type, were installed in a controlled temperature room. Three columns of each soil received deionized water alone and served as analytical control. Two replicated columns for each dosage level received deionized water amended with the volatile chlorinated hydrocarbons (Table 2).

Prior to initial application of the feed solution, the soil columns were leached three times per week for 2 weeks with deionized water to aid settling and to stabilize biological and chemical processes in the soils. The feed solution was applied once a week for 10 weeks.

Headspace above the soil was continually swept with air by applying a vacuum. Approximately 50 mL/min of air

Table 2. Dosage levels of volatile chlorinated hydrocarbons in column study

Compound	Low level (μg/ kg soil)	High level (μg/ kg soil)
Chloroform	70	150
1,1,1-trichloroethane	20	100
Carbon tetrachloride	20	50
Dichlorobromomethane	25	50
Trichloroethylene	40	200
Dibromochloromethane	20	80
Bromoform	40	200
Tetrachloroethylene	20	50
1,3-dichlorobenzene	1000	5000
1,2-dichlorobenzene	1000	5000

was removed from the headspace; this produced an air exchange about once every 30 min. Chlorinated chlorinated compounds were trapped by passing the evacuated air through an impinger (30 mL capacity, Wheaton Scientific Co., Millville, NJ) in which 25 mL of n-hexane was placed. The impinger was cooled by a dry ice/acetone suspension (approximately -70°C) to inhibit hexane evaporation. Air samples were collected for 6 hours at 6, 18, 30, and 168 hours after application.

Samples were analyzed for chlorinated hydrocarbons using a Hewlett Packard 5880 gas chromatography equipped with a Ni-63 electron capture detector.

Multiple-way analysis of variance was used to identify significant differences between removals of individual compounds, and to ascertain the effects of soil types, temperature, and influent concentration levels (high and low) on evaporation (SPSS, 1983).

3. Results and Discussion

The observed evaporation of volatile chlorinated hydrocarbons was approximately the same pattern through the initial 18 hours of application period, and then approximately 90% of volatile chlorinated hydrocarbon decreased for the following after 30 hours. The typical evaporation pattern of chlorinated hydrocarbons from the soil column was presented in Fig. 2.

The evaporation values were obtained for the ten chlorinated hydrocarbons at two temperatures (12°C and 21°C) from columns of silty clay loam and sandy loam soils. These values are summarized in Table 3 for input concentration of each compound. The chlorinated compounds studied were categorized into three groups according to the average amount of evaporation. Table 4 shows that in general, 1,1,1-trichloroethane, trichloroethylene and chloroform evaporated considerably (36.7~54.6% removal), while carbon
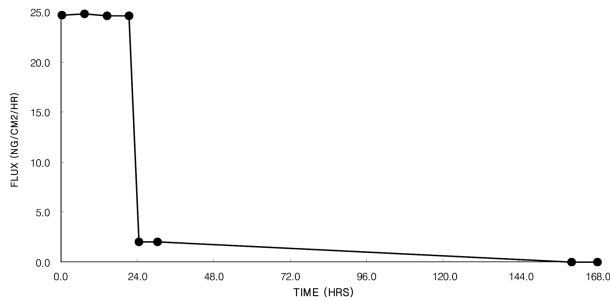
Fig. 2. Evaporation pattern of volatile chlorinated hydro-carbons from the laboratory experimental columns.

tetrachloride, 1,2-dichlorobenzen, tetrachloroethylene, 1,3-dich-lorobenzen, dichlorobromethan and dibromochloromethan to a less extent (15.3~39.3% removal), and bromoform evapo-rated poorly (<10 % removal) at both temperature. The differences between groups were statistically significant (p=0.001).

