

Article

Evaluation of Indirect-Heated Microwave Thermal Desorption Treatment on Engineering Properties of Lubricant-Contaminated Soil

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Featured Application: Study on the environmental and geotechnical engineering properties of soil remediated by the indirect-heated microwave thermal desorption method.

Abstract: Soil pollution caused by oil leakage from various industrial facilities such as gas stations, oil plants, military bases, and railway depots has become a serious global environmental and geotechnical issue. The indirect-heated microwave thermal desorption technology has been developed in this study for economical and efficient remediation of oil or organic pollutants. The conclusions were made based on laboratory tests and analyses of the environmental (TPH; total petroleum hydrocarbons) and geotechnical (physical and mechanical) properties of the soil before and after treatments. (1) As the newly-developed equipment was operated for 3 h with the electric power of 32 kW to reach target temperature of 600 °C, more than 99.8% of TPH was removed. (2) In the aspect of geotechnical properties, the internal friction angle, maximum dry density and permeability coefficient of the soil were reduced by oil contamination and were finally restored to the almost initial level of the soil after treatment. Therefore, treated soil is expected to be reusable for geotechnical construction purposes such as construction fill materials. (3) It was also found that the developed technology reduces 75% of energy cost and 25% of CO₂ emissions for the remediation of lubricant oil-contaminated soil comparing with conventional one.

Keywords: microwave; treatment; thermal desorption; lubricant-contaminated soil; TPH (total petroleum hydrocarbons)



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1. Introduction

Soil pollution caused by oil leakage from various industrial facilities such as gas stations, oil plants, military bases and railway depots has become a serious global environmental and geotechnical issue [1–3]. However, recent studies on the remediation of oil-contaminated soil have been mostly performed based on the environmental, mechanical, chemical engineering or microbial technology instead of soil mechanics or geotechnical engineering. Physical properties of the soil tend to be a completely different state (solid, semisolid, plastic and liquid) depending on soil particle size, void ratio and moisture content, etc., but the remediation technology applied to design and operation has been limited to fully reflect such soil conditions [4].

As solutions to treatment of oil-contaminated soil, conventional (biological and physicochemical) remediation technologies have difficulties when it comes to remediating highly concentrated oil or organic pollutants [5,6]. Remediation technologies that can efficiently deal with such pollutants have been reported as thermal treatment methods which are classified into thermal desorption (800 °C or lower), pyrolysis (800 °C or higher), incineration (800 °C or higher) and vitrification (1200 °C or higher), depending on the operation temperature to remove the pollutants [7–10].

Even though high-temperature thermal treatment such as thermal desorption is very effective to remediate the oil-contaminated soil, the thermal desorption method can change the texture and mineralogy of fine-grained soil [11]. In other words, the heating process causes dihydroxylation in its mineral structure and decomposition of its mineral structure at threshold temperatures above 400 °C [12], kaolinite deteriorates when heated between 420 °C and 500 °C [13] and the dehydroxylation of illites begins above 550 °C [11].

When it comes to the thermal desorption of fine-grained soil, following dihydroxylation in its mineral structure during the heating process, the effect of decomposition of its mineral structure on its geological function should be considered when designing the reuse of contaminated fine-grained soil.

Thermal desorption technology, as one of the thermal treatment technologies, can remove more than 99% of volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), diesel, BTEX, gasoline and jet fuel [14], but as it uses fossil fuel, its remediation cost is high since energy efficiency is low, and it generates secondary emissions [15]. Furthermore, as the resource of fossil fuel is expected to be exhausted sooner or later, the development of alternative energy sources becomes more important.

In this study, microwave instead of fossil fuel is considered as one of the alternative energies in the form of electrical energy. Soil remediation technology using microwave is expected to be the optimal method that enhances the energy efficiency for thermal desorption, and reduces the secondary emissions [16,17]. Heating technology using microwave is based on the heating principle by molecular friction while polar materials such as water and iron contained in the material are rotating by changing the electromagnetic field [18]. Jeong et al. studied the remediation of contaminated soil based on microwave heating technology with advantages of rapid heating, uniform temperature distribution and high thermal efficiency [17]. Oil-contaminated soil remediation technology using microwave has been applied to the remediation of soil contaminated by organic matter and the disposal of sludge containing heavy metals. In particular, the microwave heating method is known to be effective for removing volatile or semi-volatile organic pollutants with polarity [19–22].

A rotary kiln is one of the most widely used technologies for the thermal desorption process, which is classified into direct-heated and indirect-heated types according to how the heat is introduced into the target material [23]. In a direct-heated technology, the heat which comes from the heat source is pushed through the kiln and directly transferred to the target material [24–26]. However, indirect-heated technologies may be recommended since there is a risk of the explosion from the heat source in the direct-heated method [27]. Therefore, indirect-heated microwave thermal desorption technology has been developed in this study for economical, safe, and efficient treatment of oil or organic matter [15].

