REGENERATION AND LONG-TERM STABILITY OF SURFACTANT-MODIFIED ZEOLITE FOR REMOVAL OF VOLATILE ORGANIC COMPOUNDS FROM PRODUCED WATER

by

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DEDICATION

This is dedicated in loving memory of my grandfather, Arthur Joecks**.**

ABSTRACT

This work provides the results of laboratory-scale experiments of a produced-water treatment system. This treatment system used surfactant-modified zeolite (SMZ) to remove volatile organic compounds, including benzene, toluene, ethylbenzene, *p*-, *m*-and *o*-xylene (BTEX) from produced waters generated as a result of oil and gas recovery. Previous studies showed that SMZ was an effective sorptive medium for BTEX and that SMZ was easily and cost-effectively regenerable by air sparging. Furthermore, BTEX sorption and regeneration was reproducible for 10 cycles in the laboratory. Field-measurements from a pilot-scale treatment system showed good agreement with the laboratory results.

The focus of the current study was to use laboratory-scale column studies to (1) investigate how different airflow rates impact regeneration and (2) perform long-term tests to infer the chemical and physical stability of SMZ in a produced-water treatment system.

The results of the regeneration airflow rate studies showed that kinetic effects of varying airflow rates (from 1.3 to 10 pore volumes of air per minute) did not significantly affect removal of BTEX. Rather, the volume of air pumped through the column during air sparging was the predictor of removal rates. The implication of these results is that simple predictions can be made about BTEX removal rates from SMZ by knowing the airflow rate and number of pore volumes that have passed through the column. This is important for coupling of the SMZ treatment system with a process designed to treat the

off-gas, such as a vapor phase bioreactor (VPB). End-users of such a system must be able to predict the rate of regeneration and tune it to an optimal level for the VPB.

Long-term laboratory-scale results of the SMZ produced-water treatment system were promising. Fifty sorption/regeneration cycles were carried out, each consisting of sorption from 100 PV of produced water followed by regeneration with approximately 2000 PV of air. A weakly decreasing trend was observed for the BTEX distribution coefficients (K_d), indicating only a small loss in sorption capacity after 50 cycles of sorption and regeneration. Hydraulic conductivity of the SMZ decreased by roughly 30% after the 50 cycles. Most of this hydraulic conductivity loss was likely caused by particle attrition.

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Finally, I would like to thank Heather Shannon and my family, without whom none of this would have been possible.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIX FIGURES

LIST OF APPENDIX TABLES

INTRODUCTION

This document is the result of a thesis project and contains a manuscript to be submitted to a scientific journal as well as supporting appendices. The study examines the use of surfactant-modified zeolite (SMZ) to remove dissolved organic compounds, particularly BTEX (benzene, toluene, ethylbenzene, and the xylenes), from produced waters. Two main objectives were investigated. The first was to examine the regeneration of BTEX-saturated SMZ. This process must be understood for interfacing with other treatment methods that can degrade the stripped-off BTEX. The second objective was to perform long-term laboratory column experiments with the SMZ treatment system. These results will be useful for designing and predicting the effectiveness of field-scale treatment systems.

The following manuscript, entitled “Regeneration and long-term stability of surfactant-modified zeolite for removal of volatile organic compounds from produced water” was prepared for submission to a scientific journal. The article presents results of laboratory-scale column experiments described above.

The appendices contain the complete data sets from the laboratory work performed as well as further discussion on some key points.

MANUSCRIPT:

REGENERATION AND LONG-TERM STABILITY OF SURFACTANT-MODIFIED ZEOLITE FOR REMOVAL OF VOLATILE ORGANIC COMPOUNDS FROM PRODUCED WATER

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The focus of the current study was to use laboratory-scale column studies to (1) investigate how different airflow rates impact regeneration and (2) perform long-term tests to infer the chemical and physical stability of SMZ in a produced-water treatment system.

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Long-term laboratory-scale results of the SMZ produced-water treatment system were promising. Fifty sorption/regeneration cycles were carried out, each consisting of sorption from 100 PV of produced water followed by regeneration with approximately 2000 PV of air. A weakly decreasing trend was observed for the BTEX distribution coefficients (K_d), indicating only a small loss in sorption capacity after 50 cycles of sorption and regeneration. Hydraulic conductivity of the SMZ decreased by roughly 30% after the 50 cycles. Most of this hydraulic conductivity loss was likely caused by particle attrition.

INTRODUCTION

Oilfield produced water is an enormous waste stream in the United States. Produced water is brought to the surface as a result of oil and gas recovery and includes both formation water and water injected to enhance the recovery process. The ratio of produced water to recovered oil and gas generally increases during the lifetime of a well and cumulative produced water generation can be 10 times that of oil and gas (Stephenson 1992). The Rocky Mountain region of the U.S. (Colorado, Montana, New Mexico, Utah, and Wyoming) generated more than 3 billion bbl (1 bbl = 42 gal) of produced water in 2000 (Boysen et al. 2002).

Produced waters are highly variable in composition but often contain high total dissolved solids (TDS), dissolved organic compounds, heavy metals, radionuclides, and chemical additives associated with the recovery process (Stephenson 1992). Among the dissolved organic compounds are the volatile organic compounds benzene, toluene, ethylbenzene, and *para*-, *ortho*- and *meta*-xylenes, known collectively as BTEX. Additionally, produced water often contains high amounts of organic acids (API 2002).

The majority of produced water, including up to 92% of that produced onshore, is disposed via injection into the subsurface (API 2000). This includes produced water injected to further enhance oil recovery. Remaining onshore produced water is disposed and/or used at the surface in evaporation pits, irrigation, or for application to roads (U.S. EPA 2000). Onshore surface discharge is regulated at the Federal level by the National Pollutant Discharge Elimination System (NPDES). Permits are only issued for small-volume wells, defined as less than 10 bbls oil per day, and west of the 98th meridian in instances where the water can be put to a beneficial use (40 CFR Part 465).

Boysen et al. (2002) surveyed oil and gas producers in the Rocky Mountain region and found per-barrel disposal costs for produced water ranging from \$0.01 to \$10. This cost was heavily dependant on whether the producer was able to dispose of the water on site or had to transport the water to an off-site disposal facility. Trucking costs were quoted to be as much as \$80/hr, and can only be expected to rise with increasing fuel costs. Boysen et al (2002) concluded that costs for disposal were increasing due to more stringent state regulations. This led producers to look for on-site treatment and recycling methods to lower their costs.

Several methods are available for removal of dissolved organic contaminants from produced water. One of the most widely used methods uses granular activated carbon (GAC) to remove aromatic organic compounds from solution. However, as Hansen and Davies (1994) explained, GAC must be regenerated by wet-air oxidation (WAO) once it is saturated with organic compounds. WAO oxidizes organic and inorganic contaminants in the aqueous phase at elevated temperature and pressure. Furthermore, Hansen and Davies (1994) noted that, for typical gas-field produced-water volumes (1000 bbl per day), WAO could be used to remove organic contaminants without the use of GAC. Where organic concentrations exceed 10 – 40 mg/L, costs associated with GAC became prohibitive for oil and gas producers (Hayes and Arthur, 2004).

Miller et al. (1997) performed a pilot test using a granular activated-carbon fluidized-bed biological reactor (GAC-FBR) to remove dissolved organic material from produced water. In this process GAC was coated with a fixed microbial film that degraded the sorbed organic compounds. The GAC-FBR could be run under either aerobic conditions, which gave higher removal efficiency, or anoxic conditions, which were capable of handling higher organic concentrations. The field test described by Miller et al. used an anoxic GAC-FBR in series with an aerobic GAC-FBR. BTEX removal efficiencies for this apparatus ranged from 95 to 99.8%. The GAC-FBR's did not need to be regenerated because the organic compounds were constantly being degraded. Costs for the system were not reported.

Another method for removing dissolved organics from produced water is air stripping. Fang and Lin (1988) described three types of air-stripping methods common in industrial applications – (1) a fixed tank with air spargers; (2) air and water in countercurrent flow through a packed column; (3) a tray column where air passes through flowing produced water. The authors provided laboratory results from a scaled-down type (1) apparatus. Their findings showed greater than 99% benzene removal from an aqueous solution after less than 1 hour of air stripping. Disadvantages of air stripping are that it does not remove non-volatile compounds (Fang and Lin, 1988) and scale deposition may prove problematic (Hansen and Davies, 1994).

Additionally, modified zeolites have been proposed as a treatment option for removing BTEX compounds from contaminated water. Zeolites are a group of naturally occurring aluminosilcate minerals with a cage-like crystal structure. They are characterized by high internal and external surface areas and high cation exchange capacities (CECs). Zeolites are mined as aggregates and as such can be ground to any desired mesh size, making them ideal for flow-through and column applications that are sensitive to hydraulic properties of the medium.

Positively charged surfactant molecules such as hexadecyltrimethylammonium (HDTMA) can replace positively charged counterions on the surface of the zeolite. A surfactant bilayer forms on the zeolite surface with addition of sufficient surfactant. Organic compounds such as BTEX can then partition into this hydrophobic, nonpolar layer.

Batch tests have been performed using zeolites modified with several different amines to remove BTEX from produced water. Janks and Cadena (1991) reported removal efficiencies ranging from 9.4 to 85.2% depending on the amine used. Highest removal efficiencies were achieved with lower-molecular-weight amines. Bowman et al. (1995) reported the results of batch experiments using HDTMA-modified zeolite to remove benzene, toluene, *p*-xylene, and ethylbenzene. Linear sorption isotherms, non-competitive sorption, and increasing sorption with decreasing solubility for each compound led Bowman et al. (1995) to conclude that BTEX sorption on SMZ could be explained by a simple partitioning mechanism.

Unlike the energy- and cost- intensive WAO required to regenerate activated carbon, SMZ can be regenerated simply by blowing room-temperature air through the column. Li and Bowman (2001) reported full regeneration of perchloroethylene-(PCE) saturated SMZ with air sparging. The vapor-phase stream of organic compounds can then be treated in various ways, including use of a vapor-phase bioreactor (VPB) (Kwon et al., 2005), which degrades the compounds into respiration products such as carbon dioxide and water. At roughly $460 per ton (Bowman et al., 2001), SMZ offers a low cost, regenerable option for removing volatile organics from produced water. When coupled with additional processes, such as reverse-osmosis filtration to reduce salinity, SMZ can potentially treat water so that it is clean enough to be put towards an improved use such as irrigation, road watering, or make-up water for industrial processes.

Ranck et al. (2005) further investigated using SMZ for treating produced water by perfoming laboratory- and field-scale column experiments. The laboratory-scale studies described in Ranck et al. (2005) demonstrate that BTEX sorption and regeneration on SMZ is repeatable for 10 cycles. Pilot-scale field tests were performed at a produced-water treatment facility in Wyoming and agreement was good between laboratory and field observations. Ranck et al. (2005) concluded that SMZ has the potential to be a successful, cost effective treatment option for produced water.

The purpose of the current study was to address two critical issues for deployment of full-scale produced-water treatment systems. The first component of the study, termed the regeneration rate tests (RRT), examined airflow rate during regeneration. When interfacing SMZ treatment with a VPB or other off-gas treatment system, it is necessary to know the rate at which BTEX will be removed based on the flow rate of air through the column. VPB's and other gas treatment systems are sensitive to concentrations of BTEX that are either too high or too low. The regeneration portion of this study utilized laboratory-scale column tests to investigate air stripping of SMZ at several flow rates.

Additionally, concerns have been raised regarding the long-term stability of SMZ for a produced-water treatment system. Ranck et al. (2005) found that high backpressure and significant particle deterioration occurred in laboratory columns after 10 sorption and regeneration cycles. Approximately 500 pore volumes (PV) of produced water were treated during each cycle in that study. Mean SMZ particle diameter for the Ranck et al. (2005) study was 0.164 mm. The second component of the current study, termed the long-term stability tests (LST), utilized laboratory-scale columns packed using SMZ with a mean particle diameter of 0.90 mm. This grain size was chosen because it is typical of the size that would be used in a full-scale treatment system, it replicates the grain size used in the previously discussed pilot-scale tests (Ranck et al., 2005), and the larger grain size may be more resistant to particle attrition.

MATERIALS AND METHODS

Produced Water

The produced water for the RRT experiments was obtained from the Crystal Solutions, LLC, produced-water treatment facility in Wamsutter, Wyoming in December 2002. This was the site of the Ranck et al. (2005) pilot-scale field tests. Water at this site was placed in separation tanks before being sent to a series of lined evaporation ponds. The water was collected from the separation tanks and stored in sealed 208-L metal drums at room temperature. The composition of this water is listed in Table 1.

The produced water for the LST experiments was obtained from a produced-water reinjection facility owned by Burlington Resources located near Farmington, NM, in the San Juan basin. This facility was also the site of pilot-scale SMZ and VPB field tests conducted in August 2005 (Altare et al., 2005). Water was trucked in to the site and stored in tanks. The water was then put through a separation tank, sand filters, and 1-μm filters before being reinjected. The water for the laboratory experiments was collected in July 2005 downstream of the sand filters and sealed in 208-L metal drums. Composition of the water from the treatment facility collected for laboratory experiments was analyzed in June 2006 and the results are shown in Table 1. Produced water used in the LST laboratory experiments described below was spiked with toluene so that concentrations were similar to that of the influent produced water from the August 2005 pilot tests (toluene = 3.3 mg/L)[1].

