≪ Research Paper ≫

Pilot Scale Feasibility Test of In-situ Soil Flushing by using 'Tween 80' Solution at Low Concentration for the Xylene Contaminated Site

Jae-Yeon Um[1] · Gyusang Lee[1] · Sung-Ho Song[1] · Sunwook Hong[2] · Minhee Lee[3]*

[1]*Rural Research Institute, Korea Rural Community Corporation*
[2]*Office of Environmental Geology, Korea Rural Community Corporation*
[3]*Dept. of Earth Environmental Sciences, Pukyong National University*

ABSTRACT

This study was performed to identify the optimal operating conditions and to evaluate the xylene removal efficiency, applying in-situ soil flushing with the low concentrated solution of 'Tween 80' at the xylene contaminated site. The pilot scale test site (5 m × 5 m × 3 m), was mainly composed of 'sandy loam', with the average hydraulic conductivity of 9.1×10^{-4} cm s^{-1}. The average xylene concentration of the site was 42.1 mg kg^{-1}, which was more than 2.5 times higher than Korea soil pollution warning limit (15 mg kg^{-1}). For the soil flushing, 7,800 L of 0.1~0.2% surfactant solution was injected into three injection wells at the average injection time of 9 hr d^{-1} for 10 days, followed by the additional only groundwater injection of 6,000 L. The same amount of the effluent solution was extracted from three extraction wells. From the analysis for xylene concentration of all effluent at 3 extraction wells, total 166 g of xylene was removed by in-situ surfactant flushing. Even though the residual xylene concentrations of 7 soil sampling locations in the test site were different due to the soil heterogeneity, from the comparison of xylene concentration at 7 locations before/after the feasibility test, 53.9% of the initial xylene in the site was removed from three extraction wells (mainly Ext-N and Ext-M well). The results showed that the in-situ soil flushing by using low concentrated 'Tween 80' solution had a great potential to remediate the xylene contaminated site.

Key words : NAPL, Surfactant flushing, Tween 80, In-situ soil flushing, Xylene, Soil remediation

1. Introduction

The most of causative materials for the soil contamination are the chlorinated organic compounds and the petroleum-based fuels such as TCE (trichloroethylene), PCE (tetrachloroethylene), TPH (total petroleum hydrocarbon), BTEX (benzene, toluene, ethyl-benzene and xylene) and MTBE (methyl tertiary butyl ether) (Mackay and Cherry, 1989; Eve, 1998). Among them, BTEX account for 18~30% of gasoline as the carcinogenic and the toxic volatile mono aromatic ring hydrocarbons (Cline et al., 1991). For the relatively high water solubility, BETX widely influence soil and groundwater contamination and the development of their remediation processes is urgent (Lowe et al., 1999). Since they act as NAPLs (non-aqueous phase liquids), it has been reported that it takes long time to remediate them and

the cost is also very expensive when they spilled down the surface (Paria, 2008; Khalladi et al., 2009; Yang et al., 2010; Heo and Jeong, 2011). In early 2000s, the large-scale remediation project of petroleum contaminants for soil and groundwater in Korea was begun by the Ministry of National Defense. Several remediation projects such as LPP (land partnership plan) and TKP (trans Korea pipeline) have been carried out on a large scale in Korea (Korea Rural Community Corporation, 2005, 2010). For petroleum contaminants, ex-situ remediation processes such as soil land farming, thermal desorption and soil washing have been applied mainly and in-situ soil remediation has been applied in very limited sites of Korea (Lee et al., 2005; Lee et al., 2012).

Currently, in case of few developed countries such as the United States, in-situ remediation process and technology for NAPLs has already entered in the stabilization stage.

However, the activation of soil and groundwater remediation market in the world started from the beginning in 2000s, and more than 70% of the remediation sites were belong to developed countries where the ex-situ remediation processes were still mostly appled for. Even in Korea, the application of in-situ remediation process to the real contaminated sites lags behind, compared to that of the ex-situ process (Korea Rural Community Corporation, 2011). The reason for preferring the ex-situ process in large-scale remediation projects is the limitation to remove NAPLs below the tolerance level within a short period of time because of non-uniformity of the site. However, the in-situ remediation process should been applied if the excavation of the contaminated site is impossible. Recently, the pilot scale feasibility test for the in-situ soil flushing with surfactant solution for fuel oil contaminated sites in Korea has been successfully conducted (Lee et al., 2004; Kim, 2010; Lee et al., 2011; Lee et al., 2012). Results showed that the soil flushing has a short recovery time in comparison with the conventional pump and treat process and it does not destroy the ground structure such as a storage facility, rail road and the gas pipe arrangement around the site (Kim and Lee, 1999; Lee et al., 2002).

In this study, the site where the application of the excavation is difficult for the continued use of oil storage facility, was selected for the feasibility test. The in-situ soil flushing with low concentrated 'Tween 80' (named as 'TW80' from now on) surfactant solution was performed to investigate xylene removal from the site before operating the large scale remediation project. Most of the researches related to the soil flushing with surfactant solution were limited to only the use of relatively high concentrated surfactant solution (1-4%) and it is novel to use low concentrated surfactant solution (0.1-0.2%) for the soil flushing in the pilot scale feasibility test. Before applying the in-situ soil flushing method with a surfactant solution, the tracer test with Br^- solution was also conducted to estimate the average hydraulic conductivity and the mobility of NAPLs (retardation) at the test site. The total xylene mass removed and its removal efficiency during the test were calculated through the quantitative analysis of xylene in pumped groundwater and soil before/after the test, verifying the feasibility of the in-situ soil flushing process with low concentrated TW80 solution in xylene contaminated site.