In this study, the soil sampled from the railway roadbed construction site was intentionally contaminated by mixing with SVOCs such as lubricant oil, and it was then treated by microwave thermal desorption rotary kiln using indirect-heated technology for the assessment of the treatment efficiency of SVOCs and geotechnical properties of the soil before and after remediation. Based on the laboratory test results, indirect-heated microwave thermal desorption technology is expected to make a substantial contribution to enabling SVOCs-contaminated soil to be purified in an eco-friendly and energy-efficient way.

2. Experimental Materials and Methods

2.1. Experimental Materials

For this study, 100 cm of the soil profile was divided into two vertical strata at depth of 100 to 200 cm below the ground surface after removing topsoil from the railway roadbed construction site. Two randomly sampled soils at each layer were thoroughly mixed together for the prevention of environmental heterogeneity. Sample soil was naturally dried, and the soil impurities were removed by sieving with a #10 sieve (2 mm). The soil was classified by the United Soil Classification System (USCS), and laboratory soil tests were conducted in accordance with the ASTM (American Society for Testing and Materials). The results are shown in Table 1 and Figure 1. Specific gravity, Atterberg limits (liquid limit,

plastic limit and plastic index) and permeability of initial soil are in the typical range of silty sand (SM). The tested soil was classified as silty sand (SM) as resulted from the sieve analysis and Atterberg limit test; (1) more than 50% of retained on No. 200 (0.075 mm), 75~87.5%; (2) 50% or more of coarse fraction passing No. 4 sieve (4.75 mm), 98.2~100%; and (3) plasticity index is less than 4.

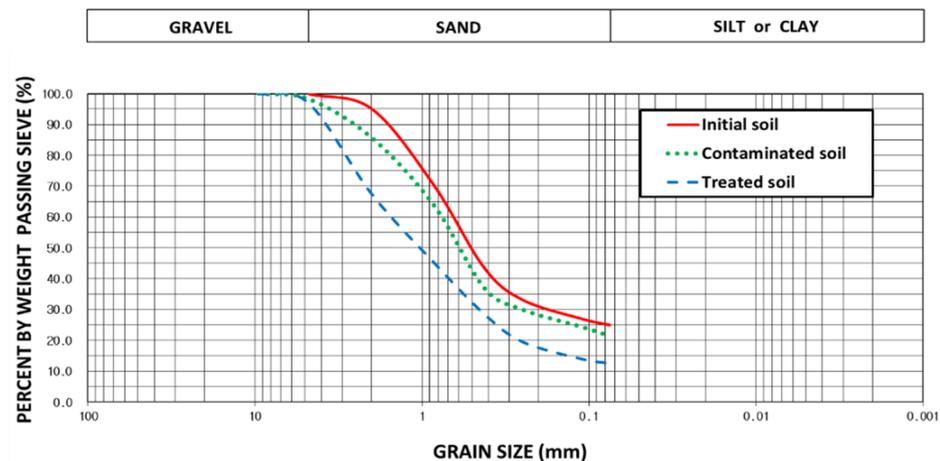


Figure 1. Particle size distribution curves of initial, lubricant-contaminated and treated soil (Based on ASTM D-6913) [28].

Table 1. Physical properties of initial, lubricant-contaminated and treated soil.

Parameters	Unit	Results			References
		Initial Soil	Contaminated Soil	Treated Soil	
USCS Classification	-	[†] SM	SM	SM	ASTM D-2487 [29]
Natural Water Content	%	7.1	5.5	0.2	ASTM D-698 [30]
# Liquid Limit	%	* N.P.	29.3	N.P.	ASTM D-4318 [31]
# Plastic Limit	-	N.P.	N.P.	N.P.	ASTM D-4318 [31]
# Plastic Index	-	N.P.	N.P.	N.P.	ASTM D-4318 [31]
Specific Gravity	-	2.6	2.6	2.6	ASTM D-792 [32]
Coefficient of Permeability	cm/s	2.1×10^{-4}	5.6×10^{-5}	7.1×10^{-4}	ASTM D-2434 [33]

* N.P.: Non-plastic. [†] SM: Silty Sand. # Atterberg limits: liquid limit, plastic limit and plasticity index.

The sampled soil was intentionally contaminated by lubricant oil of which the chemical composition (Table 2) had a concentration level of about 26,000 mg/kg, and its physical characteristics are shown in Table 1 and Figure 1. Lubricant-oil contaminated soil becomes more compressible and less permeable than initial soil with respect to liquid limit and coefficient of permeability due to the penetration of viscous oil into the pores between soil particles.

Table 2. Chemical composition of lubricant oil.

Chemical Substance	CAS No.	EC No.	Content (%)
Distillates (petroleum), hydrotreated heavy paraffinic	64742-54-7	265-157-1	85~95
Phosphorodithioic acid mixed O,O-bis(1,3-dimethylbutyl and iso-Pr) esters zinc salts	84605-29-8	283-392-8	0~2
Dodecylphenol, branched	121158-58-5	310-154-3	0~2
Acrylic copolymer	-	-	0~1

2.2. Experimental Methods

The indirect-heated microwave thermal desorption method as shown in Figure 2 can be applied for the rapid and effective treatment of high concentrated oil and organic matter-contaminated soil, which is difficult to complete by physicochemical or biological treatment method.