Surfactant-Modified Zeolite

The zeolite used in this study was obtained from the St. Cloud mine in Winston, NM. Mineralogical analysis of this zeolite showed that it had a composition of 74% clinoptilolite, 5% smectite, 10% quartz/cristobalite, and 1% illite. The internal and external CEC's were 800 meq/kg and 90-100 meq/kg, respectively (Bowman et al. 2000).

The RRT experiments used zeolite crushed to 0.18 – 0.15 mm grains (80 – 100 mesh). This zeolite was then treated with 0.10 M HDTMA-Cl (Aldrich, Milwaukee, WI) as described by Ranck et al (2005). HDTMA loading was 157 mmol/kg of zeolite. SMZ used for the LST experiments was crushed to a grain size of 1.4 – 0.4 mm (14-40 mesh) and bulk produced by the St. Cloud mine (Bowman et al. 2001). HDTMA loading on this zeolite was 180 mmol/kg zeolite. Discrepancies in HDTMA loading rates likely resulted from differences in the zeolite content of the material mined at different times.

Regeneration Airflow-Rate Column Studies

Columns for the RRT experiments were scaled down from the Wyoming field columns using the rapid small-scale column method developed for GAC (Crittenden et al. 1991), as discussed in Ranck et al. (2005). Columns were prepared by packing 80-110 mesh SMZ into four glass columns (ID = 0.4 cm, L = 10 cm) (Ace Glass, Vineland, NJ) capped with polytetrafluoroethylene (PTFE) end fittings. Four-way valves (Cole-Parmer,

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[1] Unpublished data from Lily Chen, University of Texas at Austin

Vernon Hills, Ill.) were attached to the end fittings with Luer connections and served as sampling ports for influent and effluent waters.

A separate column was packed for each RRT experiment. Each column was saturated from the bottom with a synthetic brine that matched the inorganic composition of the Wyoming produced water (Table 1). The brine was injected using a Waters model 501 HPLC pump.

A 10-L Tedlar® gas sampling bag (Alltech Associates, Inc., Deerfield, Ill.) filled with Wyoming produced water was attached to the pump with Teflon tubing. A 0.45-μm nylon syringe-tip filter (Supelco, Bellefonte, Pa.) was plumbed in between the pump and column to remove particulates. Produced water was pumped through each column individually until effluent BTEX concentrations equaled influent concentrations (~400 PV). Influent and effluent water samples were collected approximately every 10 PV for the first 100 PV and every 50 PV for the duration of the experiment. Three-milliliter water samples were withdrawn using a 10-mL gastight syringe, injected into 10-mL glass headspace vials, and capped with Teflon-faced butyl septa (Supelco) for subsequent analysis.

The BTEX-saturated SMZ was then regenerated by air sparging. A compressed air tank was attached to the effluent end of the column and a 65-mm single-float flow controller (Cole-Parmer) was placed between the tank and column to regulate airflow. The flow rate was measured downstream of the column with a soap-film flow meter. The four RRT columns were regenerated at 4.0, 7.5, 15 and 30 mL/min (1.3, 2.7, 5.0, and 10 PV/min), respectively. The effluent gas was sampled by withdrawing 0.2-mL samples with a 1.0-mL gastight syringe. These samples were analyzed immediately using gas chromatography. Regeneration was continued for at least 3000 PV to ensure effluent gas BTEX concentrations were less than 2% of initial values. The RRT columns were not replicated.

Long-Term Stability Column Studies

Columns for the LST experiments were prepared by adding 14-40 mesh SMZ to two replicate glass columns with a length of 11 cm and radius of 2.5 cm (Omnifit, Boonton, NJ). These columns were outfitted with replaceable 100-µm PTFE frits and one fixed and one adjustable end fitting. The adjustable end fitting allowed any headspace that developed due to particle loss to be eliminated. The LST columns were saturated with NaCl brine with electrical conductivity similar to the New Mexico produced water (21.5 mmho/cm). A constant-head tank was attached to the column inlet and the volumetric flowrate was measured at the effluent end in order to determine the hydraulic conductivity. This measurement was repeated after every fifth regeneration cycle.

A 2-PV slug of tritiated water was then injected into each column at a specific discharge of 2.5 cm/min in order to determine the hydraulic properties of the SMZ bed. This discharge was chosen to be similar to that of the New Mexico field experiments (~2.4 cm/min) (Altare et al., 2005). Effluent samples were collected in 7-mL glass vials in 0.5-min intervals using a Retriever II fraction collector (ISCO Inc., Lincoln, NE). One milliliter of each effluent sample was combined with 5 mL of scintillation cocktail solution (ICN Biomedicals, Inc., Irvine, CA) and analyzed with a LS6500 liquid scintillation counter (Beckman Coulter, Inc., Fullerton, CA). The tritium tracer tests were repeated after the 25th and 50th cycles to monitor changes in hydraulic properties.

Fifty sorption and regeneration cycles were performed on the LST columns, with water and off gas analyzed every fifth cycle. Each BTEX saturation step was carried out for 100 PV in order to better simulate operating conditions of the New Mexico field-scale experiments. The produced-water specific discharge during sorption cycles was 2.5 cm/min. The columns were regenerated using 160 mL/min (5.5 PV/min) of air.

After the LST experiments were complete, the end fittings were removed, the used frits were replaced with new ones, and the columns were reassembled. The conductivity was measured once again to determine how much of the conductivity loss, if any, could be explained by clogging of the frits. The columns were then disassembled. Two 0.5-g SMZ samples were taken from the inlet end of each LST column, one for biological analysis and one for electron microprobe analysis. The biological analysis consisted of DNA extractions using the methods described by Sambrook et al. (1989) and a protein analysis using SDS-PAGE gel (Laemmli, 1970). Microprobe images were obtained from a Cameca (Trumbull, CT) model SX 100 electron probe using an accelerating voltage of 15 kV and a beam current of 20 nA. X-ray chemical distribution maps were collected at a resolution of 512 by 512 pixels with a 7 millisecond per pixel collection time.

The remainder of the used SMZ from each column was removed and homogenized. An additional 0.5-g sample was taken from the homogenized SMZ from each column for a total chemical analysis. The chemical analysis was performed by digesting the samples with a four-acid method after Briggs (1996) and analyzing the digestion products by inductively coupled plasma (ICP) - atomic emission spectroscopy. The rest of the used SMZ from each column was used for a hydrometer particle size analysis (ASTM, 1995) to determine changes in particle size and the amount of particle attrition.

Analytical Methods

The influent and effluent produced-water sample vials were loaded into a Hewlett-Packard (HP) model 7694 headspace autosampler. The autosampler operating conditions were: oven temperature 70°C, loop temperature 75°C, transfer line temperature 75°C, equilibrium time 1.0 min, pressurization time 1.0 min, loop fill time 1.0 min, loop equilibration time 0.5 min, and injection time 0.09 min.

The autosampler was attached to a HP model 5890A gas chromatograph (GC) with a 10-m long, 0.53-mm I.D. HP-5 capillary column and a flame ionization detector (FID). Operating conditions of the GC were: carrier gas (He) flow rate 35 mL/min, split gas (He) flow rate 28 mL/min, oven temperature (isothermal) 55°C, injector temperature 210°C, and detector temperature 240°C. The GC was calibrated before each cycle was analyzed using five BTEX standards over a range from 0.5 to 40 mg/L. *p*-xylene and *m*-xylene were not resolved by this method and as such were treated as a single compound.

Gas-phase BTEX concentrations from the regeneration cycles of the RRT columns were measured by direct injection into the HP 5890A GC. Operating conditions of the GC were the same as for the sorption analysis with the exception of the split flow rate, which was increased to 63 mL/min. Calibration for these analyses was conducted by preparing BTEX standard solutions in 10-ml glass vials capped with Teflon-faced septa. BTEX concentrations in the headspace of the standards were calculated based on the Henry's Law constant for each compound.

Gas-phase BTEX concentrations for the LST regeneration experiments were measured using a Varian Inc. (Walnut Creek, CA) model 5890 GC equipped with an automated gas-sampling valve, FID, and a 15-m long, 0.25-mm I.D Varian Factor Four VF-1ms column. The valve, which used a 0.25 mL sampling loop, automatically collected a sample every 20 minutes and injected it into the column. Off-gas from the LST columns was plumbed into the sampling valve with Teflon tubing. Operating conditions of this GC were: carrier gas (He) flow 25 mL/min, split ratio 50, oven temperature (isothermal) 55°C, column flow 2.0 mL/min, injector temperature 140°C, and detector temperature 200°C. Calibration was carried out by manual injection of BTEX standards in a similar fashion as the manual-injection calibration for the HP 5890 GC.

RESULTS AND DISCUSSION

Regeneration-Rate-Test Experimental Results

All four columns in the RRT experiments were fully and reproducibly saturated with BTEX. Figure 1 shows BTEX breakthrough on column RRT1. Benzene, which has the highest aqueous solubility and the lowest octanol-water partition coefficient (K_{ow}) of the BTEX compounds (Table 2), is the first compound to elute from the columns. The other compounds elute in order of decreasing solubility and increasing K_{ow}, with ethylbenzene and the xylenes eluting at nearly the same time, as their similar K_{ow} values would predict. Figure 2 shows the reproducibility of sorption for toluene and *p*- and *m*-xylene.

The four RRT columns were then regenerated at airflow rates of 1.3 PV/min, 2.7 PV/min, 5.0 PV/min, and 10 PV/min, respectively. Off-gas *p*- and *m*-xylene concentrations are shown in Figure 3a as a function of time and in Figure 3b as a function of PV of air. As Figure 3a shows, for an airflow rate of 10 PV/min, nearly all of the *p*- and *m*-xylene has been removed before 500 min. However, for an airflow rate of 1.3 PV/min, similar removal takes at least 1500 min. When these data are viewed as a function of PV of air (Figure 3b), rather than time, we see that for early-time regeneration, xylene concentration for the two highest flow rates (10 PV/min and 5 PV/min) is lower than the concentration for the two lowest flow rates (1.3 PV/min and 2.7 PV/min). This is consistent with a kinetically-limited desorption mechanism for BTEX compounds during air sparging. However, nearly all of the p- and m-xylene was removed after 2000 PV of air, regardless of airflow rate. This means that while removal of BTEX from SMZ during air sparging was somewhat kinetically limited, kinetic effects did not play a large role in regeneration. The number of pore volumes of air required for regeneration can be predicted simply by knowing the volume of air that was pumped through the columns. Additionally, deviations in early-time removal may have been due to variations in the rate at which the column dried. No water was removed by gravity drainage prior to regeneration, resulting in saturated conditions as the cycle was begun. As the column dried an increasing percentage of the BTEX-saturated SMZ surface was available for air stripping.

Long-Term Stability Experimental Results

Tritium breakthrough curves (BTCs) from column LST1 for the virgin SMZ, after the 25th regeneration cycle, and after the 50th regeneration cycle are shown in Figures 4a, 4b, and 4c, respectively. These BTCs were well described by the 1-dimensional advection-dispersion equation:

$$R\frac{\partial C^*}{\partial T} = \frac{1}{P}\frac{\partial^2 C^*}{\partial X^2} - \frac{\partial C^*}{\partial X} \tag{1}$$

where:

$$C^* = \frac{c}{c_0} \tag{2}$$

$$P = \frac{vL}{D} \tag{3}$$

$$R = 1 + \left(\frac{\rho}{\theta}\right)K_d \tag{4}$$

$$T = \frac{vt}{L} \tag{5}$$

$$X = \frac{x}{L} \tag{6}$$

and R is the retardation factor, C^* is the dimensionless solute concentration, T is dimensionless time (pore volumes), P is the Peclet number, X is the dimensionless length, c is the effluent solute concentration (ML^{-3}), c_0 is the influent solute concentration (ML^{-3}), v is the pore-water velocity (LT^{-1}), L is the column length (L), D is the dispersion coefficient (L^2T^{-1}), ρ is bulk density (ML^{-3}), θ is volumetric water content, K_d is the linear equilibrium sorption constant (L^3M^{-1}), t is the time (T), and x is the distance (L).

Equation 1 was fit to the observed tritium data using the nonlinear, least-squares optimization program CXTFIT 2.1 (Torride et al. 1999). A flux-type upper boundary and semi-infinite lower boundary condition were used, *v* was treated as a known value, and *R* and *D* were fitted. As seen in Figure 4, a good fit was achieved with the equilibrium model. The fitted *D* and *R* values are shown in Table 3. No distinct trends were observed that would have indicated a change in the column hydraulic properties over time. The fact that the tritium tracer is well described by Equation 1 suggests that physical nonequilibrium (immobile water zones) was not a major factor for these column tests.