The compounds in each group evaporated at similar rates as predicted by the two-film model (Xie et al., 2006). Based on similar molecular weights and Henry's raw constants, the compounds should have similar overall mass

Table 3. Evaporation of volatile chlorinated hydrocarbons from columns of two soils at 12°C and 21°C

Compound	Temperature (°C)	Concentration applied (μg/kg soil)	Percent evaporated[a]	
			Silty clay loam	Sandy loam
Chloroform	12	68.4	30.0 ± 6.0	34.1 ± 6.3
	12	131.8	38.6 ± 5.3	39.6 ± 7.2
	21	79.8	42.1 ±15.9	45.3 ±11.8
	21	161.3	40.6 ± 3.2	42.1 ± 4.2
1,1,1-trichloroethane	12	12.5	41.8 ± 8.5	44.4 ± 9.6
	12	71.2	41.2 ± 8.7	39.9 ± 8.1
	21	14.9	56.1 ±21.4	63.0 ±19.7
	21	81.6	50.8 ± 9.8	52.9 ±10.2
Carbon tetrachloride	12	17.3	28.2 ± 6.7	30.0 ± 8.1
	12	44.2	31.0 ± 5.1	28.6 ± 5.6
	21	23.9	27.5 ± 7.7	28.7 ± 3.9
	21	56.4	28.0 ± 5.1	27.6 ± 6.7
Dichlorobromomethane	12	24.6	15.1 ± 1.2	18.0 ± 1.5
	12	49.5	18.5 ± 1.7	19.1 ± 2.0
	21	27.5	25.0 ±10.9	26.9 ± 7.7
	21	55.6	24.5 ± 4.7	24.1 ± 3.1
Trichloroethylene	12	41.6	37.1 ± 4.4	36.7 ± 2.9
	12	109.6	38.4 ± 2.6	33.2 ± 3.0
	21	50.2	47.5 ±13.3	46.9 ± 9.4
	21	236.3	44.5 ± 4.0	40.1 ± 3.9
Dibromochloromathane	12	21.9	12.7 ± 0.7	14.0 ± 2.4
	12	74.1	16.8 ± 1.3	17.4 ± 1.6
	21	25.8	20.0 ± 5.2	22.1 ± 4.6
	21	86.9	22.7 ± 2.0	21.8 ± 2.5
Bromoform	12	34.4	<3.8	<4.5
	12	153.5	8.0 ± 1.3	8.6 ± 1.3
	21	43.5	<7.2	<8.8
	21	185.0	14.0 ± 6.4	11.7 ± 6.5
Tetrachloroethylene	12	18.0	23.5 ± 9.1	17.3 ± 8.4
	12	45.8	18.8 ± 2.0	19.4 ± 1.6
	21	22.4	15.2 ±12.6	15.5 ± 6.1
	21	57.2	18.9 ± 4.8	9.5 ± 3.9
1,3-dichlorobenzene	12	1033	<17.9	<17.1
	12	5186	21.5 ± 1.6	21.5 ± 3.4
	21	1161	<25.6	<25.0
	21	5578	32.3 ± 2.6	31.4 ± 1.8
1,2-dichlorobenzene	12	872	<33.0	<35.1
	12	4972	24.6 ± 3.0	26.6 ± 4.5
	21	1010	<41.5	<43.9
	21	5189	28.2 ± 6.4	35.9 ± 2.2

[a]Mean ± 95% confidence intervals

Table 4. Classification of volatile chlorinated hydrocarbons

Class	12°C		21°C	
	Compound	Evaporated[a] (%)	Compound	Evaporated[a] (%)
1	1,1,1-trichloroethane	42.5 ± 2.4	1,1,1-trichloroethane	54.6 ± 4.1
	Trichloroethylene	36.8 ± 2.0	Trichloroethylene	44.6 ± 2.5
	Chloroform	36.7 ± 3.1	Chloroform	42.2 ± 1.5
2	Carbon tetrachloride	29.6 ± 1.2	1,2-dichlorobenzene	39.3 ± 3.0
	1,2-dichlorobenzene	29.5 ± 4.0	1,3-dichlorobenzene	27.8 ± 2.9
	Tetrachloroethylene	19.8 ± 1.7	Carbon tetrachloride	27.3 ± 0.9
	1,3-dichlorobenzene	19.0 ± 1.8	Dichlorobromoethane	23.9 ± 1.8
	Dichlorobromoethane	17.9 ± 1.2	Dibromochloromethane	20.4 ± 1.8
	Dibromochloromethane	15.3 ± 1.5	Tetrachloroethylene	19.8 ± 3.8
3	Bromoform	6.4 ± 1.7	Bromoform	9.7 ± 2.6