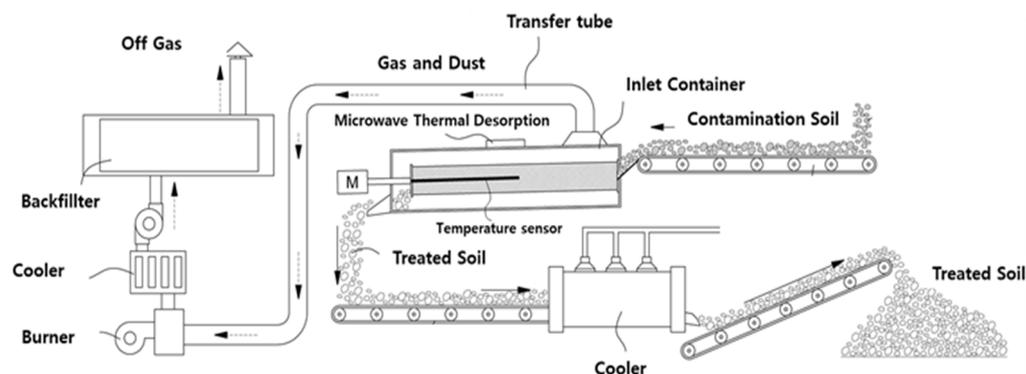


Figure 2. Process of indirect-heated microwave thermal desorption treatment.

The recently developed microwave thermal desorption technologies have been compared according to the heating modes as shown in Table 3.

Table 3. Comparison of microwave heating technology.

Microwave Heating	This Study	Dawei et al. [34]	Lin et al. [35]	Y. C. Chien [15]	Falciglia et al. [36]
Heating modes	Indirect	Direct	Direct	Direct	Direct
Types of Microwave absorber	Slag	Carbon fiber	Activated carbon	None	None
Microwave exposure	Exposure to absorber	Exposure to mixture of soil and absorber	Exposure to mixture of soil and absorber	Exposure to soil	Exposure to soil
Applications	Ex situ	Ex situ	Ex situ	In situ	Ex situ

An indirect-heated microwave thermal desorption technology developed in this study uses a microwave and microwave absorber as a heat source instead of fossil fuel. As shown in Figure 3, the indirect-heated microwave thermal desorption equipment (rotary kiln) consists of an outer container on which a microwave generator (magnetron) is set and an inner (soil) container on which a microwave absorber is circumferentially installed. In this technology, 2.45 GHz microwave stimulates microwave absorber to absorb microwaves, as well as to generate heat in order to highly and rapidly heat the surface of the inner container, and the heat is fully transferred into the inner (soil) container to finally uniformly heat the soil. The design specifications of the indirect-heated microwave thermal desorption equipment are described in Table 4.



Figure 3. Indirect-heated microwave thermal desorption equipment.

Table 4. Design specifications of indirect-heated microwave thermal desorption equipment.

Driving Part	
Operation Type	Rotary, Batch
Treatment Heat Source	Microwave and Microwave Absorber
Rotatory Inner Container	Ø 0.6 m × L 1.6 m
Outer Container Size	W 1.5 m × L 2.4 m × H 2.4 m
Rotation Speed	Max. 12.5 rpm
Operation Angle	0°~3°
Capacity	50 kg/batch
Heating Part	
Microwave Output Power	1 kW
Frequency	2.45 GHz
Peak Anode Voltage	4.0 kV
Average Anode Current	340 mA
Filament Voltage	3.3 V
Filament Current	10 A
Capacity of Air Cooling	800 L/min

The rotary inner (soil) container was designed to be preheated to target temperatures corresponding to the target contaminants prior to the main remediation process. Target temperatures were designed to 400, 500 and 600 °C for the remediation of lubricant-oil-contaminated soil in this study. As shown in Figure 4, it took 180 min to reach the temperatures of 400, 500 and 600 °C with power consumptions of 16, 24 and 32 kW, respectively. During the test, the temperature in the center of the inner container was monitored with a type-k thermocouple, and the temperature variations at each section in the soil container were recorded using GRAPHTHEC’s DATA LOGGER (GL840).

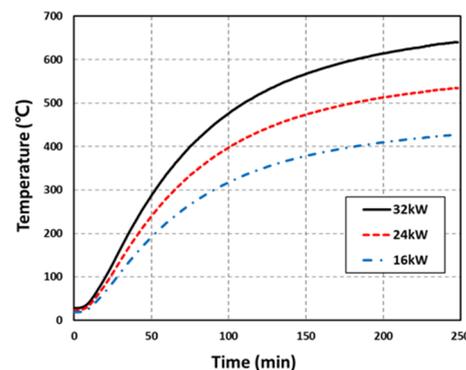


Figure 4. Monitored temperature preheated for indirect-heated microwave thermal desorption.