BTCs for benzene and *p*- and *m*-xylene for every 5th cycle on column LST1 are shown in Figures 5a and 5b. Figure 6 shows observed *p*- and *m*-xylene breakthrough from the first sorption cycle on column LST1, as well as the fitted BTC using Equation 1. Clearly, the simple equilibrium advection-dispersion equation did not adequately describe the sorption of *p*- and *m*-xylene on SMZ, indicating nonequilibrium processes were present. Similar trends were found during 50 cycles of sorption and regeneration for each of the other BTEX compounds. The presence of immobile water domains was ruled out by the tritium experiments. Chemical nonequilibrium may have occurred due to slow kinetics during the partitioning of BTEX compounds from the aqueous phase into the hydrophobic regions of the SMZ (Pignatello and Xing, 1996). Thus, a two-site chemical nonequilibium advection-dispersion model was chosen based on Toride et al. (1999):

$$\beta R\frac{\partial C_1}{\partial T}=\frac{1}{P}\frac{\partial^2 C_1}{\partial X^2}-\frac{\partial C_1}{\partial X}-\omega(C_1-C_2) \qquad (7)$$

$$(1-\beta)R\frac{\partial C_2}{\partial p}=\omega(C_1-C_2) \qquad (8)$$

where:

$$\beta = \frac{\theta + f\rho\ K_d}{\theta + \rho K_d} \tag{9}$$

$$C_1 = \frac{c}{c_0} \tag{10}$$

$$C_2 = \frac{s_k}{(1-f)K_d c_o} \tag{11}$$

$$\omega = \frac{\alpha(1-\beta)RL}{v} \tag{12}$$

and subscripts 1, 2, and k refer to equilibrium sites, nonequilibrium sites, and kinetic adsorption sites, respectively; f is the fraction of sorption sites that are always at equilibrium, s is the concentration of the adsorbed phase, and α is a first-order kinetic rate coefficient (T^{-1}).

Equations 7 and 8 were fit to the observed BTEX data using CXTFIT (Toride et al., 1999). A flux-type upper boundary and semi-infinite lower boundary condition were imposed, v was treated as a fixed value, and D, β, and ω were fitted with the program.

K_d for each BTEX compound was calculated for every analyzed sorption cycle using Equation 4 and the fitted value of R. Figure 7 shows the values of K_d plotted for benzene and *p*- and *m*-xylene, respectively, from column LST1 along with error bars representing the 95% confidence interval of the fitted K_d and a line that was fit to the data using a linear regression. The slopes for these best-fit lines, in addition to the best-fit lines for the other BTEX compounds, are shown in Table 2. A loss in sorptive capacity over time would be indicated by a decreasing trend in K_d values as the number of sorption cycles increased. As Table 2 shows, all of the slope values are negative. However, as demonstrated by the large error associated with each fitted value of K_d, the trend is weak. Additionally, attempts were made to fit the data using a non-linear curve. These attempts also failed to yield a good fit to the observed data. Although these attempts were not successful, changes in sorption capacity may not be a linear process. Several factors influence sorption capacity. Among these are surfactant wash-off and sorption of other organic compounds that are not removed by air sparging but which can increase the sorption of volatile organics.

Off-gas concentrations of toluene and *p*- and *m*-xylene are shown in Figure 8 for each of the measured regeneration cycles on column LST1. Reproducibility of the regeneration experiments was excellent. Early-time variability in off-gas concentration was once again observed. This may be indicative that the degree of water saturation of the column dictates early-time off-gas concentrations during regeneration.

The hydraulic conductivity of the columns was measured after every fifth regeneration cycle. After the 25th cycle, the conductivity of column LST1 had dropped to approximately 3% of the virgin-SMZ column. After 50 cycles both columns appeared to have lost 98% of their original conductivity. However, conductivity measured after the inlet and outlet frits were replaced showed that the columns had retained roughly 70% of their original conductivity, indicating the majority of the conductivity loss can be accounted for by clogging of the frits.

Several factors could account for the remaining 30% loss in hydraulic conductivity, among them particle attrition, formation of coatings on the SMZ grains, and biofouling of the column. However, biological testing for the presence of DNA and/or proteins on the used SMZ was negative for both replicate columns. This rules out biofouling as a mechanism for hydraulic conductivity loss.

As the LST column experiments proceeded, a distinct brown coloring of the zeolite particles was noted. Total digestion and compositional analysis of the used SMZ was conducted to determine whether the discoloration was due to precipitation of iron or manganese surface coatings on the SMZ. These analyses did not reveal any measureable increase in iron or manganese relative to virgin SMZ.

Images of the used SMZ were prepared using an electron microprobe in order to determine whether a surface coating was in fact accumulating on the SMZ in the column. Backscattered electron images of used- and virgin-SMZ grains are shown in Figures 9-11. Figure 9 is an image of a virgin SMZ particle, showing that the particle is largely made up of smaller zeolite mineral grains (the plate-like grains on the right hand side of the image) with uniform, clean surfaces. Figures 10 and 11 show images of used-SMZ from the influent ends of column LST1 and LST2, respectively. These figures show that a change in surface texture has occurred for certain regions of the used-SMZ grains. This change in surface texture was interpreted to be a surface coating. The coatings were not continuous over the used SMZ grains and appeared, due to the fact that surface features could still be interpreted below the coatings, to be thin. Coatings were likely caused by accumulation of non-volatile organics that were not removed during air sparging, or mineral precipitation that occurred when the column was being regenerated. At that time, water was evaporating within the column, leading to precipitation of mineral phases on the SMZ surfaces. Those phases that were water-soluble would be washed off during subsequent sorption cycles, while non-water-soluble mineral phases would accumulate on the SMZ grains. Chemical distribution maps were non-indicative and inconclusive for determining the composition of the proposed surface coatings. The maps were made using an SMZ particle that was mounted in epoxy and ground to a flat surface. This grinding step eliminated the ability to look at the external surface of the SMZ particle. Due to the discontinuous, thin nature of the coatings it is unlikely they played a large role in the loss of hydraulic conductivity.

Particle-size analysis conducted by the hydrometer method revealed a high amount of particle attrition. Virgin SMZ contained only 1.83% fines (smaller than 0.075 mm) while the used SMZ from columns LST1 and LST2 contained 13.9% and 17.9% fines, respectively. Particle attrition appears to be the most likely cause of the observed hydraulic conductivity loss.

Attempts were made to quantify the amount of surfactant lost from SMZ during the 50 cycles of the LST experiments. HDTMA concentration in the effluent water was measured using an HPLC method described by Li and Bowman (1997). The results of these attempts were confounded by a compound present in the influent produced water that had a similar elution time as HDTMA. Even though direct measurements of HDTMA loss were inconclusive, indirect evidence exists to infer the limits of surfactant wash-off. If HDTMA washed off such that the coverage on the zeolite surface was below monolayer coverage (below 90 mmol/kg), pronounced decrease in sorption capacity would be have been observed. This was shown by Li and Bowman (1998), who observed that sorption of PCE on SMZ increased linearly as a function of surfactant loading rate up to the equivalent of monolayer loading capacity. Additional surfactant loading led to minimal increases in sorptive capacity for PCE (Li and Bowman, 1998). Since little to no loss in sorptive capacity was observed for the current study, it was presumed that surfactant loading remained, at a minimum, at the equivalent monolayer loading capacity throughout the LST experiments. It is expected, however, that some surfactant wash-off occurred. Li et al. (2003) presented the results of column experiments designed to determine surfactant wash-off from modified clinoptilolite. Li et al. (2003) determined that, after 100 PV of a 0.5 mM $NaHCO_3$ solution had passed through the column, 17% of the total surfactant was washed off from 14-40 mesh SMZ that originally had been loaded to almost twice the external CEC. Furthermore, Li et al. (2003) found that wash-off of the outer surfactant layer occurred at a faster rate than wash-off of the surfactant molecules that were held to the zeolite surface by cation exchange. The fact that the monolayer coverage is more stable than bilayer coverage is expected considering the forces holding surfactant molecules to the zeolite surface (electrostatic interactions) are stronger than the forces holding the upper layer of surfactant to the lower layer (hydrophobic interactions) (Li et al., 1998).

CONCLUSIONS

Surfactant-modified zeolite (SMZ) is an effective sorptive medium for removing dissolved organics from produced water. It offers a low-cost, easily regenerable option for producers who want or need to treat their produced water.

Regeneration-curve predictions can be made simply by knowing the volume of air pumped through the column. Kinetic effects due to various airflow rates do not have a large impact on the removal rate of BTEX during air sparging. Thus, when interfacing the

SMZ regeneration process with a VPB or other off-gas treatment system, the end user can tailor the delivery of BTEX to the VPB by changing the airflow rate.

Long-term laboratory-scale column tests (50 sorption and regeneration cycles; 5000 PV total water treated) show that SMZ retains its ability to remove BTEX compounds over many cycles. Observation of K_d over the 50 cycles reveals a weakly decreasing trend. Even if the K_d in a field column dropped too low, additional HDTMA could be pumped through the column to restore surfactant loading on the SMZ. Hydraulic conductivity of the SMZ decreased by approximately 30% during the tests. This decrease was attributed to particle breakdown in the column and cannot be explained by biofouling or the accumulation of surface coatings on the SMZ particles. Future work should focus on the issue of particle attrition. Knowledge of conditions that inhibit or promote attrition of SMZ particles should be determined. Methods to stabilize the SMZ particles should also be investigated. Particle breakdown will lead to high backpressure in columns and decreased treatment capacity.

Further work needs to be done in order to quantify the amount of HDTMA washed off during the long-term tests. Although quantification of HDTMA wash-off was not successful for this study, indirect evidence suggests that surfactant loading did not drop below equivalent monolayer coverage. Additionally, work must be done at the laboratory and field scales to couple SMZ treatment with other treatment methods. These systems should aim to remove organic acids and reduce the TDS of the effluent waters. Successful implementation of these practices can yield water that meets state-imposed discharge requirements.

ACKNOWLEDGEMENTS

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Table 1. Compositions of the produced water used for regeneration, long-term laboratory experiments, and field tests.

Produced water sample	Wyoming (used for RRT experiments) [1]	San Juan Basin, NM (used for LST experiments; collected July 2005, analyzed May 2006) [2]	San Juan Basin, NM (collected May 2005) [3]
Constituent	Concentration (mg/L)		
Benzene	15.8	1.37	2.23
Toluene	36.7	ND [4]	7.07
Ethylbenzene	1.4	0.21	0.38
p- & m-xylene	6.4	2.58 (total xylenes)	3.89
o-xylene	3.4		1.08
Cl^-	4400	7000	5360
HCO_3^-	3120	2150	672
F^-	57	<10	
Br^-	22	19	12
$SO4^-$	13	<100	408
Na^+	4100	4870	3700
K^+	44	150	74.7
Ca^{2+}	30	20	77.8
Mg^{2+}	6.4	46	25.4
Total Dissolved Solids	11792	13180	10076
Total Organic Carbon	1000	NA [5]	318

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[1] from Ranck et al., 2005

[2] BTEX analysis performed by General Engineering Laboratories, Charleston, SC. Inorganic analysis performed by New Mexico Bureau of Geology

[3] Unpublished data from Lily Chen, University of Texas at Austin

[4] ND = not detected above reporting limit

[5] NA = not analyzed

Table 2. Octanol water coefficients (K_{ow}) and solubility at 25°C for the BTEX compounds. Additionally, the calculated distribution coefficients (K_d) and their standard deviations from the LST columns, the slopes of linear regressions fit to K_d values as a function of the number of cycles, and the calculated p-values.

		Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
	log K_{ow}[1]	2.13	2.69	3.15	3.15, 3.20	3.15
	Solubility[1] (mg/L) 25°C	1850	470	140	200,173	204
Column						
LST1	K_d (L/kg)	13.1	31.8	67.6	67.7	64.6
	Std. Dev.	2.3	3.9	7.8	5.2	9.3
	Slope (K_d/cycle)	-0.05	-0.03	-0.27	-0.09	-0.36
LST2	K_d (L/kg)	14.6	29.4	62.7	62.8	62.9
	Std. Dev.	1.8	3.3	4.6	5.2	5.1
	Slope (K_d/cycle)	-0.04	-0.15	-0.12	-0.22	-0.16

Table 3. Fitted D and R values for tritium tracer tests conducted on columns LST1 and LST2 for the unused column, after the 25th regeneration cycle, and after the 50th regeneration cycle.

Column		D (cm^2/min)	R
LST1	Virgin SMZ	0.46	1.02
	after 25 cycles	0.73	1.10
	after 50 cycles	0.45	1.09
LST2	Virgin SMZ	0.38	1.03
	after 25 cycles	0.40	1.14
	after 50 cycles	0.26	1.14

FIGURE CAPTIONS

Figure 1. BTCs for each BTEX compound from column RRT1.

Figure 2. BTCs for toluene and *p*- and *m*-xylene on four different virgin-SMZ columns. The columns were saturated with BTEX under identical conditions but regenerated at airflow rates of 1.3 PV/min, 2.7 PV/min, 5 PV/min, and 10 PV/min, respectively.

Figure 3. *p*- and *m*-xylene regeneration curves as a function of (a) time and (b) pore volumes of air. Columns RRT1, RRT2, RRT3, and RRT4 used airflow rates of 1.3 PV/min, 2.7 PV/min, 5 PV/min, and 10 PV/min, respectively.

Figure 4. BTCs of tritiated water in column LST1 for (a) virgin SMZ and (b) after the 25th regeneration cycle and (c) after the 50th regeneration cycle. Solid lines represent fitted values using an equilibrium advection-dispersion equation.