2. Theory of In-situ Soil Flushing with a Surfactant

2.1. Remediation Mechanism of the Surfactant

Surfactant is the compound having both a polar and non-polar in the molecular structure. In the aqueous phase, the non-polar portion of the surfactant molecule is the hydrophobic, whereas the polar portion combines readily with water molecules as a hydrophilic (Rosen, 1989). For this reason, the non-polar portion causes internal instability and an increase of free energy in aqueous solution due to the deformation (distortion) of water molecules surrounding and the constraints of movement of the interior of the carbon chain (Clint, 1992). In aqueous solution, surfactant molecules forms an internal conjugates called, "Micelle" in order to stabilize this system (Edward et al., 1991). The non-polar portion of the surfactant molecule is oriented towards the interior of the 'Micelle', and the polar portion is located outside to bind water, maintaining a phase stable in aqueous solution. Fig. 1 shows the typical structure of 'Micelle' from surfactant monomers formed in aqueous solution. Because of hydrophobicity of xylene present in aqueous solution, xylene is located inside of micelle maintaining a non-polar region and, thus the apparent solubility of xylene in solution dramatically increases. This phenomenon is called as "Micellization" (Rosen, 1989). Especially, the surfactant concentration at which 'Micellization' is beginning to occur, is called "Critical Micelle Concentration (CMC)". A phenomenon in which organic contaminants entering the micelle is called "Solubilization". Below CMC, the solubility of xylene in solution remains low, but the solubility increases rapidly when the surfactant concentration in solution is higher than CMC (Edward et al., 1991).

There are several researches related to the surfactant enhanced in-situ soil flushing with 1-4% of surfactant solution and the surfactant flushing for long time was limited because of the high cost for the surfactant and the tailing effect of NAPL concentration in the effluent, which occurred even the high surfactant concentration was used as flushing solution (Lee et al., 2005; Lee et al., 2012). In this study, a low concentration surfactant solution (0.1-0.2%(v/v)) was used by using the dissolving mechanisms of xylene in groundwater, rather than by using the mobility of xylene
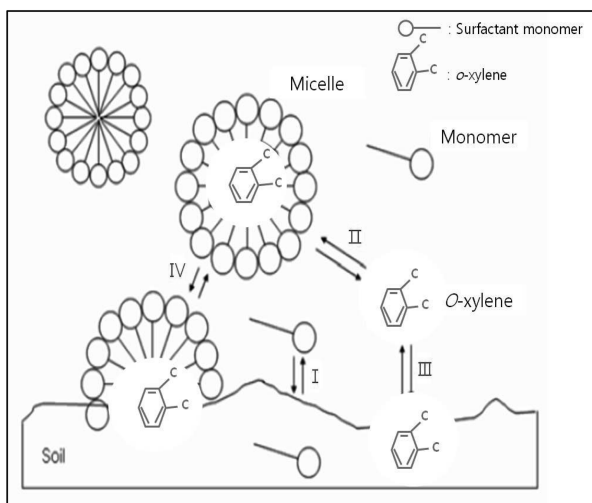
Fig. 1. Schematic for micellization of surfactant monomers with *o*-xylenes in the aqueous solution (I: Sorption of surfactant molecules, II: Partitioning of *o*-xylenes between the water phase and the micelles, III: Sorption of *o*-xylenes and IV: Solubilization of *o*-xylenes (modified from An et al., 2006)).

free phase separated from the soils occurring while the high surfactant concentrated solution was used. It is more available for the site, of which NAPL concentration is relatively low and/or NAPL mobility was limited by the surfactant flushing (Knox et al., 1999).

2.2. In-situ Soil Flushing with Surfactant Solution

Surfactant enhanced soil flushing can use two mechanisms for xylene removal from the site; increasing the mobility of xylene by lowering the interfacial tension between groundwater and xylene in the pore spaces and increasing xylene solubility in groundwater (Santanu, 2008). The schematic of the typical in-situ soil flushing with the surfactant solution is shown in Fig. 2. The site has been invaded by watering the contaminated site, so as to be passed through the contaminated area and the flushed solution move to the down gradient region of groundwater, by pumping a liquid containing a contaminants. NAPLs present in the saturated and unsaturated zone can be removed by the modified conventional pump and treat method (Anderson, 1993; Roberts, 1998). It is primarily used to give less impact on the surrounding environment during remediation of groundwater and soil (EPA, 1997). However, the in-situ soil flushing is also limited applying in the contaminated site because of less understanding for the characteristics of the
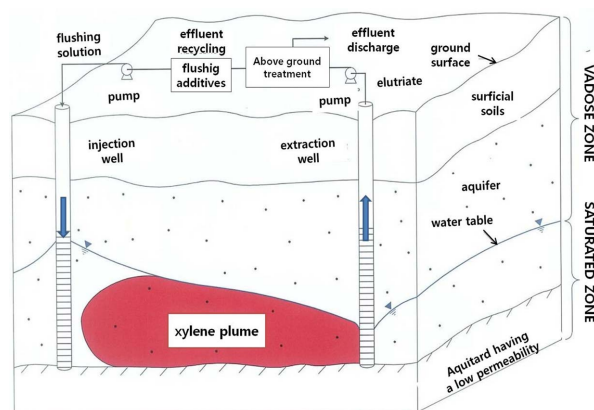
Fig. 2. Schematic of surfactant enhanced in-situ soil flushing system (modified from EPA, 1997).