2.3. Laboratory Tests

2.3.1. Environmental Properties

In this study, a series of remediation tests were repeatedly conducted with different thermal surcharges under the same boundary conditions, as shown in Table 5. To evaluate the TPH (Total Petroleum Hydrocarbon) and treatment rate, sample soil treated by indirect-heated microwave thermal desorption was analyzed in accordance with ASTM D-1945 [37]. This is the method of analyzing the components of a pretreated sample using the gas chromatogram of each component divided as a result of passing the separation tube column by the carrier gas. It is a generally used method for quantitative and qualitative analyses of organic compounds.

Table 5. Residual TPH concentration and removal efficiency by treatment temperature and time.

Treatment Temperature (°C)	Treatment Time (min)	Residual TPH Concentration (mg/kg)	Removal Efficiency (%)
400	0	∇ 26,063	-
	5	5490	78.3
	10	2866	88.7
	15	1846	92.7
500	0	25,325	-
	5	3626	85.7
	10	1995	92.1
	15	1383	94.5
600	0	26,600	-
	5	2512	90.6
	10	652	97.6
	15	38.2	99.9

∇ Calculation procedures are shown in Tables A1 and A2.

The contaminated sample was pretreated according to the ASTM D-1945 [37], and analysis of TPH was carried out using GC-FID (Flame Ionization Detector).

The TPH was extracted by the ultrasonic extractor from the 10 g of well-mixed soil sample repeatedly collected across 3 locations with 50 mL of sodium sulfate anhydride (more than 95% purity) and dichloromethane (more than 99.9% purity). The collected extracts were filtered by membrane paper and were concentrated to 2 mL using the rotary evaporation concentrator. Finally, for removal of impurities, 0.3 g of silica gel was added to the sample, which was injected to GC-FID, and TPH was measured by gas chromatography, as shown in Table 6 [37].

Table 6. Descriptions and conditions of gas chromatography (GC).

Descriptions	Conditions
GC Instrument/Detector	Varian, 450-C/300-MS
Column	Agilent CP-Sil 8CB; Ultra-2 (Cross-linked 5% phenyl methyl silicon)
Temperature	Injection 300 °C Detector FID 320 °C
Carrier gas/flow rate	12 °C/min rate to 310 °C for 18.33 min hold Helium (2.0 mL/min)
Injection volume	2 µL
Split ratio	10:1
Ultrasonic extractor model	Bandelin, Sonoplus UW3100
Type of filters	ADVANTEC, Quantitative Filter Paper 5B 110 mm

2.3.2. Geotechnical Properties

Geotechnical properties of the soil before and after treatments were estimated in the physical and mechanical aspects; physical properties (Atterberg limits, particle-size

distribution, permeability, maximum dry density and optimum moisture content, etc.) related to the movement process of the pollutants and mechanical properties (cohesion and internal friction angle) were concerned with soil stability.

Atterberg limits are defined as critical water contents of fine-grained soil (silt and clay). Soil appears in one of liquid, plastic, semisolid and solid states depending on its water content, and water contents at the boundary between each state are known as Atterberg limits, which are divided into the liquid limit, plastic limit and shrinkage limit (ASTM D-4318) [31].

Sieve analysis is often used for determining particle-size distribution of coarse-grained soil. A set of sieves is used to measure particle-size distribution defined as relative weight amount of soil particles remaining in a sieve in % (ASTM D-6913) [28].

The constant head permeability test (ASTM D-2434) was the method used to identify the relationship between water level variation and time elapsed when the water penetrates the soil sample with a certain diameter and length [33].

The compaction test (ASTM D-698) was the method used to improve the soil properties by increasing the density using artificial energy. In the process of testing, the air in the voids is discharged when tamping the soil so that the density is increased, and the ratio of void between particles is decreased. Plotting the values of dry density on the y-axis and the moisture contents on the x-axis through a series of compaction tests, maximum dry density and optimum water content can be easily determined from the smooth compaction curve connecting the plotted points [30].

Direct shear test (ASTM D-3080) determines the shear strength of soil under the consolidated drained condition. The test was performed by horizontally deforming a soil specimen at a controlled strain rate, each under a different normal load condition. Using the Mohr–Coulomb failure envelope, indicating the relationship between shear strain and maximum shear stress, shear strength (cohesion and internal friction angle) of the soil was finally determined [38].

3. Results and Discussion

The treatment of lubricant-oil-contaminated soil was performed by the selected target temperatures by adjusting the electric powers. The lubricant-oil-contaminated soil was put into the inner (soil) container at 400, 500 and 600 °C with treatment times from 5 to 15 min for volatilization and the desorption of lubricant-oil and organic pollutants from the sample. The environmental and geotechnical characteristics before and after treatments are as follows.