Figure 5. BTCs for every fifth cycle on column LST1 for (a) benzene and (b) *p*- and *m*-xylene.

Figure 6. Observed and fitted BTCs of *p*- and *m*-xylene for the first sorption cycle on column LST1. The solid line shows the fit using an equilibrium advection-dispersion equation while the dashed line shows the fit using a two-site chemical nonequilibrium advection-dispersion equation.

Figure 7. K_d's and lines fit to the K_d values for columns LST1 and LST2 for (a) benzene and (b) *p*- and *m*-xylene.

Figure 8. Vapor-phase concentrations of toluene and *p*- and *m*-xylene over 50 regeneration cycles on column LST1.

Figure 9. Backscattered electron image of virgin SMZ.

Figure 10. Backscattered electron image of SMZ from column LST1 used for 50 sorption cycles.

Figure 11. Backscattered electron image of SMZ from column LST2 used for 50 sorption cycles.

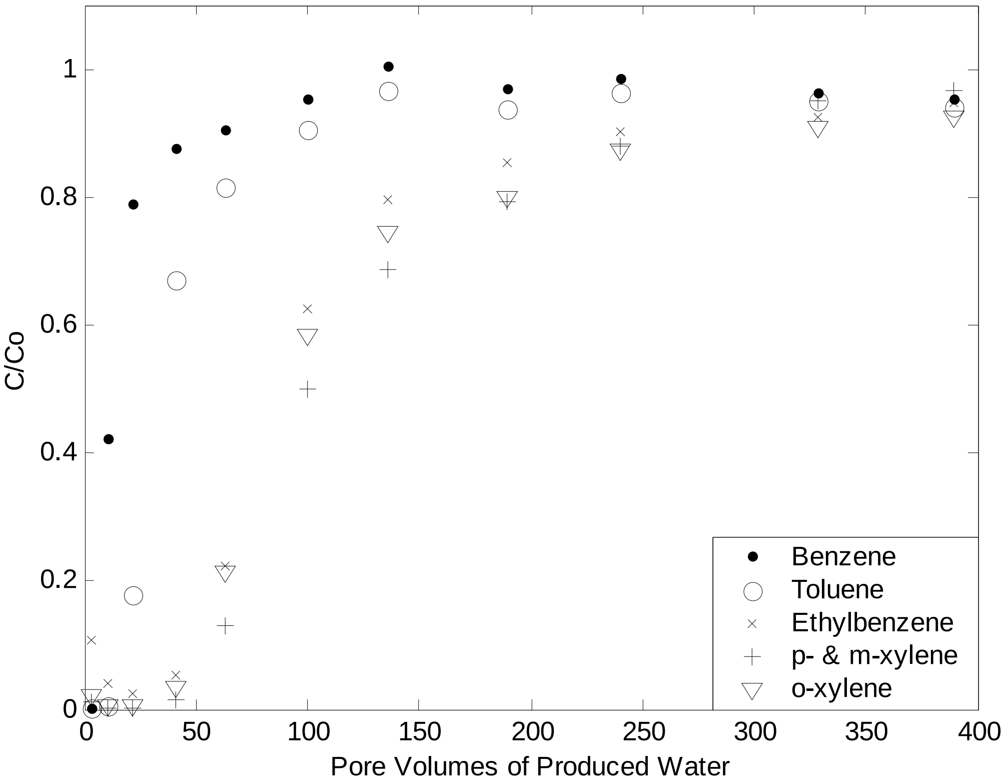

Figure 1. BTCs for each BTEX compound from column RRT1.

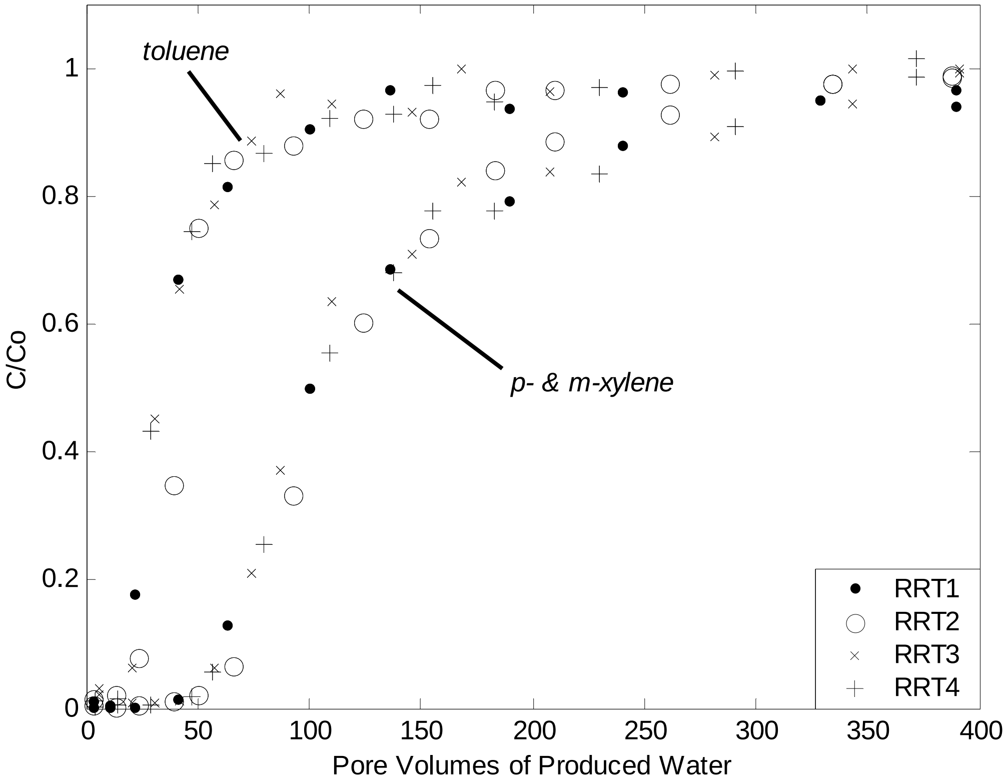

Figure 2. BTCs for toluene and *p*- and *m*-xylene on four different virgin-SMZ columns. The columns were saturated with BTEX under identical conditions but regenerated at airflow rates of 1.3 PV/min, 2.7 PV/min, 5 PV/min, and 10 PV/min, respectively.

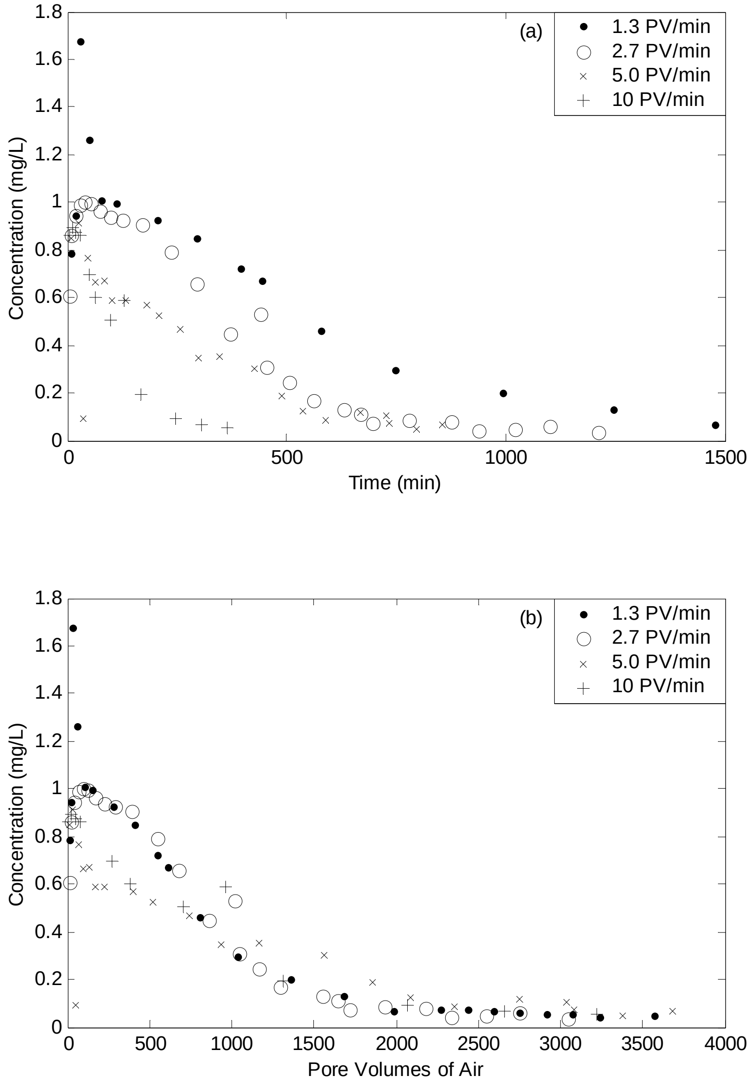

Figure 3. ***p*- and *m*-xylene regeneration curves as a function of (a) time and (b) pore volumes of air. Columns RRT1, RRT2, RRT3, and RRT4 used airflow rates of 1.3 PV/min, 2.7 PV/min, 5 PV/min, and 10 PV/min, respectively.**

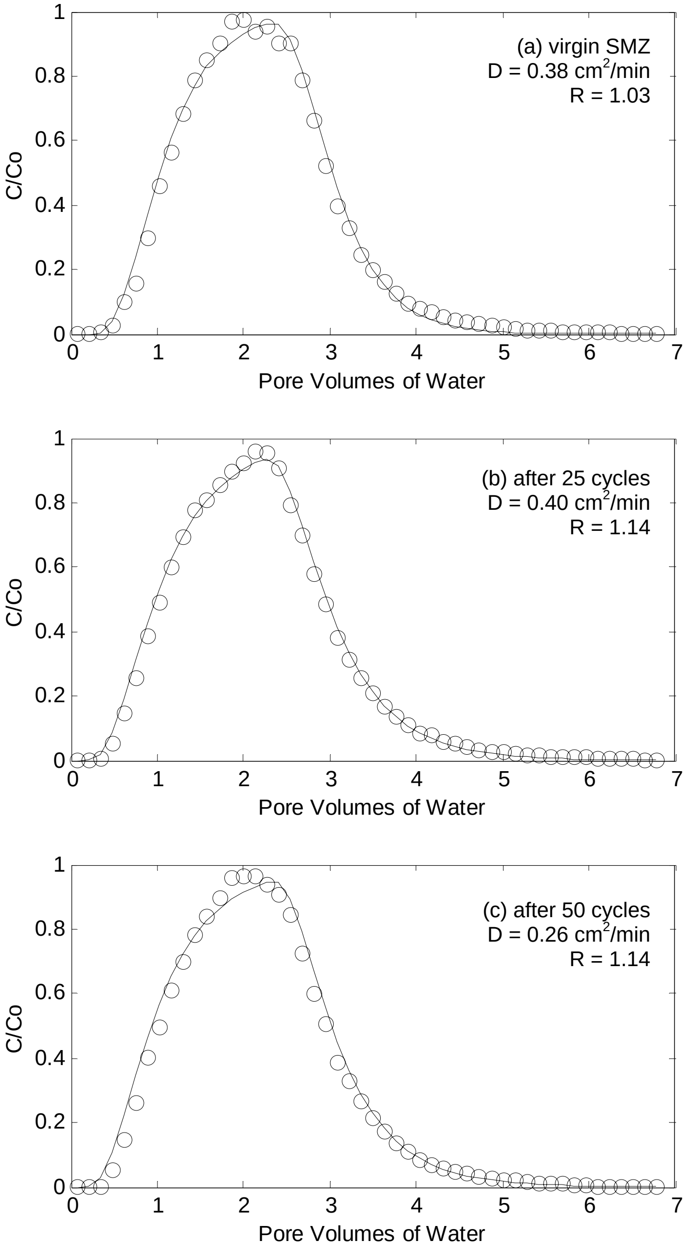

Figure 4. BTCs of tritiated water in column LST2 for (a) virgin SMZ and (b) after the 25th regeneration cycle and (c) after the 50th regeneration cycle. Solid lines represent fitted values using an equilibrium advection-dispersion equation