hydrogeology and heterogeneity in the subsurface. Recently, due to the development of technologies to investigate the hydrogeological properties of the underground and the manu facture surfactants more suitable for remediation, the use of surfactant enhanced soil flushing in the site has been on the rise. It has been investigated that several nonionic surfactants were useful to remove NAPLs from the contaminated sites and a nonionic surfactant named 'Tween 80' (sorbitan monnoleate POE20, purchased from Samchun Pure Chemical Co.) was used for this study (Lee et al., 2002; Kim, 2010). The 0.1-0.2% TW80 solution, which was 68-136 times higher than CMC (0.00148% or 0.027 mM) was prepared for the in-situ soil flushing in this feasibility study (Zhao et al., 2005).

3. Study Area and the Feasibility Test Site

Study areas is a fuel oil storage facility site of OO camp, which is located in Siheung city, Gyeonggido, Korea. It has been operated about 20 years as the military camp (110,000 km^2), except the forest in the total camp area (approximately 290,000 km^2) (Korea Rural Community Corporation, 2010). The excavation of the site and the ex-situ remediation processes such as soil land farming and soil washing will be applied for the contaminated area in the camp except this study area, where on-site fuel oil storage facilities are still active. It is considered that the in-situ soil flushing with surfactant solution is alternative for the study area. Fuel oil contaminated soil has been identified around the fuel oil waste storage yard of the study area in 2008 and
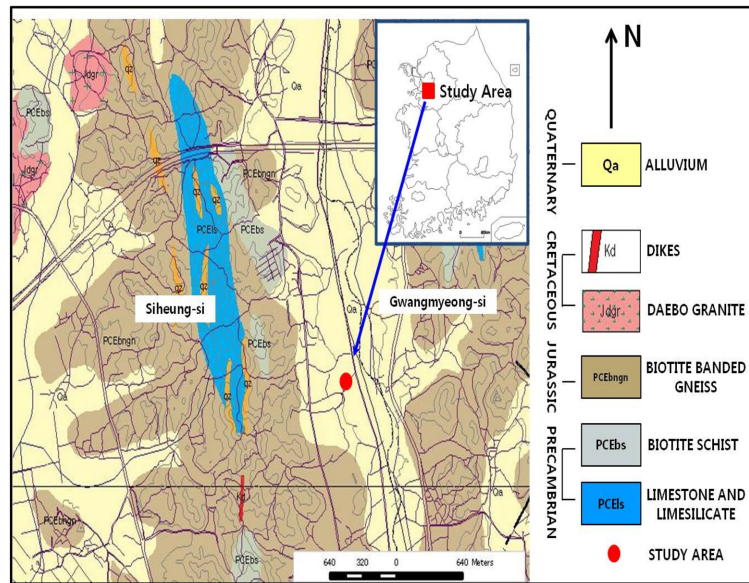
Fig. 3. Geological map around the study area (from KIGAM, 2012).

the precise soil and groundwater investigation of the entire facility site was performed in 2010 (Korea Rural Community Corporation, 2011). The study area is a relatively low altitude of 40-80 m above sea level and Bongjae mountain (elevation 147.7 m) is located to the northwest of this study area. Mokgam stream flows in the north-south direction at a distance of about 600 m to the east. The bed rock is Precambrian era biotite banded-gneiss, and the west of this study area is composed of lime silicate rock and biotite schist. Quaternary period alluvium having bad classified particles covers the unconformity at the top of these bedrocks. Gneissic banding structure that showed in the gneiss is inclined to the southeast in general, and their main composition minerals are plagioclase, quartz and biotite (Korea Rural Community Corporation, 2007) (Fig. 3).

From the results of soil investigation, TPH and BTEX were mainly distributed in the range of 0-5 m in depth at the camp. The volume and the area of soil exceeding Korea soil pollution warning limit of TPH and BTEX were 10,608 m^3 and 6,974 m^2, respectively. Maximum concentration of TPH, benzene, toluene, ethylbenzene and xylene in a fuel oil storage facility site at the camp was 11,907, 58.2, 304.5, 110.6 and 336.8 mg kg^{-1}, respectively, and their average concentrations was 317, 0.45, 1.46, 1.07 and 4.52 mg kg^{-1} (Korea Rural Community Corporation, 2010). For the fuel oil storage facility site, the total amount of xylene contaminated soil
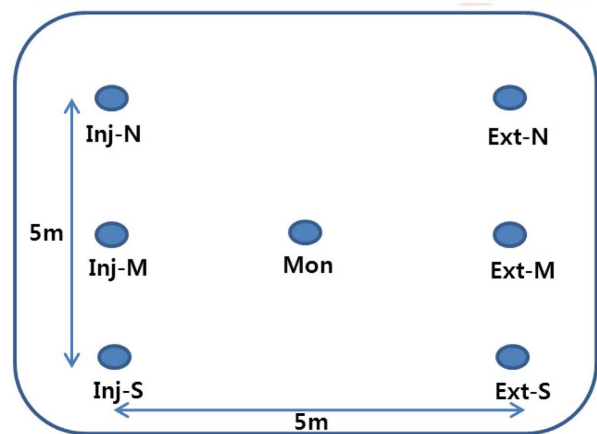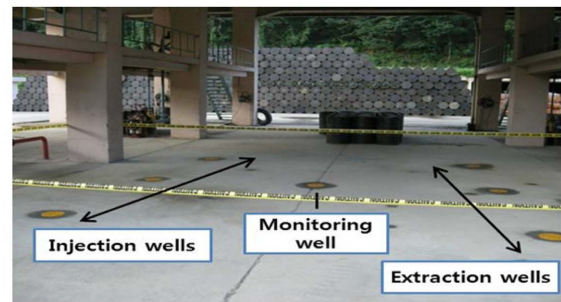