[a]Mean ± 95% confidence intervals

transfer coefficients. In the exchange of volatile compounds between air and soils, the interface between the two phases is considered as a two-layer (film) system. The main body of each fluid is assumed to be well mixed; the main resistance to gas transport coming from the gas and liquid phase interfacial layer, across which the exchanging gases transfer by molecular processes, Equation 1 was used for estimating the overall liquid mass transfer coefficient (Dilling, 1997):

$$K_\ell = \frac{13266}{\left(\dfrac{1.042}{H} + 100\right) \cdot M^{1/2}} \qquad (1)$$

where

K_ℓ = overall liquid mass transfer coefficient (cm/hr)

H = Henry's law constant (dimensionless)

M = molecular weight of solute (g/mole)

H is calculated by using Equation 2 :

$$H = \frac{C \cdot air}{C \cdot water} = \frac{16.04 \cdot P \cdot M}{T \cdot S} \qquad (2)$$

where

C = solute concentration

P = vapor pressure of solute (mm Hg)

M = molecular weight of solute (g/mole)

T = absolute temperature (oK)

S = solubility of solute (mg/L)

The calculated mass transfer coefficients (K_ℓ) for the ten volatile chlorinated hydrocarbons used in this study are presented in Table 5. As can be seen Table 5, the chlorinated compounds in the different classes have K_ℓ values that vary by a factor of 1.5. However, the differences in the amount of evaporated chlorohydrocarbons between classes was significant ($p \leq 0.05$), approximately 1.4 to

Table 5. Evaporation parameters and rates for volatile chlorinated hydrocarbons

Compound	M (g/mole)	S (mg/L)	P (mmHg)	H (25°C, KPa)	K_ℓ (cm/hr)	$t_{1/2}$ (min)
Chloroform	119.4	9600	198	0.14	11.4	25.7
		8890[d]	123	0.092	11.0	24.6
1,1,1-trichloroethane	133.4	720	124	1.20	11.4	24.9
Carbon tetrachloride	153.8	800	113	1.24	10.6	28.8
		907[d]	72.2	0.68	10.6	25.5
Dichlorobromoethane	163.8	-	-	0.088	9.30	29.1
		-	-	0.046	8.49	31.8
Trichloroethylene	131.4	1100	74.3	0.48	11.4	23.5
		-	-	0.31	11.3	23.9
Dibromochloromethane	208.3	-	50	0.032	6.97	38.6
Bromoform	252.8	3130	5.6	0.022	5.68	47.6
Tetrachloroethylene	165.9	150	19.6	1.17	10.2	27.1
		159[d]	10.3	0.56	10.1	26.8
1,3-dichlorobenzene	147.0	123	1.9	0.11	10.0	27.0
1,2-dichlorobenzene	147.0	145	1.5	0.079	9.71	27.8

2.8 folds between class 1 and 2, and 5.6 to 6.6 folds between class 1 and 3, respectively. These results indicate that the theoretical two-film model is not working the laboratory soil column systems. As indicate two-film model, the model is unrealistic for any real system. Turbulence level as determined by water currents or wind and physicochemical properties such as diffusivity or molecular size and temperature are known to be very important factors affecting the mass transfer constant (Mackay and Yeun, 1983).

The experimently measured flux of the volatile chlorinated compounds evaporating from the soil surface was compared to the flux expected from free water to evaluate the influence of soil on the evaporation of halogenated hydrocarbons (Table 6). The expected flux from free water was calculated from half-lives for evaporation experimentally determined at concentrations and temperatures near those encountered in this study (Dilling, 1997).