3.1. Analysis of Environmental Properties

The temperature conditions, TPH concentration and treatment time are major factors for the remediation of lubricant-oil-contaminated soil in this study. With the treatment of the contaminated soil (initial TPH concentration of 26,063 mg/kg) at 400 °C and the treatment times of 5, 10 and 15 min, the residual TPH concentration was measured as 5490, 2866 and 1846 mg/kg, respectively, indicating removal efficiencies of 78.3%, 88.7% and 92.7%, respectively. In the test at 500 °C, with an initial TPH concentration of 25,325 mg/kg and treatment times of 5, 10 and 15 min, the residual TPH concentration was measured at 3626, 1995 and 1383 mg/kg, respectively, indicating removal efficiencies of 85.7%, 92.2% and 94.5%. In the test at 600 °C, with an initial TPH concentration of 26,600 mg/kg and the treatment times of 5, 10 and 15 min, residual TPH concentration was measured at 2512, 652 and 38.2 mg/kg, indicating removal efficiencies of 90.6%, 97.6% and 99.7%, respectively.

As shown in Figure 5 and Table 5, the removal efficiency increases as the thermal desorption temperature and treatment time increases, and it was found that the concentration level and condition of treated soil with even elapsed time of 15 min is restored to almost initial conditions.

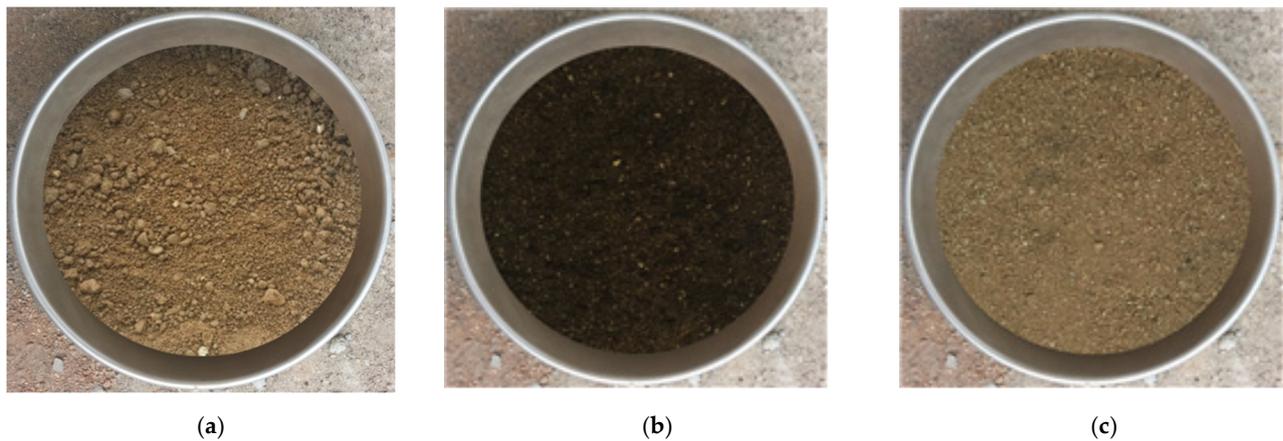


Figure 5. (a) Initial soil; (b) Lubricant-oil-contaminated soil before treatment [TPH 26,600 mg/kg]; (c) Cleaned soil after treatment (600 °C) [TPH 38.2 mg/kg].

Based on the test results (Figure 6), we can assess the optimal operating conditions (target temperature and treatment time required for residual TPH concentration or removal efficiency) which satisfy the remediation period, as well as the remediation cost in the real site.

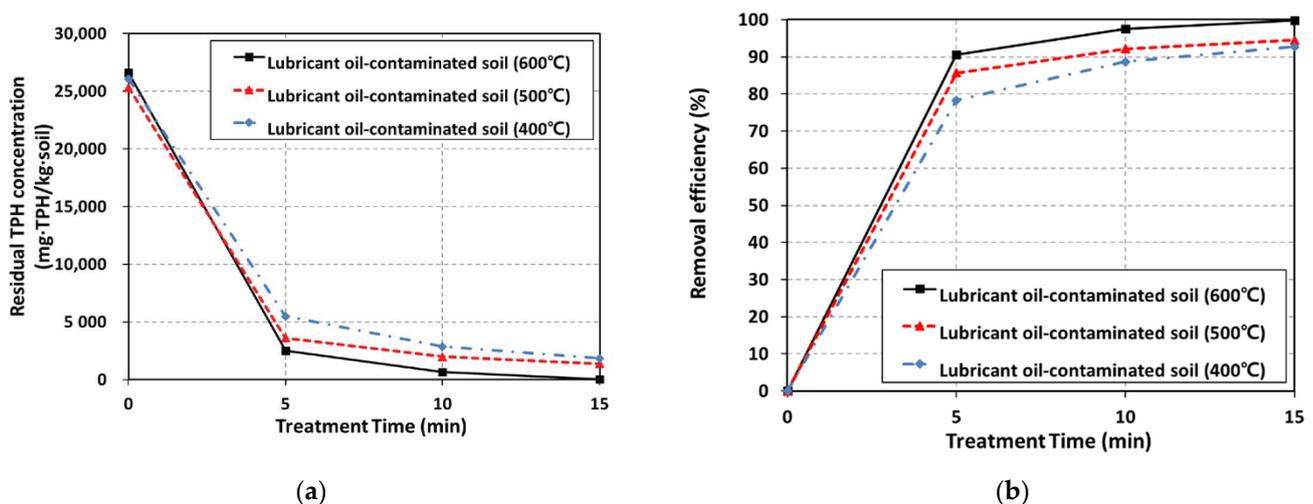


Figure 6. Remediation results: (a) Residual TPH concentration and (b) Removal efficiency.