Fig. 4. Location of the feasibility test and installed wells (Inj-: injection well, Ext-: extraction well and Mon: monitoring well).

was 4,029 m^3, which was 2.6% of the entire storage facility area. In the fuel oil storage facility site, the pilot scale feasibility test site (5 m × 5 m × 3 m) was contaminated due to damaged pipelines and storage tank worn out and xylene was found in the maximum 3 m depth at the test site. The
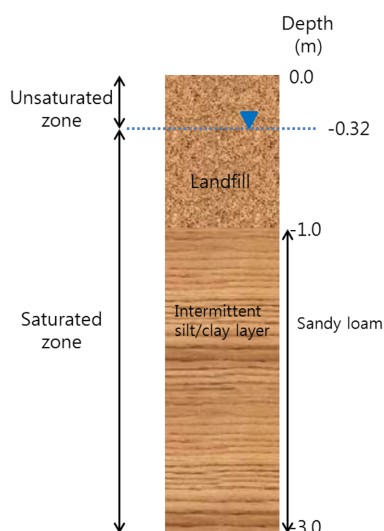
Fig. 5. Soil profiles at the feasibility test site.

feasibility test site covered with the thick concrete layer was still used for the oil storage tanks and thus only in-situ reme-diation process was available for the site. Fig. 4 shows the test site for the feasibility study.

For the feasibility test, a total of seven wells were installed (3 injection wells (Inj-N, -M and -S), 1 monitoring well (Mon) and 3 extraction wells (Ext-N, -M and -S)) at 3 m in depth (Fig. 4) and the average groundwater table is 0.32 m below the surface. The subsurface of the site was not homo-geneous and had two main layers in the following order, landfill soil layer (the soil used to cover the surface for the specific land usage)(1 m in thickness) and the sandy loam layer having intermittent silt/clay layer (2-3 m in thick-ness)(Fig. 5). From the soil analysis, xylene was mainly dis-tributed around 0-1 m in depth at the test site.

4. Experimental Methods

4.1. Soil Sampling and Analysis

Soil samples of 10 kg were collected for the soil particle size analysis by using an automatic geo-probe. After dried for 24 hours at 20ºC, 200 g of soil samples was placed in a automatic sieve vibrator for 3-4 minutes for the particle size analysis. To measure the size distribution of clay and silt, of which diameter was smaller than 200 mesh or less, Laser Diffraction Particle Size Analyzer (BECKMAN COULTER, LS13320) was used. Soil texture of the soil was determined

by using the triangle diagram of United States Department of Agriculture (USDA). The pH, CEC (cation exchange capacity), TOC (total organic carbon) and water contents of the soil were also measured to identify its chemical properties.

4.2. Tracer Test

In this study, the tracer test with bromide ion (Br^-) was conducted for analyzing the flow characteristics of injected solution or groundwater in the test site by operating three injection and three extraction wells. Convergence flow tracer test was performed to interpret the radial flow velocity of extraction well around the site and to investigate the hetero-geneous flow between the injection and the extraction well, measuring the tracer concentration in the effluent from the extraction well at different time intervals (Fig. 6). For the tracer test, the injection and the extraction of groundwater were operated for 12 hr day^{-1} (only daytime). As the tracer, 1,200 g of KBr (potassium bromide) was mixed with groundwater and then the mixed Br^- solution (initial Br^- concentration: 671 mg L^{-1}) was injected into each injection well at 1.5-2.8 L min^{-1} for about 200 minutes, maintaining a constant groundwater level. At the extraction wells, ground-water was pumping out continuously, maintaining the steady state at which the head depression did not occur. Fifty ml of water sample from the extraction wells was collected every 2 hours and Br^- concentration in each water sample from the extraction wells was analyzed on IC (Ion Chromatography; Dionex, ICS-1000) during the tracer test (about 10 days).