Table 6. Flux of volatile chlorinated hydrocarbons from soil and water

Compound	Temperature (°C)	Concentration applied (μg/kg soil)	Flux measured from soil		Flux calculated from water
			Silty clay loam	Sandy loam	
			$(ng/cm^2/hr)$		
Chloroform	12	68.4	11.4	13.0	752
	12	131.8	28.3	29.0	1450
	21	79.8	18.7	20.1	910
	21	161.3	36.4	37.7	1839
1,1,1-trichloroethane	12	12.5	2.9	3.1	-[a]
	12	71.2	16.3	15.8	-
	21	14.9	4.6	5.2	164
	21	81.6	23.1	24.0	898
Carbon tetrachloride	12	17.3	2.7	2.9	183
	12	44.2	7.6	7.0	469
	21	23.9	3.6	3.8	253
	21	56.4	8.8	8.6	598
Dichlorobromoethane	12	24.6	2.1	2.5	209
	12	49.5	7.6	5.2	420
	21	27.5	3.6	4.1	256
	21	55.6	8.8	7.4	517
Trichloroethylene	12	41.6	8.6	8.5	470
	12	190.6	40.7	35.2	2154
	21	50.2	13.2	13.1	572
	21	236.3	58.4	52.6	2694
Dibromochloromathane	12	21.9	1.5	1.7	-
	12	74.1	6.9	7.2	-
	21	25.8	2.9	3.2	180
	21	86.9	11.0	10.5	606
Bromoform	12	34.4	<0.7	<0.9	-
	12	153.5	6.8	7.3	-
	21	43.5	<1.7	<2.1	247
	21	185.0	14.4	12.0	1051
Tetrachloroethylene	12	18.0	2.3	1.7	182
	12	45.8	4.8	4.9	463
	21	22.4	1.9	1.9	228
	21	57.2	6.0	6.2	583
1,3-dichlorobenzene	12	1033	<103	<98	-
	12	5186	619	619	-
	21	1161	<165	<161	11610
	21	5578	1001	973	55780
1,2-dichlorobenzene	12	872	<160	<170	-
	12	4972	679	735	-
	21	1010	<233	<246	9810
	21	5189	1101	1035	50390

Flux from water = $0.693 \cdot D \cdot C/t_{1/2}$

where

$t_{1/2}$ = evaporation half-life (hour)

D = mL of water

C = input concentration of compound (μg/mL)

The average flux from soil was calaulated by Equation 3.

Flux from soil (μg/cm^2) = $C \cdot V \cdot F/A$ (3)

where

A = surface area of column (cm^2)

V = mL of feed solution applied/hour

F = fraction of material that evaporated

C = input concentration of compound (μg/mL)

Compared to evaporation from water, the soil inhibited evaporation by 32 to 145 times. These results suggest that the inhibition of evaporation from soil is controlled by the hydrodynamic characteristics of the soil system, sorption of organic compounds by soil particulate material, and chlorinated hydrocarbon solute diffusion in soil. Sorption of the

solute onto or into particulate material depress the effective concentration of the solute and complicate estimating mass transfer by evaporation. The movement of volatile chlorinated organic compounds in the unsaturated soil regime was limited by diffusion through the air filled pores.

The effects of soil type, compound concentration and temperature on the evaporation of volatile chlorinated hydrocarbons were analyzed by comparing the percent evaporation data in Table 3. No statistically significant difference in evaporation due to soil type was found. However, the results of the temperature comparison (Fig. 3) showed that the evaporation values at 21°C were higher than those at 12°C.

Differences in evaporation between low and high concentration were also found for four compounds: bromoform, tetrachloroethylene, 1,2-dichlorobenzene, and 1,3-dichlorobenzene (Fig. 4). Evaporations of bromoform and 1,3-dichlorobenzene were significantly greater at higher concentration, but the effect of concentration on the evaporation of these compound was not conclusive, since the percent evaporation values at low concentration were below the limit of detection, and the data below the detection limit were arbitrarily input at one-half the detection limit value
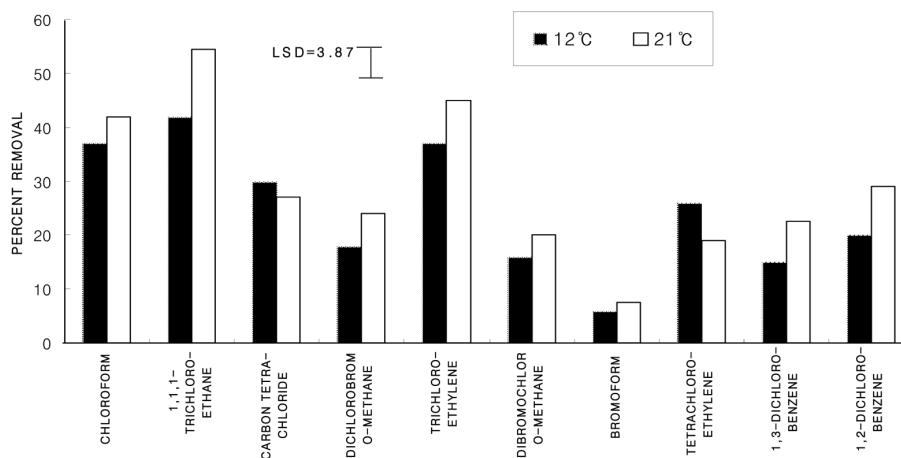