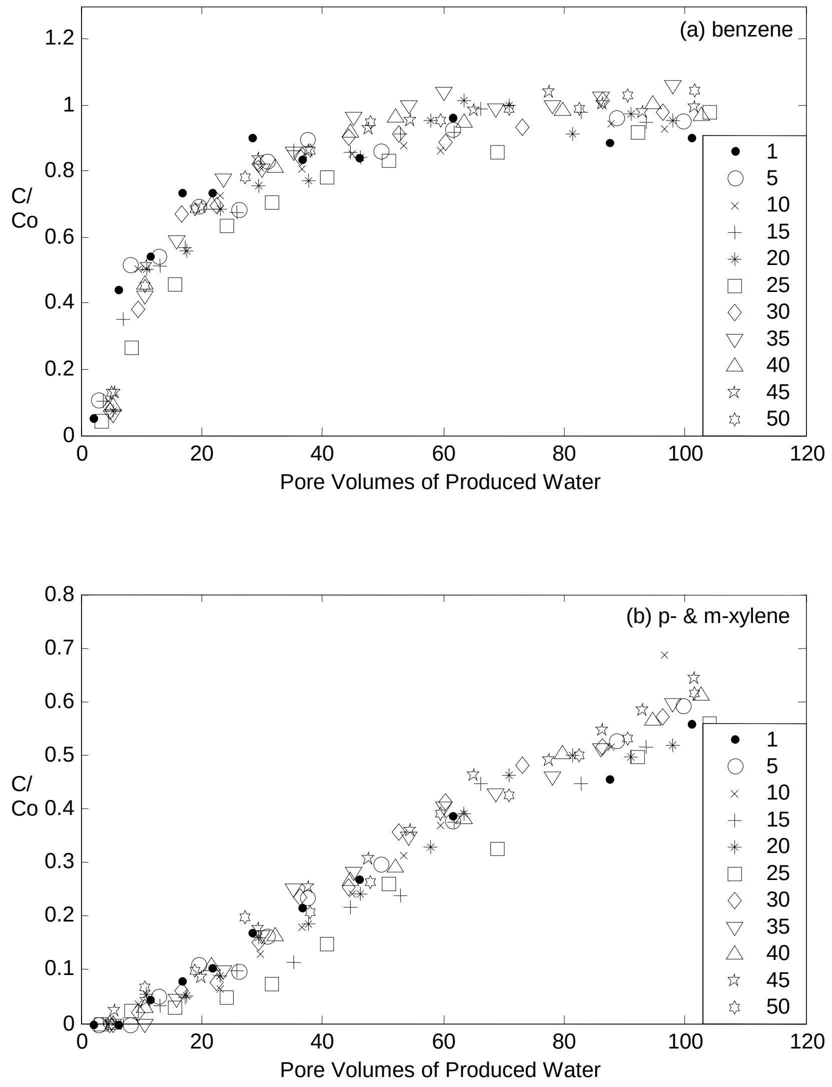

Figure 5. BTCs for every fifth sorption cycle on column LST1 for (a) benzene and (b) *p*- and *m*-xylene

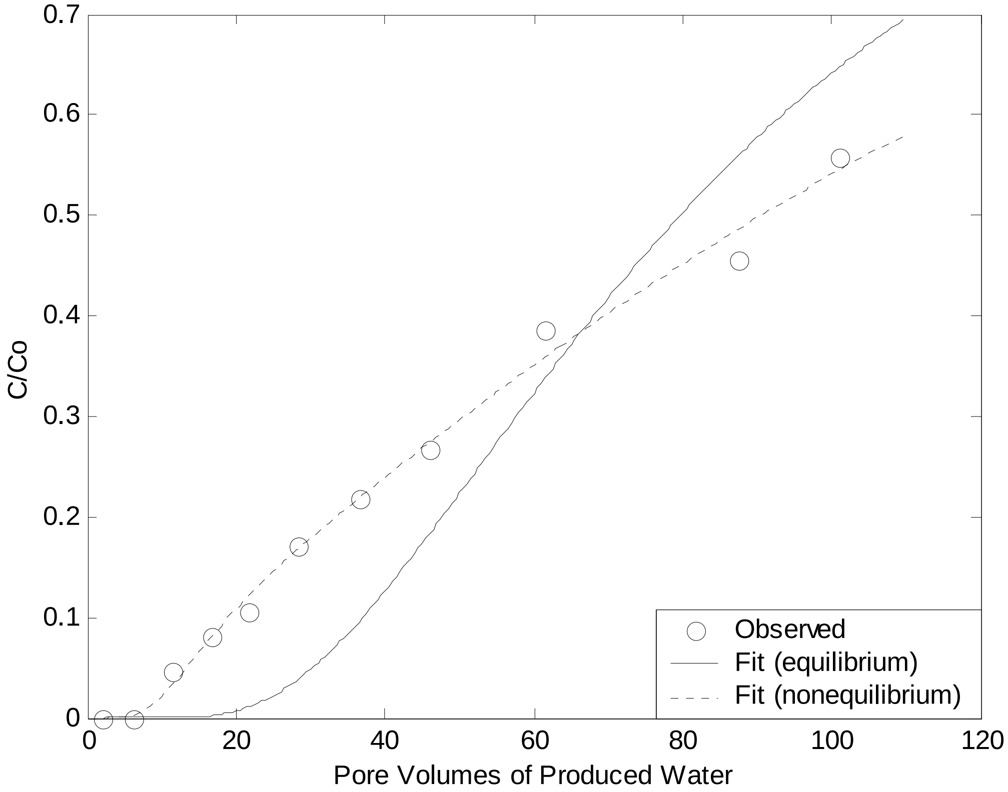

Figure 6. Observed and fitted BTCs of *p*- and *m*-xylene for the first sorption cycle on column LST1. The solid line shows the fit using an equilibrium advection-dispersion equation while the dashed line shows the fit using a two-site chemical nonequilibrium advection-dispersion equation.

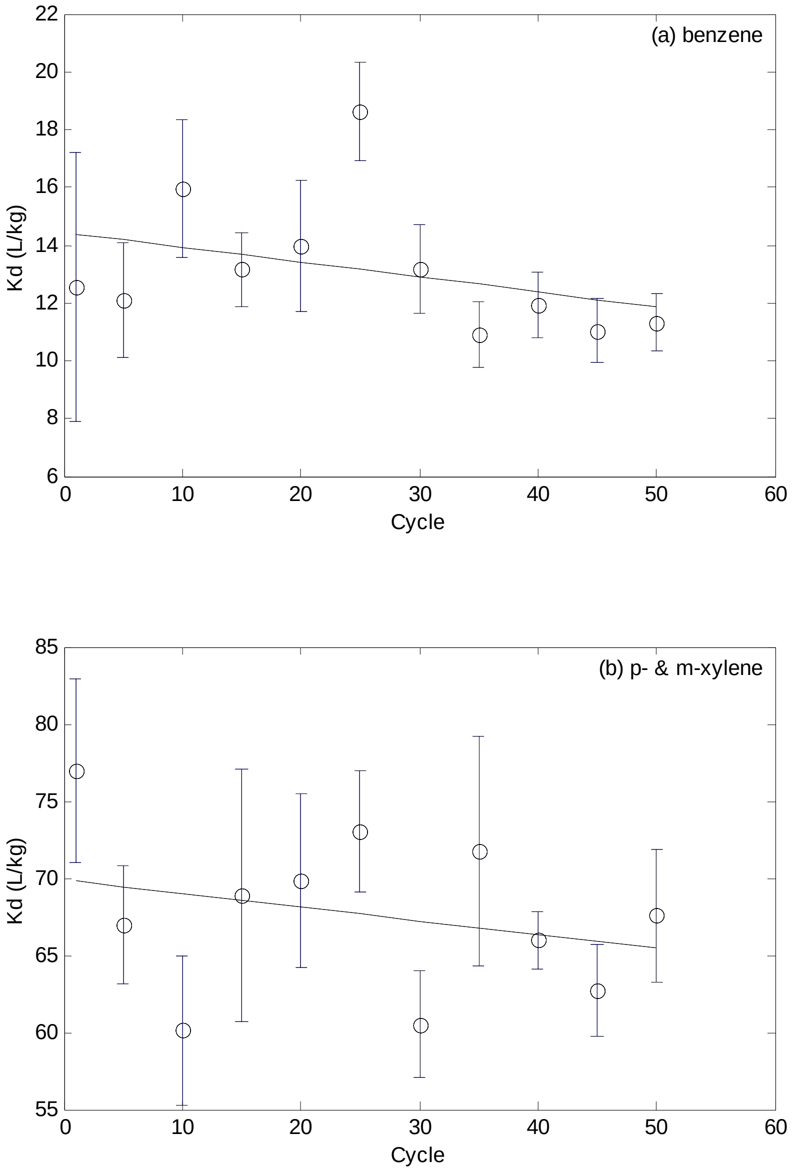

Figure 7. ***K_d*'s and lines fit to the *K_d* values for (a) benzene and (b) *p*- & *m*-xylene from column LST1. Error bars represent the 95% confidence interval from the curve-fit process using CXTFIT.**

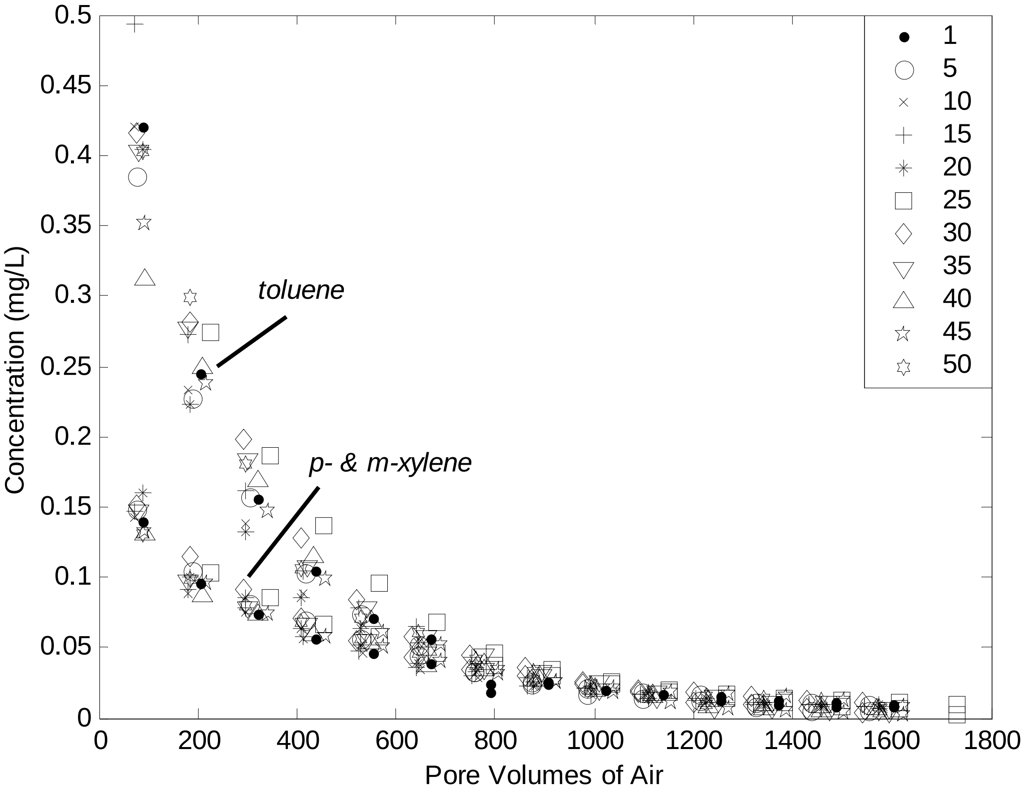

Figure 8. Vapor-phase concentrations of toluene and *p*- and *m*-xylene over 50 regeneration cycles on column LST1.

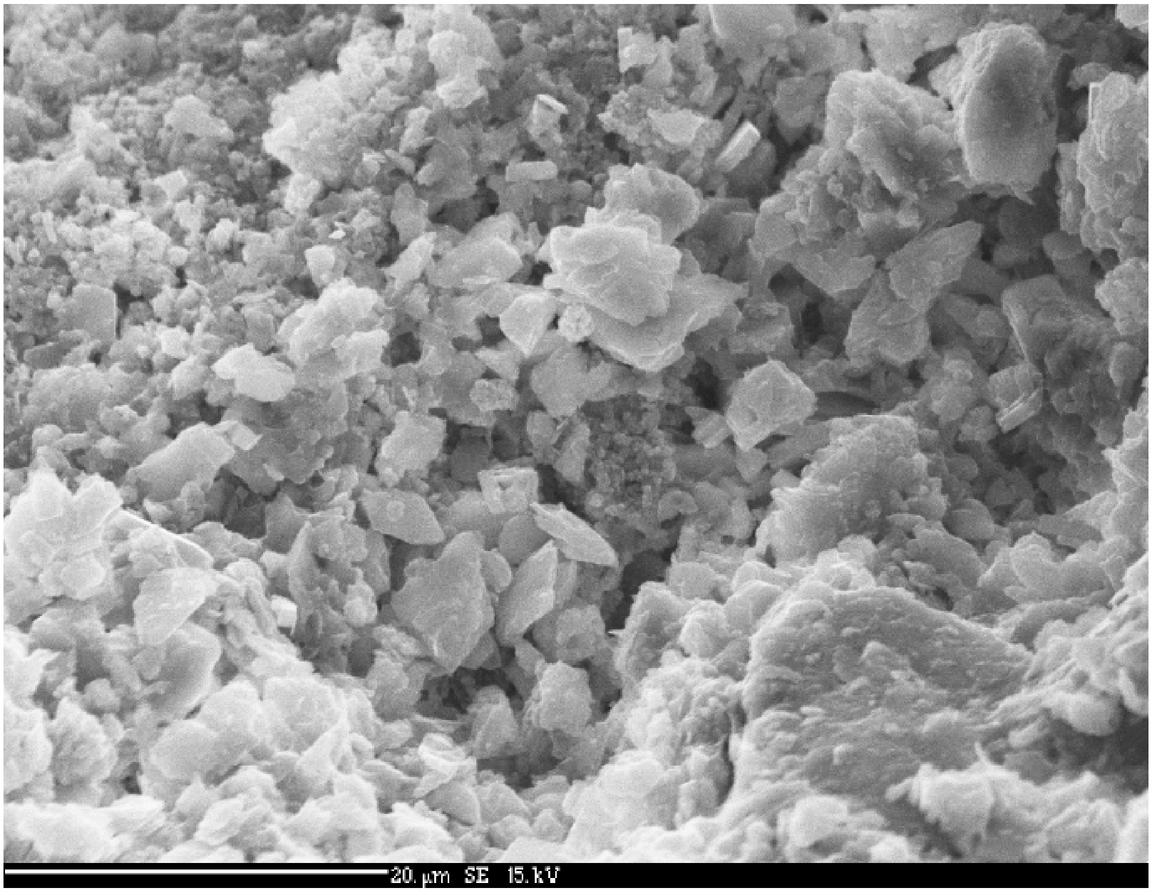

Figure 9. Backscattered electron image of virgin SMZ.