4.3. Pilot Scale Feasibility Test

Surfactant solution of 0.1-0.2% TW80 was injected into 3 injection wells (Inj-S, Inj-M and Inj-N) in the test site at a rate of 1.6 L min^{-1}, respectively and the groundwater was extracted by using the electric water pump from 3 extrac-tion wells (Ext-S, Ext-M and Ext-N) at the similar rate. Total injection volume of surfactant solution was 7,800 L which was approximately one pore volume of the test site. After the injection of the surfactant solution, the additional 6,000 L of groundwater was injected to collect residual groundwater containing xylene from the site, maintaining the constant flow conditions between the injection and the extraction wells. The groundwater level of extraction wells was maintained at 2.0~2.5 m at the surface, inducing the
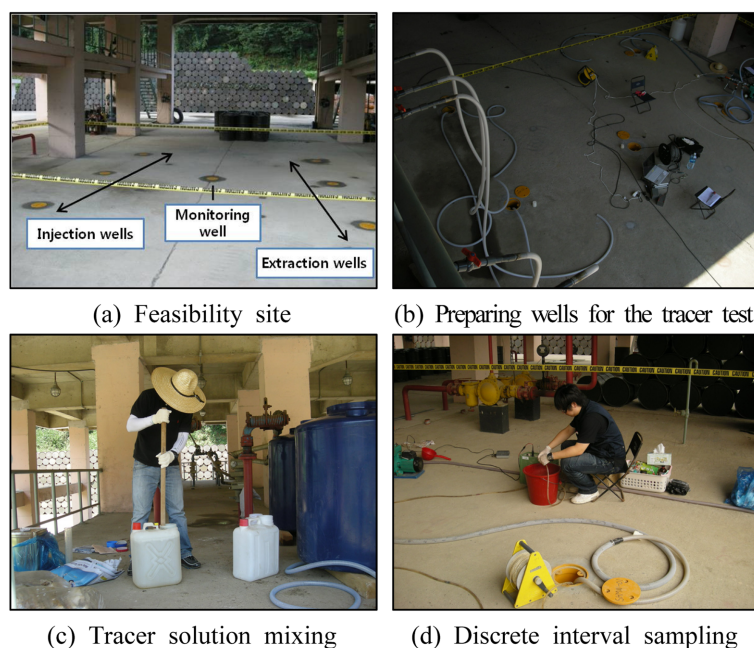
(a) Feasibility site

(b) Preparing wells for the tracer test

(c) Tracer solution mixing

(d) Discrete interval sampling

Fig. 6. Photography for the procedures of the convergent flow tracer test at the feasibility test site.

constant gradient flow during the feasibility test. The water samples were collected every 2-3 hour for 10 days and all water samples were delivered to National Instrumentation Center for Environmental Management (NICEM) for the analysis of xylene concentration in the water samples to calculate the amount of xylene removed by the surfactant flushing. Xylene concentration was analyzed by GC-FID (HP 6890, Agilent, U.S.A.) with purge & trap-autosampler (Teledyne TekMar, U.S.A.). In order to verify the xylene removal efficiency at the pilot scale feasibility test, 7 locations around 7 wells in the site were randomly determined. Soil samples were taken by using the automatic geo-probe at 7 locations before/after the feasibility test and their xylene concentrations were also analyzed to estimate xylene remained in the site after the feasibility test. All extracted solution from the extraction wells were gathered into the storage tank and were post-treated by the private company. The photographs of the facilities for the feasibility site are shown in Fig. 7.

5. Results and Discussion

5.1. Soil Characteristics

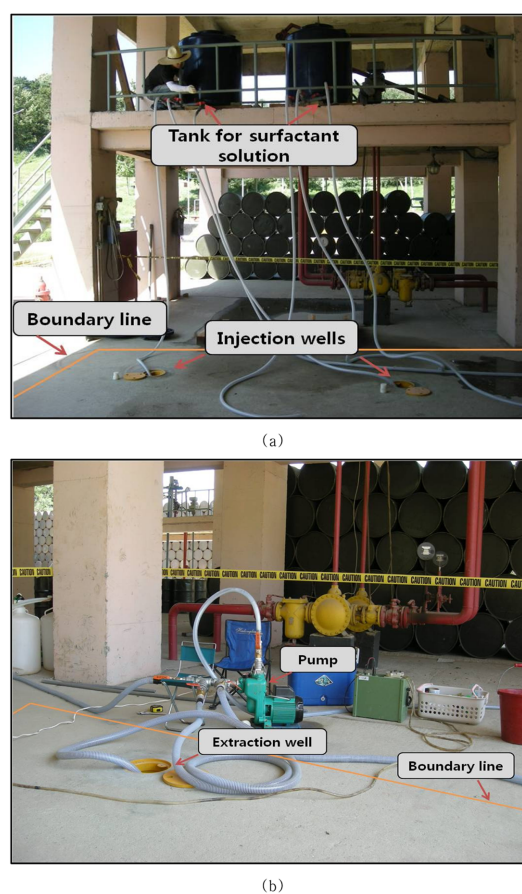The physical and chemical characteristics of the soil are

(a)

(b)

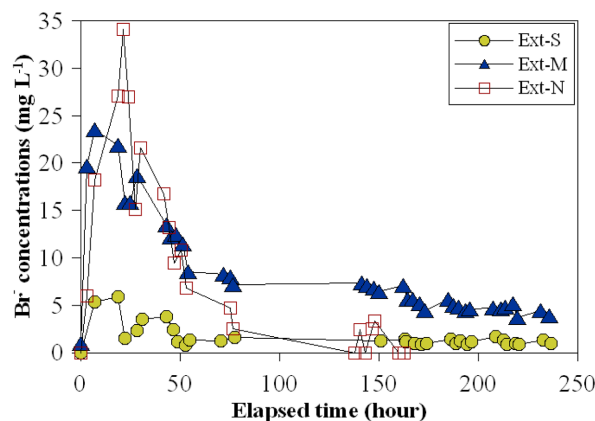**Fig. 7.** Photography for the feasibility test facility ((a) injection system and (b) extraction system).