3.2. Analysis of Geotechnical Properties

After treatment as shown in Table 1 and Figure 1, the proportion of coarse-grained soils retained in sieve No. 200 (0.075 mm) was increased compared to initial as well as contaminated soil due to the desorption of oil and organic matters absorbed in the soil particle and even fine-grained soil particles in the form of dust and mist. It was found that the liquid limit and permeability coefficient were almost recovered to the initial state due to the desorption of oil occupied in the pores between soil particles.

After lubricant-oil contamination (Figure 7a), the cohesion (C) which was initially 14.33 kN/m² was increased to 24.04 kN/m², and the internal friction angle (ϕ) which was initially 41.7° was decreased to 32.6° due to the lubrication effect of viscous oil and organic matters contained in the pores between soil particles [39]. However, after thermal treatment, the cohesion was decreased to 10.73 kN/m², and the internal friction angle was increased to 44.1°, which is attributed to desorption of oil, organic matters from the lubricant-oil contaminated soil [40,41].

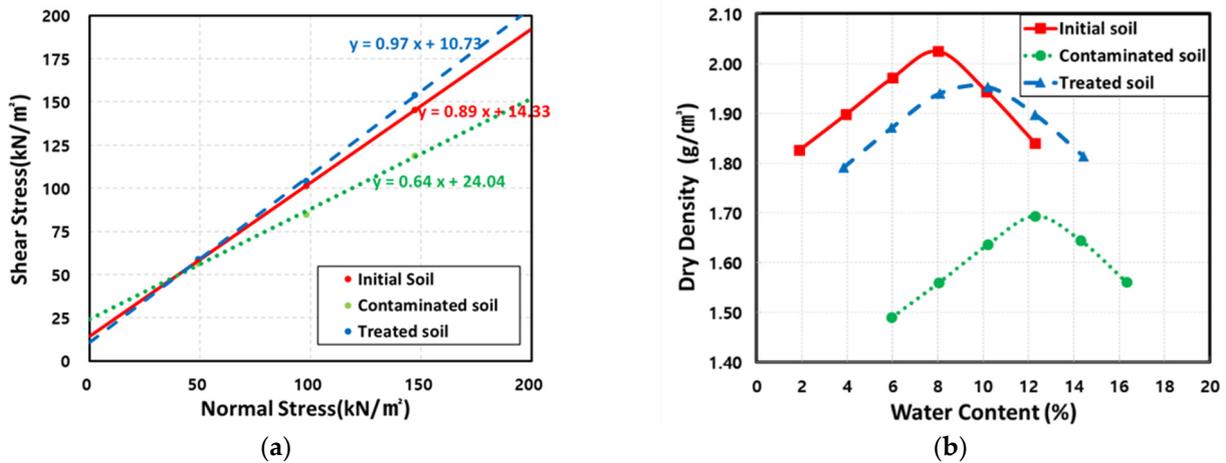


Figure 7. Results of the (a) Direct shear test and (b) Compaction test.

The maximum dry density which was initially 2.02 g/cm³ was decreased to 1.70 g/cm³, and optimal moisture content, which was initially 8.0%, was increased to 12.4% after oil contamination. However, thermal treatment had then been restored to the almost initial level of 1.96 g/cm³ and 9.6% (Figure 7b), which results from the fact that thermal treatment removes the lubrication effect of oil, which makes the soil a looser material [42].

3.3. Analysis of CO₂ Emission and Energy Cost

The estimated remediation energy cost is shown in Figure 8a based on the test results at 600 °C. Conventional thermal desorption technology costs 51.9 USD/ton (per metric ton) to remediate the oil-contaminated soil based on the burning of fossil fuel, while indirect-heated microwave thermal desorption technology without fossil fuels reduces the remediation energy cost by 75% based on an effective microwave heating mechanism.