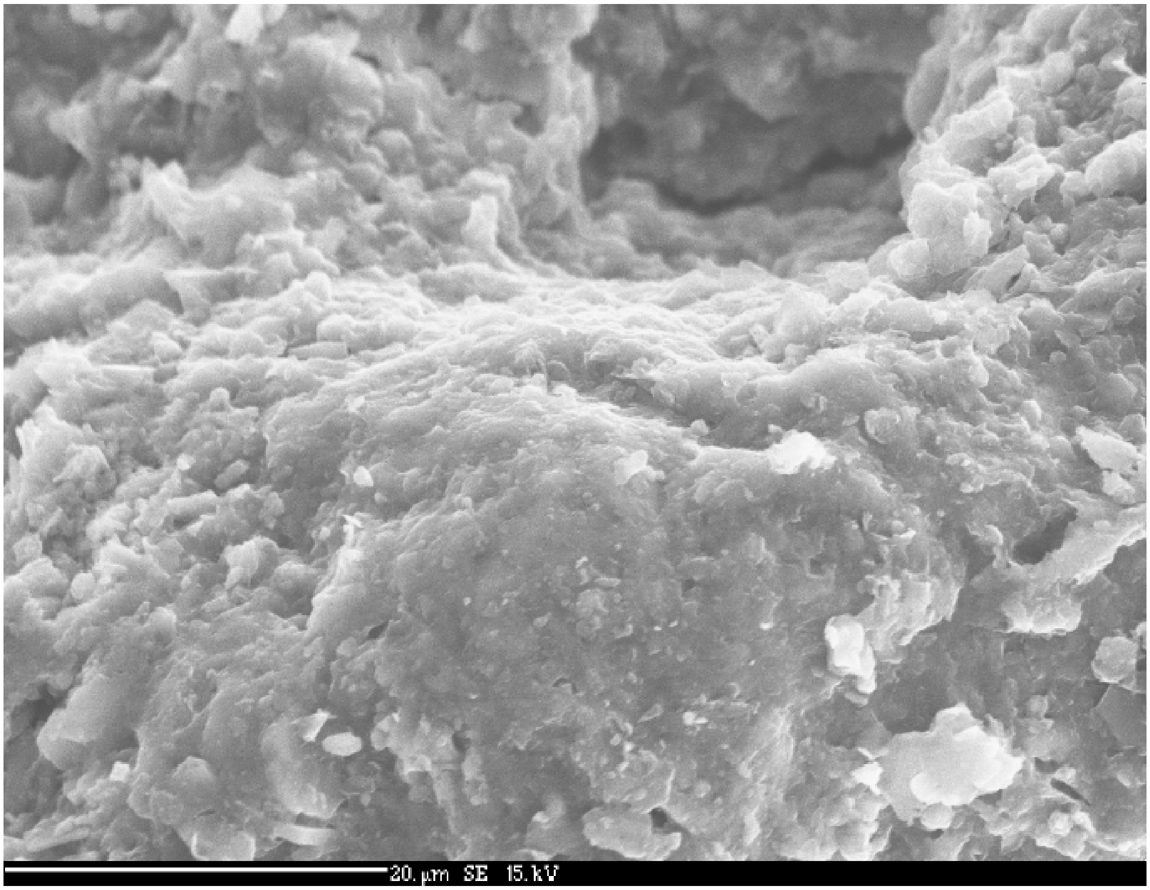

Figure 10. Backscattered electron image of SMZ from column LST1 used for 50 sorption cycles.

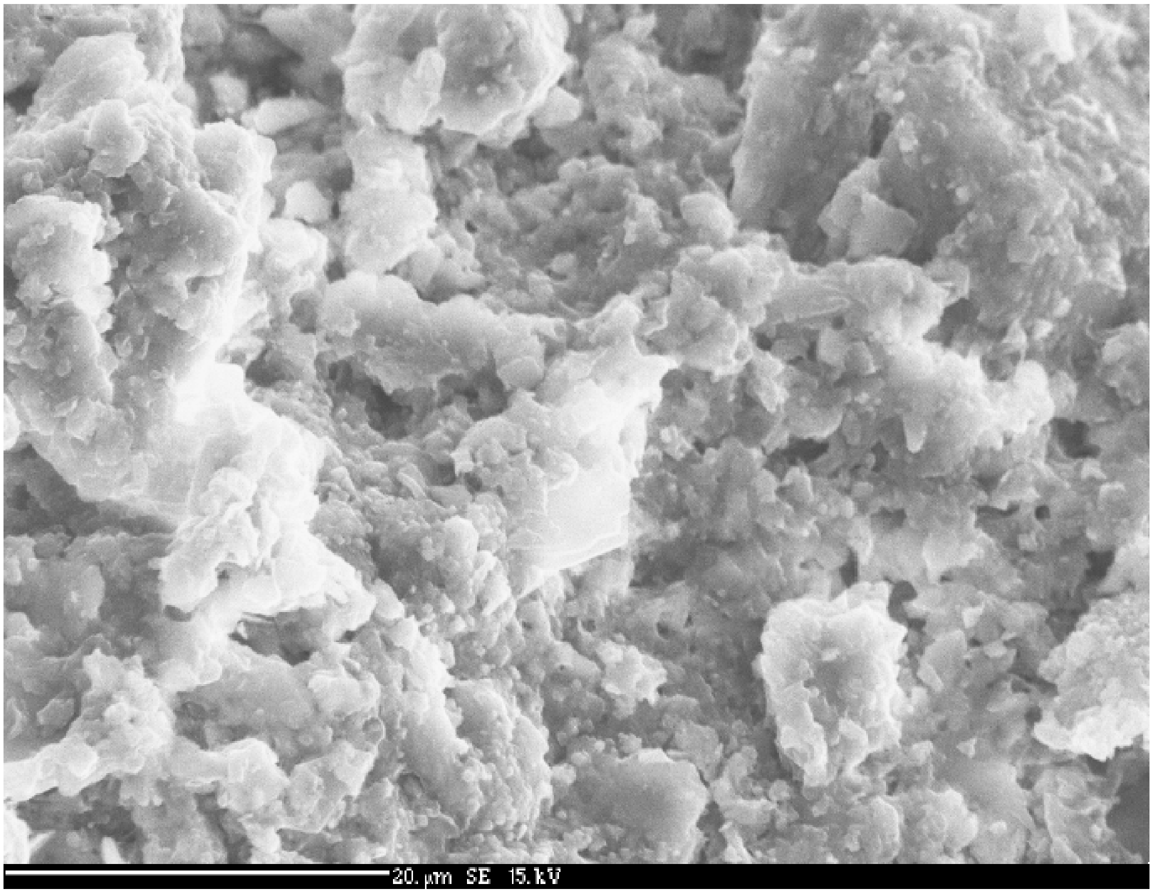

Figure 11. Backscattered electron image of SMZ from column LST2 used for 50 sorption cycles.

APPENDIX A. REGENERATION AIRFLOW RATE SORPTION AND REGENERATION DATA

This appendix contains the breakthrough curves (BTCs) and data for the regeneration rate test (RRT) experiments. Columns RRT1, RRT2, RRT3, RRT4 were all sorbed and regenerated as described in the manuscript. The only difference in the column runs was the airflow rate used during regeneration. Tables A-1 through A-4 contain the BTC data for columns RRT1, RRT2, RRT3, and RRT4, respectively. Tables A-5 through A-8 contain the vapor phase BTEX concentrations and cumulative mass removed for the regeneration of columns RRT1, RRT2, RRT3, and RRT4, respectively. Table A-9 shows the cumulative mass of each BTEX compound sorbed and removed on the RRT columns. Figures A-1 through A-5 show BTEX sorption on virgin SMZ. Figures A-6 through A-10 show BTEX regeneration for each column as a function of both time and PV of air.

Table A- 1. Data for BTEX BTCs from column RRT1

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	3.1	0.001	0.002	0.109	0.010	0.021
2	10.6	0.423	0.003	0.039	0.003	0.006
3	21.7	0.788	0.178	0.023	0.002	0.004
4	41.1	0.877	0.671	0.054	0.016	0.034
5	62.8	0.905	0.814	0.223	0.131	0.213
6	100.4	0.953	0.906	0.627	0.499	0.584
7	135.9	1.005	0.967	0.795	0.688	0.746
8	189.5	0.971	0.937	0.854	0.794	0.800
9	240.3	0.987	0.964	0.902	0.879	0.873
10	328.3	0.964	0.950	0.926	0.950	0.908
11	389.6	0.952	0.942	0.947	0.967	0.926

Table A- 2. Data for BTEX BTCs for column RRT2

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	3.4	0.004	0.015	0.049	0.004	0.009
2	13.1	0.709	0.019	0.028	0.003	0.006
3	23.8	0.886	0.080	0.036	0.006	0.015
4	38.7	0.895	0.350	0.041	0.011	0.025
5	49.9	0.960	0.752	0.062	0.020	0.047
6	65.6	0.931	0.856	0.130	0.066	0.098
7	92.8	0.975	0.879	0.459	0.332	0.410
8	123.6	0.966	0.922	0.719	0.602	0.692
9	153.2	1.011	0.923	0.838	0.735	0.795
10	182.9	0.987	0.966	0.892	0.841	0.856
11	209.6	1.001	0.967	0.899	0.888	0.903
12	261.2	1.017	0.977	0.934	0.928	0.924
13	333.9	1.009	0.977	0.973	0.978	0.963
14	387.2	0.987	0.991	0.976	0.987	0.988

Table A- 3. Data for BTEX BTCs for column RRT3

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	5.9	0.028	0.022	0.118	0.031	0.041
2	20.6	0.751	0.064	0.043	0.010	0.013
3	31.3	0.897	0.451	0.032	0.007	0.011
4	41.7	0.891	0.654	0.038	0.010	0.022
5	57.9	0.887	0.787	0.124	0.062	0.121
6	74.1	0.946	0.885	0.319	0.212	0.316
7	87.1	1.008	0.961	0.482	0.372	0.483
8	110.4	0.994	0.943	0.706	0.634	0.693
9	146.0	0.965	0.932	0.754	0.710	0.748
10	168.0	1.058	1.000	0.852	0.823	0.852
11	207.7	1.008	0.963	0.862	0.836	0.845
12	281.1	1.005	0.989	0.902	0.892	0.901
13	343.6	1.013	1.000	0.913	0.942	0.933
14	391.4	1.004	0.994	0.972	0.998	0.947

Table A- 4. Data for BTEX BTCs for column RRT4

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	4.5	0.004	0.002	0.094	0.012	0.022
2	14.7	0.709	0.013	0.036	0.005	0.009
3	29.0	0.886	0.432	0.000	0.005	0.000
4	47.4	0.895	0.745	0.065	0.018	0.045
5	56.6	0.960	0.850	0.136	0.056	0.121
6	80.0	0.931	0.866	0.389	0.257	0.375
7	108.8	0.975	0.923	0.664	0.555	0.647
8	137.7	0.966	0.928	0.775	0.679	0.736
9	155.7	1.011	0.972	0.851	0.777	0.814
10	182.7	0.987	0.946	0.844	0.777	0.816
11	230.0	1.001	0.969	0.891	0.835	0.844
12	290.4	1.017	0.995	0.926	0.909	0.932
13	372.1	1.009	1.013	1.007	0.986	0.973

Appendix Table A-1. Regeneration data for column RRT1. Airflow rate equals 1.3 PV/min.