Table 1. Results of the analysis for soil properties

Size distribution (%)			Soil texture	pH	Organic content (%)	Water content (%)	CEC (cmol kg^{-1})
Sand	Silt	Clay					
61.12	26.16	12.72	Sandy loam	4.4	4.5	28.5	16.90

shown in Table 1. According to the USDA classification level, the soil texture was belong to 'sandy loam'. An artificial landfill soil layer extended down to 1 m in depth and the lower parts of the subsurface (1-3 m in depth) were mainly distributed by 'sandy loam' soils except intermittent clay/silt layers. Oxidized Fe component was 10%, which was relatively high in the soil (KOSSGE, 2001). Therefore, pH of the soil was 4.4. The moisture content of the soil was 28.5% which ranges 12% to 30% of common soil (Khan et al., 2004) and its TOC (total organic carbon content) was 4.5%, which was relatively high compared to 2.5% of common domestic soil. CEC was 16.9 cmol kg^{-1}, which was relatively high compared to 10.0 cmol kg^{-1} of common domestic soil (KOSSGE, 2006).

5.2. Tracer Test

Results of the tracer test are shown in Fig. 8. The highest Br$^-$ concentrations at three extraction wells were 34.1 mg L^{-1}, 23.5 mg L^{-1} and 6.1 mg L^{-1}, respectively (Ext-N, Ext-M and Ext-S in order). Their arrival times of the highest Br$^-$ concentrated solution after injection were 7 hours, 22 hours, and 22 hours at the extraction wells (Ext-M, S and N), respectively. Assuming that the groundwater flow was mainly in the horizontal direction between the injection and the extraction well, the average flow velocity of groundwater could be estimated from the arrival time of the highest Br$^-$ concentrated solution and the distance between the injection and the extraction well. From the calculation, the middle part of the test site had the fastest flow velocity of 0.71 m hr^{-1} and the northern and the southern part of the site had the slow flow velocity of 0.23 m hr^{-1}, suggesting that the site was heterogeneous and the amount of surfactant solution needed to dissolve xylene in the site might be increased according to the bypass of the solution. From the calculation, the injection rate of the surfactant solution in the feasibility test was determined to 1.6 L min^{-1} (based on the slow average flow velocity data).

Fig. 8. Results for the tracer test by using Br$^-$ solution at the test site.

5.3. Pilot Scale Feasibility Test

The surfactant solution of 7,800 L and groundwater of 6,000 L were injected for 240 hours at 3 injection wells. Results showing xylene concentration of the effluent from 3 extraction wells are shown in Fig. 9. The elapsed time for the highest xylene concentrated effluent from 3 extraction wells ranged from 36 to 38 hours, suggesting the retardation of xylene dissolved solution in the site, compared with those of Br^{-1} solution in the tracer test. Xylene concentrations of the effluent at all extraction wells increased with the injection of surfactant flushing but they declined after 100 hours of the surfactant flushing. At the Ext-N, xylene concentration of the effluent increased from 2 mg L^{-1} to 13 mg L^{-1} at 38 hours of the flushing and maintained about 5 mg L^{-1} after 100 hours of elapsed time. At the Ext-M of the middle part of the test site, the xylene concentration increased from about 4 mg L^{-1} to 9 mg L^{-1} at 38 hours of the flushing and then decreased rapidly at the range of 1~5 mg L^{-1}. Xylene concentration of the effluent at Ext-S well increased from 1 to 4 mg L^{-1} and decrease slightly to 3 mg L^{-1} for the test. The gradual increase in xylene concentration of the effluent at all extraction wells investigated that the increase of xylene solubility in groundwater was directly resulted from TW80 and the xylene removal successfully occurred in the direction of Ext-N and –M. It was considered that the variation of
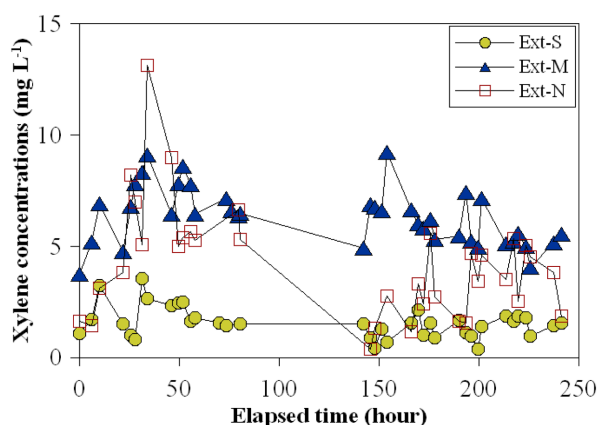
Fig. 9. Results for xylene concentration of the effluent at three extraction wells during the pilot scale feasibility test.

xylene concentration in the effluent at different pumping time and different well location resulted from the heterogeneity of xylene distribution in the subsurface. It might be also because of the shutdown of pumping at night according to the regulation of the military camp. Total 39,764 L of the groundwater was pumped during the test period and 166 g of xylene was removed based on the analysis for the xylene concentration of all effluent at the test site.