Fig. 3. Effects of temperature on the evaporation of volatile chlorinated hydrocarbons.
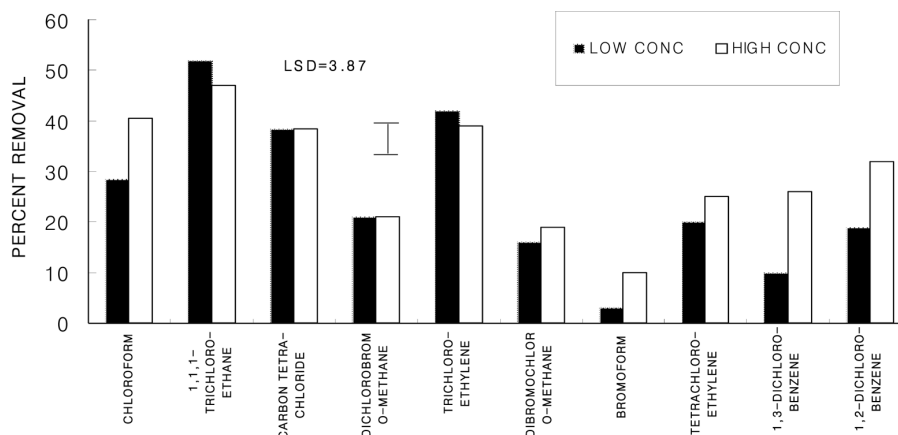

Fig. 4. Effects of concentration on the evaporation of volatile chlorinated hydrocarbons.

for purpose of the statistical evalution. For tetrachloroethylene a small but sifnificant increase in evaporation was observed at high concentration.

4. Conclusions

1,1,1-trichloroethane, trichloroethylene and chloroform evaporated considerably (36.7~54.6% removal), carbon tetrachloride, 1,2-dichlorobenzene, tetrachloroethylene, 1,3-dichlorobenzene, dichlorobromethane and dibromochloromethane to a lesser extent (15.3~39.3% removal), and bromoform evaporated poorly (<10 percent removal) at both temperature.

Compared to evaporation from water, soil inhibited evaporation by 32 to 145 times. These results suggest that the inhibition of evaporation from soil is controlled by the hydrodynamic characteristics of the soil system, adsorption of chlorinated organic compounds by soil particulate material, and hydrocarbon solute diffusion in soil.

Temperature comparison showed that the evaporation values at 21°C were higher than those at 12°C for seven compounds : chloroform, 1, 1, 1-trichloroethan, dichlorobromomethan, trichloroethylen, dibromochloroethan, 1, 2-dichlorobenzene and 1,3-dichlorobenzene. For the remaining compounds, the effects in volatilization due to increased temperature were not significant.

요 약

독성 성질을 가진 휘발성 염소계 탄소수소류의 휘발특성에 대하여 실험실 규모의 토양컬럼실험을 진행하였다. 실트 점토성 토양과 사질성의 양질 토양 2개 컬럼으로부터 12℃, 21℃의 각각 다른 조건으로 실험한 결과 총 10가지의 휘발성염소계 화학물질이 검출되었다. 1,1,1-trichloroethane, trichloroethylene 그리고 chloroform은 초기 농도대비 36.7~54.6% 제거되었고 carbon tetrachloride, 1,2-dichlorobenzene, tetrachloroethylene, 1,3-dichlorobenzene, dichlorobromethane 그리고 dibromochloromethane는 초기 농도대비 15.3~39.3% 제거되었으며 특히 bromoform 물질의 경우 초기 농도대비 10%이하의 가장 낮은 저감 비율이 보였다. 염소계 탄화수소류 초기 농도값, 토양 성상은 휘발량에 큰 영향을 끼치지 않았다. 그러나, 온도비교에서 12℃보다 21℃에서 저감비율이 더 높았다.