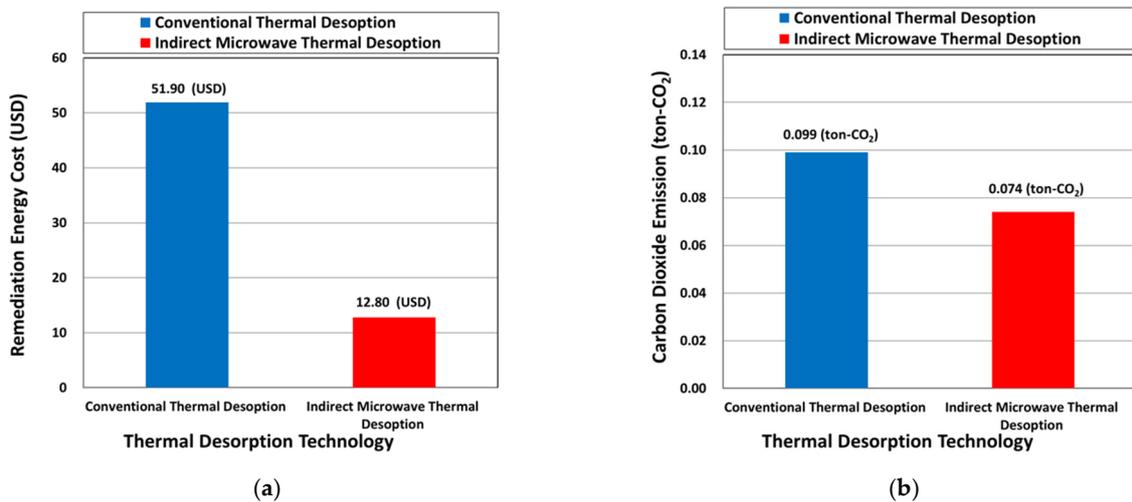


Figure 8. Comparison analysis of (a) Remediation energy cost (USD) and (b) Carbon dioxide emissions (ton-CO₂).

Figure 8b shows CO₂ emissions resulting from this study. Conventional thermal desorption technology shows 0.01 ton-CO₂ emissions from burning fossil fuels to clean up the soil. However, fossil-fuel-free indirect-heated microwave thermal desorption technology can reduce CO₂ emission by 25%. These calculation procedures are shown in Table A3.

4. Conclusions

Direct-heated thermal desorption technology using fossil fuel has been considered as one of the typical thermal treatment methods for oil-contaminated soil. However, it has been limited in its applicability due to the inefficiency and high energy cost for the heat generation process necessary for the desorption of oil and organic matter. In this study, an indirect-heated microwave thermal desorption treatment technology has been developed in order to overcome disadvantage of conventional technology.

In this study, thermal treatment was performed by heating the lubricant-contaminated soil up to 400~600 °C using an indirect-heated microwave thermal desorption technology to volatilize and desorb oil and organic pollutants from the soil. The following conclusions were made based on a review and analysis of the environmental and geotechnical properties of the soil before and after treatments.

- The indirect-heated microwave thermal desorption equipment was preheated for 3 h with the electric power of 32, 24 and 16 kW to reach the target temperatures of 600, 500 and 400 °C, and the contaminated soil was put into the soil container for the desorption of the oil and organic pollutants from the soil. With treatment times of 5, 10 and 15 min as the main processes, environmental TPH concentrations were reduced to 2512, 652 and 38.2 mg/kg, respectively, indicating removal efficiencies of 90.56, 97.55 and 99.86% accordingly. Based on these environmental test results, it was found that the developed indirect-heated microwave thermal desorption method in this study has an excellent effect on removing semi-volatile organic pollutants.
- The analyses of the geotechnical properties are as follows: (1) The proportion of coarse-grained soils retained in sieve No. 200 (0.075 mm) was increased compared to the initial as well as contaminated soils due to the desorption of the oil and organic matters absorbed in the soil particles and even fine-grained soil particles in the form of dust and mist. It was found that the liquid limit and permeability coefficient were almost recovered to levels of the initial state due to the desorption of the oil occupying the pores between soil particles. (2) The internal friction angle, maximum dry density and permeability coefficient of the soil were reduced by oil contamination and were finally restored to the almost initial level of soil after treatment. (3) The cohesion of the soil was increased by oil contamination due to the lubrication effect of viscous oil and decreased after treatment.
- Due to the fossil-fuel-free heating mechanism designed for the remediation of lubricant-oil-contaminated soil at 600 °C in this study, newly developed indirect-heated microwave thermal desorption technology reduces energy costs and CO₂ emissions by 75% and 25%, respectively, compared with conventional thermal desorption methods using fossil fuels.
- It is finally found that soil treated by an indirect-heated microwave thermal desorption technology is expected to be reusable for geotechnical construction purposes such as road and railway fill materials.

5. Patents

- United States Patent
- Title of Invention: Thermal desorption system for oil-contaminated soil and gravel, using microwave indirect irradiation method and including microwave leakage prevention device and preheating device using waste heat, and thermal desorption method for oil-contaminated soil and gravel, using same.
- Applicant: Korea Railroad Research Institute (KR)
- Inventors: Tae Hoon Koh, (KR); Dong Geun Lee, (KR); Han Ju Yoo, (KR)
- Patent No.: US 10,518,303 B2
- Publication Number: WO/2018/151451
- Publication Date: 23.08.2018
- International Application No.: PCT/KR2018/001538

Author Contributions: D.L.: conceptualization, resources, visualization, methodology, validation, formal analysis, investigation, data curation, writing—original draft; T.K.: conceptualization, resources, writing—review and editing, funding acquisition, supervision, project administration; D.P.: conceptualization, writing—review and editing, supervision, project administration. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Appendix A.1. Data of Chromatogram (Peak Results)

Table A1. Data of chromatogram (peak results).