		Concentration (mg/L)					Mass Removed (mg)				
Sample	PV	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	9.3	2.102	3.863	0.071	0.784	0.250	0.057	0.105	0.002	0.021	0.007
2	22.6	1.837	4.263	0.084	0.946	0.314	0.134	0.264	0.005	0.055	0.018
3	36.3	2.636	6.634	0.087	1.676	0.605	0.224	0.482	0.008	0.108	0.036
4	63.5	1.610	5.119	0.118	1.261	0.434	0.393	0.951	0.017	0.225	0.078
5	102.5	0.978	3.993	0.090	1.010	0.342	0.541	1.471	0.028	0.354	0.122
6	149.1	0.649	3.752	0.085	0.998	0.337	0.652	2.000	0.040	0.492	0.168
7	279.9	0.216	2.618	0.080	0.927	0.320	0.818	3.220	0.072	0.860	0.294
8	406.7	0.116	1.478	0.071	0.849	0.305	0.880	3.981	0.100	1.190	0.410
9	547.9	0.072	0.790	0.057	0.724	0.279	0.918	4.451	0.126	1.516	0.531
10	614.8	0.053	0.608	0.049	0.672	0.273	0.931	4.588	0.137	1.653	0.585
11	806.6	0.040	0.383	0.034	0.459	0.227	0.957	4.866	0.160	1.970	0.726
12	1034.3	0.032	0.287	0.027	0.299	0.176	0.981	5.090	0.180	2.223	0.860
13	1357.3	0.050	0.210	0.062	0.202	0.143	1.010	5.267	0.212	2.402	0.974
14	1684.4	0.026	0.145	0.040	0.133	0.088	1.047	5.437	0.261	2.563	1.085
15	1987.9	0.007	0.064	0.013	0.069	0.041	1.062	5.530	0.285	2.653	1.142
16	2275.7	0.012	0.080	0.021	0.072	0.044	1.070	5.591	0.299	2.712	1.178
17	2434.3	0.011	0.079	0.023	0.072	0.043	1.075	5.628	0.309	2.746	1.198
18	2592.3	0.007	0.061	0.021	0.066	0.040	1.080	5.660	0.319	2.777	1.217
19	2753.4	0.005	0.050	0.019	0.059	0.035	1.082	5.686	0.329	2.807	1.235
20	2918.9	0.005	0.051	0.018	0.056	0.033	1.085	5.711	0.338	2.835	1.251
21	3078.3	0.004	0.042	0.016	0.051	0.030	1.087	5.733	0.346	2.860	1.266
22	3241.8	0.003	0.035	0.014	0.044	0.026	1.089	5.751	0.353	2.882	1.279
23	3575.0	0.004	0.039	0.016	0.045	0.026	1.093	5.787	0.368	2.926	1.305

Appendix Table A-2. Regeneration data for column RRT2. Airflow rate equals 2.6 PV/min.

		Concentration (mg/L)					Mass Removed (mg)				
Sample	PV	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	9.43	1.315	3.074	0.092	0.606	0.201	0.040	0.095	0.003	0.019	0.006
2	22.36	1.652	4.450	0.113	0.862	0.275	0.103	0.253	0.007	0.050	0.016
3	42.17	1.507	4.744	0.120	0.945	0.307	0.205	0.550	0.015	0.108	0.035
4	69.80	1.268	4.837	0.125	0.991	0.323	0.330	0.981	0.026	0.195	0.063
5	94.73	1.059	4.742	0.123	0.999	0.330	0.424	1.371	0.036	0.276	0.090
6	127.65	0.785	4.518	0.124	0.992	0.326	0.523	1.868	0.049	0.383	0.125
7	173.06	0.440	4.103	0.120	0.966	0.321	0.614	2.506	0.067	0.528	0.173
8	228.61	0.238	3.712	0.117	0.941	0.315	0.675	3.213	0.089	0.700	0.231
9	293.77	0.125	3.074	0.113	0.925	0.314	0.714	3.934	0.113	0.899	0.298
10	392.92	0.065	1.915	0.114	0.908	0.323	0.745	4.740	0.149	1.195	0.401
11	544.98	0.037	0.729	0.099	0.795	0.301	0.770	5.396	0.202	1.617	0.555
12	678.96	0.026	0.396	0.077	0.660	0.279	0.784	5.641	0.241	1.935	0.682
13	858.88	0.020	0.025	0.053	0.451	0.242	0.797	5.765	0.279	2.260	0.835
14	1015.14	0.033	0.392	0.061	0.529	0.227	0.810	5.871	0.308	2.510	0.954
15	1049.78	0.032	0.285	0.068	0.306	0.212	0.814	5.909	0.315	2.557	0.979
16	1169.21	0.030	0.187	0.076	0.244	0.183	0.826	6.001	0.343	2.664	1.056
17	1298.99	0.021	0.131	0.059	0.171	0.134	0.837	6.068	0.372	2.752	1.123
18	1554.45	0.019	0.105	0.053	0.128	0.097	0.848	6.133	0.403	2.835	1.186
19	1649.34	0.014	0.087	0.046	0.108	0.080	0.853	6.161	0.417	2.869	1.212
20	1718.39	0.008	0.055	0.027	0.074	0.056	0.855	6.177	0.425	2.889	1.227
21	1928.46	0.013	0.081	0.045	0.085	0.062	0.862	6.220	0.448	2.940	1.265
22	2177.45	0.012	0.073	0.039	0.076	0.050	0.871	6.279	0.480	3.002	1.308
23	2332.60	0.008	0.036	0.018	0.041	0.026	0.876	6.305	0.494	3.030	1.326
24	2545.54	0.007	0.041	0.022	0.045	0.027	0.881	6.331	0.508	3.058	1.344
25	2754.17	0.011	0.059	0.032	0.058	0.034	0.886	6.363	0.525	3.091	1.363
26	3044.00	0.006	0.030	0.016	0.032	0.018	0.894	6.403	0.547	3.131	1.386

Appendix Table A-3. Regeneration data for column RRT3. Airflow rate equals 5.0 PV/min.

		Concentration (mg/L)					Mass Removed (mg)				
Sample	PV	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	12.04	1.340	2.890	0.082	0.848	0.271	0.053	0.113	0.003	0.033	0.011
2	32.94	1.256	2.979	0.082	0.910	0.363	0.141	0.313	0.009	0.093	0.032
3	48.34	1.083	2.947	0.082	0.090	0.281	0.200	0.462	0.013	0.118	0.048
4	68.19	0.811	2.383	0.076	0.765	0.253	0.261	0.635	0.018	0.146	0.066
5	96.08	0.619	1.977	0.067	0.665	0.222	0.326	0.833	0.025	0.211	0.087
6	137.30	0.541	1.976	0.084	0.668	0.258	0.404	1.098	0.035	0.301	0.120
7	166.22	0.382	1.722	0.059	0.590	0.196	0.447	1.273	0.041	0.360	0.141
8	225.74	0.238	1.654	0.062	0.591	0.198	0.508	1.600	0.053	0.474	0.179
9	403.47	0.214	1.623	0.061	0.566	0.188	0.638	2.550	0.089	0.810	0.291
10	519.60	0.101	1.228	0.046	0.527	0.171	0.698	3.089	0.109	1.017	0.359
11	745.97	0.053	0.553	0.050	0.468	0.164	0.755	3.746	0.144	1.384	0.483
12	932.88	0.034	0.291	0.038	0.347	0.135	0.781	4.004	0.171	1.632	0.574
13	1167.84	0.042	0.331	0.039	0.355	0.149	0.810	4.242	0.201	1.901	0.683
14	1557.91	0.050	0.235	0.042	0.300	0.136	0.869	4.602	0.252	2.317	0.864
15	1858.78	0.059	0.164	0.042	0.191	0.122	0.922	4.798	0.292	2.558	0.991
16	2091.54	0.025	0.110	0.042	0.126	0.074	0.954	4.902	0.324	2.678	1.065
17	2355.14	0.025	0.077	0.025	0.087	0.049	0.975	4.982	0.353	2.769	1.118
18	2750.59	0.025	0.160	0.047	0.118	0.067	1.007	5.135	0.400	2.901	1.193
19	3040.84	0.021	0.084	0.036	0.102	0.056	1.029	5.251	0.439	3.005	1.251
20	3084.90	0.013	0.057	0.024	0.074	0.037	1.032	5.261	0.444	3.017	1.258
21	3377.90	0.008	0.038	0.013	0.049	0.024	1.042	5.306	0.461	3.076	1.287
22	3684.15	0.010	0.052	0.023	0.066	0.034	1.050	5.351	0.479	3.133	1.316

Appendix Table A-4. Regeneration data for column RRT4. Airflow rate equals 10 PV/min.

		Concentration (mg/L)					Mass Removed (mg)				
Sample	PV	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	6.68	1.359	3.396	0.245	0.860	0.307	0.029	0.072	0.005	0.018	0.006
2	25.25	1.051	3.434	0.139	0.892	0.269	0.100	0.273	0.016	0.070	0.023
3	49.31	0.824	3.227	0.141	0.876	0.264	0.171	0.527	0.027	0.137	0.044
4	78.25	0.626	2.974	0.126	0.864	0.259	0.238	0.811	0.039	0.217	0.068
5	270.08	0.377	2.088	0.099	0.694	0.215	0.543	2.350	0.108	0.691	0.212
6	378.01	0.132	1.799	0.090	0.601	0.224	0.630	3.015	0.140	0.912	0.287
7	700.82	0.044	0.545	0.076	0.508	0.170	0.720	4.214	0.225	1.479	0.488
8	961.84	0.038	0.393	0.050	0.587	0.271	0.754	4.603	0.277	1.932	0.671
9	1310.62	0.014	0.125	0.025	0.193	0.111	0.783	4.889	0.319	2.363	0.882
10	2073.48	0.014	0.093	0.028	0.094	0.047	0.816	5.153	0.382	2.710	1.073
11	2660.01	0.007	0.066	0.023	0.068	0.033	0.835	5.301	0.429	2.861	1.147
12	3225.73	0.007	0.051	0.019	0.053	0.025	0.848	5.406	0.467	2.970	1.198

Appendix Table A-9. Total mass sorbed, removed, and the residual for columns RRT 1-4.

		Mass (mg)					Mean % recovery (std. dev.)
		Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	
RRT1	sorption	1.12	5.68	0.43	2.90	1.35	
	regeneration	1.09	5.79	0.37	2.93	1.30	
	recovery (%)	98	102	86	101	96	97 (6.2)
RRT2	sorption	0.64	5.96	0.47	2.89	1.31	
	regeneration	0.89	6.40	0.55	3.13	1.39	
	recovery (%)	140	107	115	108	106	115 (14.2)
RRT3	sorption	0.78	4.66	0.46	2.59	1.17	
	regeneration	1.05	5.35	0.48	3.13	1.32	
	recovery (%)	135	115	105	121	113	118 (11.2)
RRT4	sorption	0.78	5.19	0.44	2.83	1.16	
	regeneration	0.85	5.41	0.47	2.97	1.20	
	recovery (%)	109	104	105	105	104	105 (2.2)
	Mean % recovery (std. dev.)	120 (20.2)	107 (5.7)	103 (12.1)	109 (8.6)	105 (6.8)	

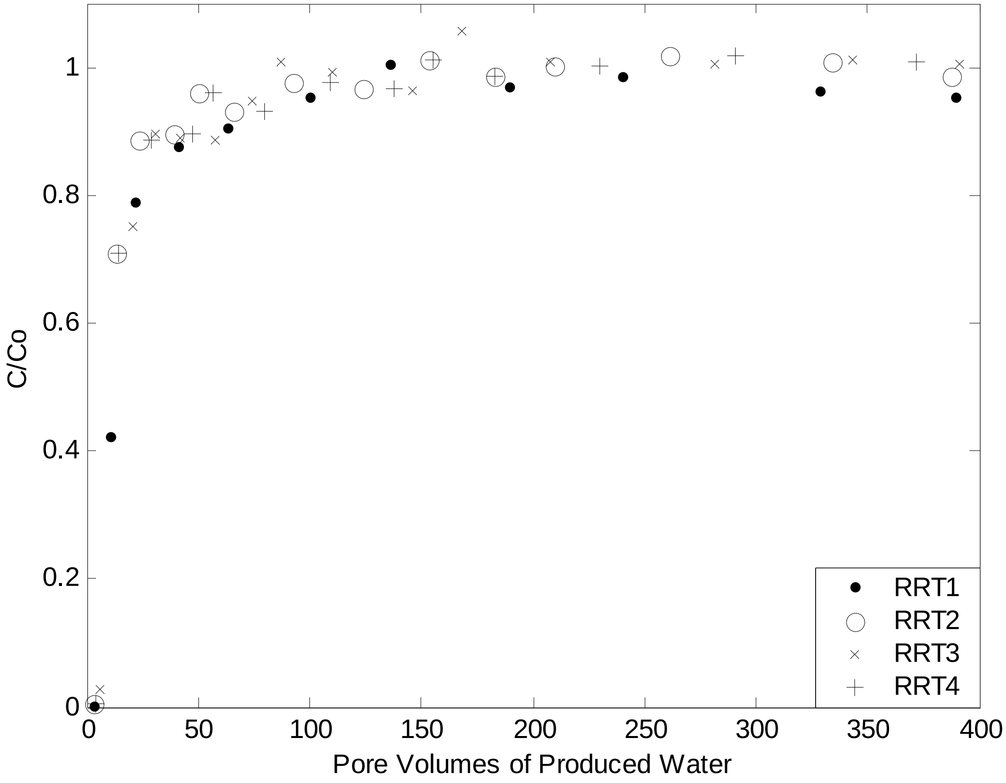

Figure A- 1. Benzene sorption on virgin SMZ for four replicate columns.