Acknowledgements

References

Acher, A. J., Boderie, P. and Yaron, P. (1990). Soil pollution by petroleum products: I. Multiphase migration of kerosene components in soil columns. *J. Contam. Hydrol.*, **4**, pp. 333-345.

Batterman, S., Kulshrestha, A. and Cheng, H. (2005). Hydrocarbon vapor transport in low moisture soils. *Environ. Sci. Technol.*, **29**(1), pp. 171-180.

Bucala, V., Saito, H., Howard, J. B. and Peters, W. A. (1996). Products compositions and release rates from intense thermal treatment of soil. *Ind. Eng. Chem. Res.*, **35**, pp. 2725-2734.

Dilling, W. L. (1997). Interphase transfer processes. 2: Evaporation rates of chloro methanes, ethanes, ethylenes, propanes, and propylenes from dilute aquifer solution, comparisons with theoretical predictions. *Environ. Sci. Technol.*, **11**, pp. 405-409.

Fine, P. and Yaron, B. (1993). Outdoor experiments on enhanced volatilization by venting of kerosene component from soil. *J. Contam. Hydrol.*, **12**, pp. 355-374.

Galin, T., McDowell, C. and Yaron, B. (1990). The effect of volatilization on the mass flow of a non-aqueous pollutant liquid mixture in an inert porous medium: experiments with kerosene. *J. Soil Sci.*, **41**, pp. 631-641.

Goss, K. (1993). Effects of temperature and relative humidity on the sorption of organic vapors on clay minerals. *Environ. Sci. Technol.*, **27**, pp. 2127-2132.

Johnson, R. L. and Perott, M. (1990). Gasoline vapor transport through a high-water-content soil. *J. Contam. Hydrol.*, **8**, pp. 317-334.

Khan, I. and Ghoshal, A. K. (2000). Removal of volatile organic compounds from polluted air. *J. Loss. Prevent. Proc.*, **13**, pp. 527-545.

Kim, K. S., Kwon, T. W., Yang, J. S. and Yang, J. W. (2007). Simultaneous removal of chlorinated contaminants by pervaporation for the reuse of a surfactant. *Desalination*, **205**, pp. 87-96.

Mackay, D. and Yeun, A. T. (1983). Mass transfer coefficient correlations for volatilization of organic solutes from water. *Environ. Sic. Technol.*, 17, pp. 211-217.

Merino, J., Pina, J., Errazu, A. F., and Bucala, V. (2003). Fundamental study of thermal treatment of soil. *Soil Sediment Contam.*, **12**, pp. 417-441.

Roulet, C. A., Pibiri, M. C., Knutti, R. and Pfeiffer, A., and Weber, A. (2002). Effect of chemical composition on VOC transfer through rotating heat exchangers. *Energy and Building*, **34**, pp. 799-807.

Ruddy, E. N. and Carroll, L. A. (1993). Select the best VOC control strategy. *Chem. Eng. Prog.*, **89**, pp. 28-35.

Serrano, A. and Gallego, M. (2006). Sorption study of 25 volatile organic compounds in several Mediterranean soils using headspace-gas chromatography-mass spectrometry. *Journal of Chromatography*, **1118**, pp. 261-270.

Shonnard, D. R. and Bell, R. L. (1993). Benzene emissions from a contaminated air-dry soil with fluctuations of soil temperature or relative humidity. *ES&T,* **27**, pp. 2909-2913.

SPSS, Inc. (1993). SPSS X user's guide. SPSS, Inc., IL.

Xie, Z., Wang, Y., Jiang, W. and Wei, X. (2006). Evaporation and evapotransiration in a watermelon field mulched with gravel of different size. *Agricultural Water Management*, **81**, pp. 173-184.