To estimate the xylene removal efficiency during the feasibility test, xylene concentration of the soil at 7 locations before/after the test were analyzed and their results are shown in Table 2. The average xylene concentration of the soil at the site before and after the feasibility test was 42.1 mg kg^{-1} and 19.4 mg kg^{-1}, respectively. Xylene concentrations of the soils around Inj-N and Ext-N decreased from 127.1 mg kg^{-1} and 67.6 mg kg^{-1} to 43.3 mg kg^{-1} and

17.4 mg kg^{-1}, suggesting 65.9-74.0% of xylene removal by in-situ surfactant flushing. For soils around Inj-M and Ext-M, xylene removal efficiencies ranged 14.2-67.2%. The decrease of xylene concentration for the soil around Inj-S, but the xylene concentration around Ext-S increased after the test, suggesting that some of xylene in soil were horizontally moved in the site by the surfactant flushing and they might be removed by the additional flushing. This phenomena also occurred around 'Mon' well, located the middle part of the site, representing the dissolved xylene in solution kept moving from Inj-S to Ext-S by the surfactant flushing. Results also suggested that the northern and the middle part of the site showing the fast flow velocity of groundwater had the high xylene removal efficiency rather than that of the southern part by the same amount of surfactant solution and this phenomena depended on the heterogeneity of the site.

About one pore volume of the site was flushed by 0.1-0.2% of TW80 solution in this study and 53.9% of initial xylene was removed for only 10 days. For the additional xylene removal at the southern part of the site, more surfactant flushing was needed to take xylene out from the site. From this study, it was suggested that continuous flushing with even low concentrated surfactant solution could accelerate xylene movement and its removal efficiency was similar to that with the high concentrated surfactant solution. Results showed that the usage of low concentrated surfactant solution is able to remove xylene by the solubility increase or the free phase movement, which is considered to be available with only high concentrated surfactant solution in the soil flushing.

Table 2. Removal efficiency and xylene concentration of the site before/after the feasibility test

Soil sampling locations	Initial xylene concentration at soils (mg kg^{-1})	Final xylene concentration after the feasibility test (mg kg^{-1})	Removal efficiency (%)[*]
Ext-S	0.0	8.7	–
Ext-M	57.3	18.8	67.2
Ext-N	67.6	17.4	74.0
Mon	19.7	31.9	–
Inj-S	6.6	1.7	74.2
Inj-M	16.2	13.9	14.2
Inj-N	127.1	43.3	65.9
Average	42.1	19.4	53.9

*: $\% = \dfrac{(inital\ concentration - final\ concentration)}{inital\ concentration} \times 100$

6. Conclusion

In-situ soil flushing feasibility test for a xylene contaminated site by using low concentrated TW80 solution was performed. LNAPLs such as xylene was successfully remediated from the heterogeneous site in a relatively short time. Conclusions from this research are shown below.

(1) From the precise investigation, the pilot scale test site (5 m × 5 m × 3 m), where was contaminated with xylene, was selected to apply the surfactant enhanced in-situ soil flushing. The northern part of the feasibility site was highly contaminated by xylene and the average xylene concentration was 97.4 mg kg^{-1}, which was 6 times higher than Korea soil pollution warning limit (15 mg kg^{-1}).

(2) To select the appropriate injection and extraction rate at the test site, the tracer test by using Br^{-} solution was performed. From the tracer test, the middle parts of the site has the fastest flow velocity (0.71 m hr^{-1}) and the average flow velocity at the northern and the southern part of the site was 0.23 m hr^{-1}, showing the heterogeneity of the site. The injection rate of 0.1-0.2% of TW80 surfactant solution at three injection wells was determined to 1.6 L min^{-1}, and the total injection volume of surfactant solution was 7,800 L which was approximately one pore volume of the test site.

(3) After the soil flushing with only one pore volume of low concentrated surfactant solution, the xylene removal efficiency at the northern part of the site was 70.0% and the average removal efficiency at the site was 53.9%, suggesting that the site was successfully remediated by using only low concentrated surfactant solution in a relatively short time (10 days).

(4) From this study, it was investigated that the continuous flushing of low concentrated surfactant solution could accelerate xylene removal and its removal efficiency was similar to that with the high concentrated surfactant solution, and thus the use of low concentrated surfactant solution (higher than CMC) for the soil flushing could be designed as a successful remediation process for LNAPLs such as xylene from the heterogeneous site.

Acknowledgement

References

Ahn, C.K., Kim, Y.M., Woo, S.H., and Park, J.M., 2006, A study on selective adsorption of phenanthrene dissolved in Triton X-100 solution activated carbons, *J. KoSSGE*, **11**(2), 13-21.

Anderson, W.C., 1993, Innovative site remediation technology: Soil Washing/Soil Flushing, Vol. 3, American Academy of Environmental Engineers, p. 1-57.

Cline, P.V., Delfino, J.J., and Rao, P.S.C., 1991, Partitioning of aromatic constituents into water from gasoline and other complex solvent mixtures, *Environ. Sci. Technol.*, **25**(5), 914-920.