Index	Sample	Time [min]	Quantity [ng]	Height [μ V]	Area [μ V·min]	Area [%]
1	400C0m	17.53	3708.41	26,044.1	73,744.6	100.0
2	400C5m	17.53	2767.28	18,626.2	54,639.0	100.0
3	400C10m	17.53	2929.44	18,231.5	57,486.2	100.0
4	400C15m	17.53	3179.31	4072.1	47,627.2	100.0
5	500C0m	17.53	4212.39	24,706.3	67,440.4	100.0
6	500C5m	17.53	3633.51	23,288.4	72,491.5	100.0
7	500C10m	17.53	1979.15	3823.0	40,664.2	100.0
8	500C15m	17.53	2788.72	4826.8	46,055.9	100.0
9	600C0m	17.53	2657.43	15,132.7	47,699.0	100.0
10	600C5m	17.53	3087.28	6243.6	63,353.0	100.0
11	600C10m	17.53	3284.47	15,847.5	52,130.9	100.0
12	600C15m	17.53	382.92	11,304.4	20,178.3	100.0

Appendix A.2. TPH Results

$$\text{Concentration of Total Petroleum Hydrocarbons (TPH) in Soil (mg/kg)} = \frac{A_s \times V_t \times D}{W_d \times V_s}$$

A_s : Area count for hydrocarbon range of interest (ng);

V_t : Volume of total extract (mL);

D : Dilution Factor;

W_d : Dry weight of sample (g);

V_s : Volume of sample extracted (μ L).

Table A2. TPH Results.

Index	Sample	A_s (ng)	V_t (mL)	D	W_d (g)	V_s (μ L)	TPH (mg/kg)
1	400C0m	3708.41	2	70	9.96	2	26,063
2	400C5m	2767.28	2	20	10.08	2	5490
3	400C10m	2929.44	2	10	10.22	2	2866
4	400C15m	3179.31	2	5	8.61	2	1846
5	500C0m	4212.39	2	60	9.98	2	25,325
6	500C5m	3633.51	2	10	10.02	2	3626
7	500C10m	1979.15	2	10	9.92	2	1995
8	500C15m	2788.72	2	5	10.08	2	1383
9	600C0m	2657.43	2	100	9.99	2	26,600
10	600C5m	3087.28	2	8	9.83	2	2512
11	600C10m	3284.47	2	2	10.07	2	652
12	600C15m	382.92	2	1	10.02	2	38.2

Appendix A.3. Calculation of Remediation Energy Cost and Carbon Dioxide Emission

Table A3. Calculation of remediation energy cost and carbon dioxide emission.

	Conventional Thermal Desorption	This Study
Remediation Energy Cost	a. Operating temperature (600 °C)	a. Operating temperature (600 °C)
	b. Fuel type (Diesel)	b. Fuel type (Electricity)
	c. Fuel cost (USD/L); 1.37 USD/L (2022)	c. Time in use (h); 1 h
	d. Fuel calorific value (kcal/L); 8450 kcal/L	d. Energy consumption (kW); 32 kW
	e. Calorific value for soil heating (kcal per kilogram); 224.4 kcal	e. Industrial energy price (USD/kWh); 0.08 USD/kWh (2022)
	f. Calorific value for water evaporation (kcal per kilogram); 95.9 kcal	f. Cost of electricity (USD); $f = c \times d \times e = 1 \times 32 \times 0.08 = 2.56$ USD
	g. Calorific value for remediation (kcal per metric ton); $g = (e + f) \times 1000 = (224.4 + 95.9) \times 1000 = 320,300$ kcal	g. Remediation time (hour per metric ton); 5 h
	h. Fuel capacity for remediation (Liter per metric ton); $h = g \div d = 320,300 \div 8450 = 38.0$ L	h. Remediation energy cost (USD per metric ton); $h = f \times g = 2.56 \times 5 = 12.8$ USD/ton
	i. Remediation energy cost (USD per metric ton); $i = h \times c = 38.0 \times 1.37 = 51.9$ USD/ton	
Carbon Dioxide Emission	a. Fuel calorific value (MJ) = Fuel capacity (Unit) \times Calorific value (MJ/Unit) (Conventional) $38 \text{ L} \times 35.3 \text{ MJ/L} = 1341 \text{ MJ}$, (This study) $160 \text{ kWh} \times 9.0 \text{ MJ/kWh} = 1536 \text{ MJ}$	
	b. Carbon emission quantity(tC) = Fuel calorific value (MJ) \times Carbon emission factors(tC/TJ)/ 10^6 (Conventional) $1341 \text{ MJ} \times 20.2 \text{ (tC/TJ)} \div 10^6 = 0.027096 \text{ tC}$ (This study) $1536 \text{ MJ} \times 13.05 \text{ (tC/TJ)} \div 10^6 = 0.020045 \text{ tC}$	
	c. Carbon dioxide emission quantity (ton-CO₂) = Carbon emission quantity (tC) $\times 44/12$ (Carbon dioxide molecular weight/Carbon dioxide) Conventional) $0.027096 \text{ tC} \times 44/12 = 0.099353 \text{ ton-CO}_2$ (This study) $0.020045 \text{ tC} \times 44/12 = 0.0735 \text{ ton-CO}_2$	

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