Clint, J.H., 1992, Surfactant aggregation. Blackie, Chaman Hall, New York, p. 116-126.

Edwards, D.A., Liu, Z., and Luthy, R.G., 1991, Solubilization of polycyclic aromatic hydrocarbons in micellar nonionic surfactant solutions, *Environ. Sci. Technol.*, **25**(1), 127-133.

EPA., 1997, Technology Overview Report: In Situ Flushing. United States Environmental Protection Agency. TO-97-02.

Eve, R.A., 1998, Remediation of petroleum contaminated soils. Lewis Publishers.

Heo, J.H. and Jeong, S.H., 2011, Simulation removal of heavy metals and diesel-fuel from a soil column by surfactant foam flushing, *J, KoSSGE*, **16**(5), 90-96

Khalladi, R., Bentahar, F., and Moulai, M.N., 2009, Surfactant remediation of diesel fuel polluted soil, *J. Hazard. Mater.*, **164**, 1179-1184.

Khan, F.I., Husain, T., and Hejazi, R., 2004, An overview and analysis of site remediation technologies, *J. Environ. Manage.*, **71**, 95-122.

KIGAM., 2012, Geological map of Siheung-city.

Kim, D.H., 2010, Flushing of petroleum-contaminated soil using mixed surfactants, Master's thesis, Kyungsung university.

Kim, J.S. and Lee, K.S., 1999, Effects of hydrophobic chain structure of nonionic surfactants on surfactant adsorption and diesel removal from kaolin soil, *J. KoSES.*, **4**, 17-24.

Knox, R.C., Shau, B.J., Sabatini, D.A., and Harwell, J.H., 1999, field demonstration of surfactant-enhanced sulubilization and mobilization at Hill air force Base, TU. In: Brusseau, M.L., Sabatini, D.A., Gierke, J.S. and Annable, M.D. (Eds), Innovative Subsurface Remediation: Field Testing of Physical, Chemical, and Characterization Technologies, ACS Symposium Series **725**, 49-63.

Korea Rural Community Corporation, 2005, LPP (land partner-

ship plan) by base scrutiny survey report.

Korea Rural Community Corporation, 2007, Bucheon-Siheung region groundwater basic survey report. No.3, p. 6-8.

Korea Rural Community Corporation, 2010, OOO Oil military camp soil·groundwater scrutiny report. p. 2-5.

Korea Rural Community Corporation, 2011, A study on the soil and groundwater remediation technique using surfactant foam technology (final), p. 3.

Korean Society of Soil and Groundwater Environment (KOSSGE), 2001, Soil Environmental Engineering, Hangmunsa, Seoul, 394 p.

Korean Society of Soil and Groundwater Environment (KOSSGE), 2006, Soil-Groundwater Environmental Dictionary, Hanrimwon, Seoul, 474 p.

Lee, D.H., Chang, H.W., and Cody, R.D., 2004, Synergism effect of mixed surfactant solutions in remediation of soil contaminated with PCE, *Geosci. J.*, **8**(3), 319-323.

Lee, G.S., Kim, Y.B., Jang, J.S., Um, J.Y., Song, S.H., and Kim, E.Y., 2012, A field study of surfactant enhanced in-situ remediation using injection wells and recovery trench at a jet oil contaminated site, *J. KoSSGE*, **17**(1), 13-21.

Lee, M., Kang, H., and Do, W., 2005, Application of nonionic surfactant-enhanced in situ flushing to a diesel contaminated site, *Water. Res.*, **39**, 139-146.

Lee, M., Kim, J., and Kim, I., 2011, In-situ biosurfactant flushing, coupled with a highly pressurized air injection, to remediate the bunker oil contaminated site, *Geosci. J.*, **15**(3), 313-321.

Lee, M., Chung, S.Y., Kang, D.H., Choi, S.I., and Kim, M.C., 2002, Surfactant enhanced in-situ soil flushing pilot test for the soil and groundwater remediation in an oil contaminated site, *J. KoSSGE*, **7**(4), 77-86.

Lowe, D.F., Oubre, C.L., and Ward C.H., 1999, Surfactant and cosolvents for NAPL remediation, Lewis Publishers, New York, p. 403.

Mackay, D.M. and Cherry, J.A., 1989, Groundwater contamination: Pump and treat remediation, *Environ. Sci. Technol.,*, **23**, 630-636.

Paria, S., 2008, Surfactant-enhanced remediation of organic contaminated soil and water, *Adv. Colloid and Interface Sci.*, **138**, 24-58.

Roberts, P.V., 1998, Remediation of petroleum contaminated soils Lewis Publishers, Florida, p. 542.

Rosen, M.J., 1989, Surfactant and interfacial phenomena, John Wiley and Sons, New York, p. 170-202.

Santanu, P., 2008, surfactant-enhanced remediation of organic contaminated soil and water, *Adv. Colloid Interface Sci.*, **138**, 24-58.

Yang, S.K., Shin, S.Y., and Kim, H.K., 2010, Removal of non-volatile contaminant from aquifer using surfactant-enhanced ozone sparging, *J. KoSSGE*, **15**(6), 37-45.

Zhao, B., Zhu, L., Li, W., and Chen, B., 2005, Solubilization and biodegradation of phenanthrene in mixed anionic-nonionic surfactant solutions, *Chemosphere*, **58**, 33-40.