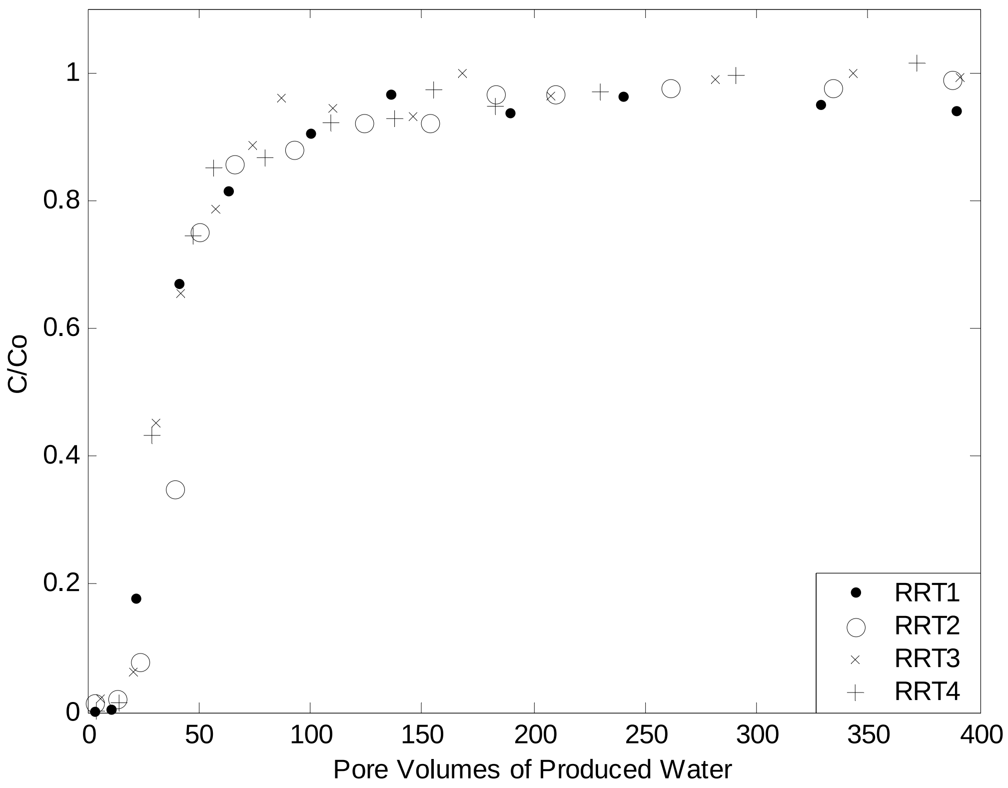

Figure A- 2. Toluene sorption on virgin SMZ for four replicate columns.

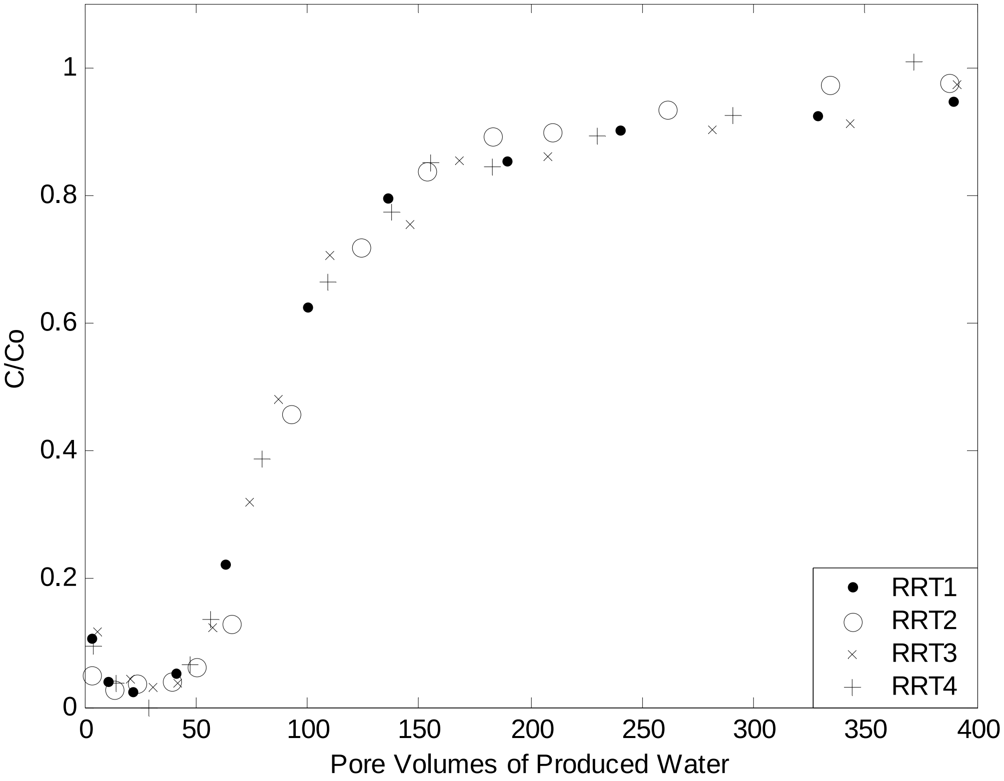

Figure A- 3. Ethylbenzene sorption on virgin SMZ for four replicate columns.

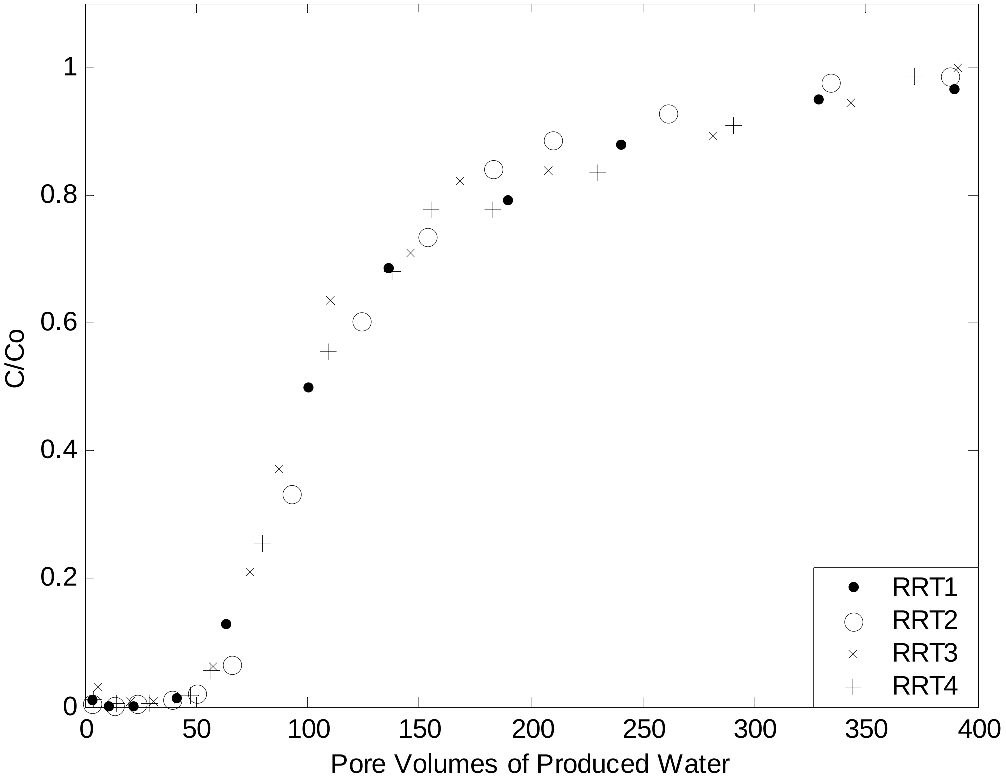

Figure A- 4. *p*- and *m*-xylene sorption on virgin SMZ for four replicate columns.

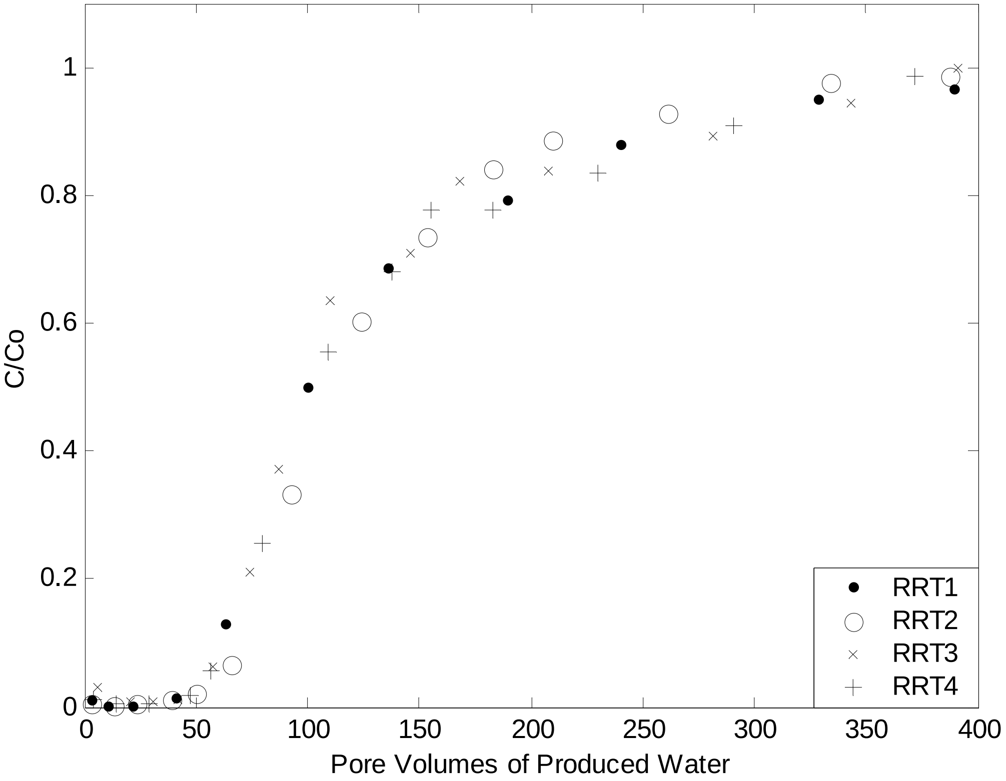

Figure A- 5. *o*-xylene sorption on virgin SMZ for four replicate columns.

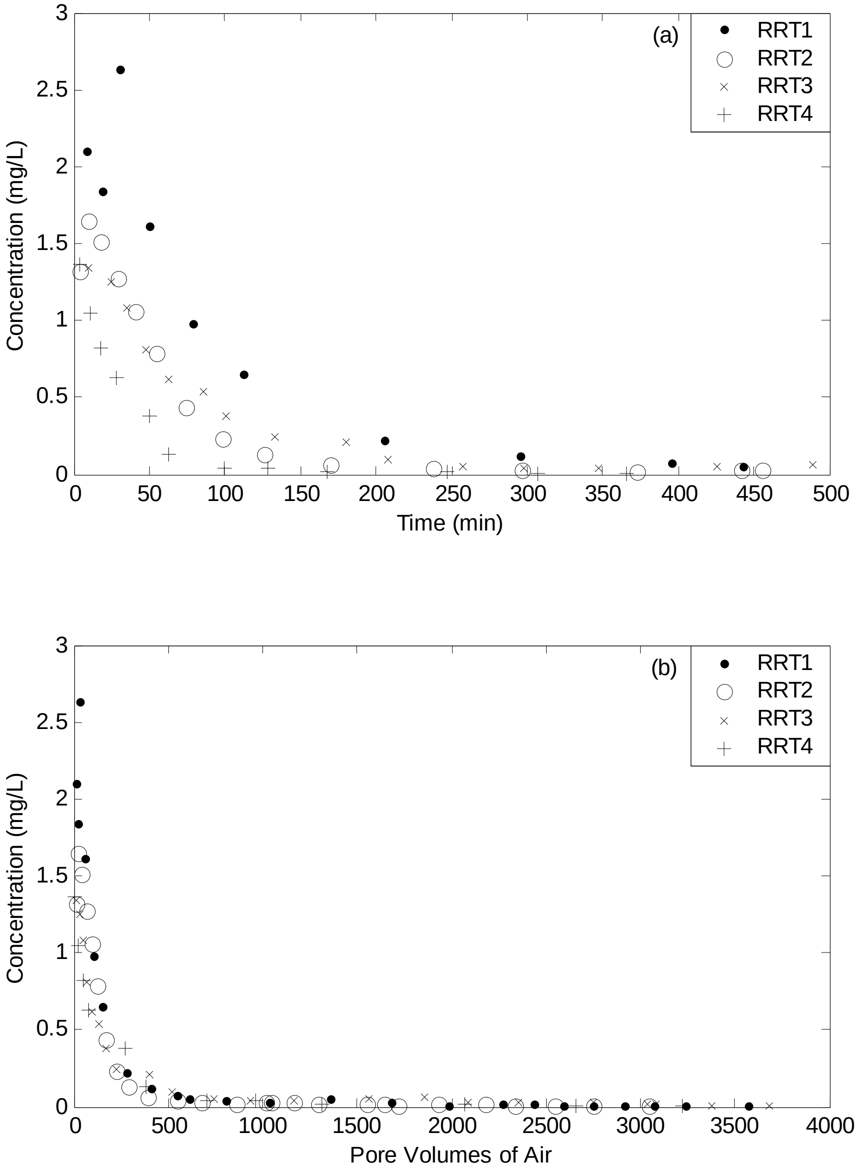

Figure A- 6. Benzene regeneration at four different airflow rates as a function of (a) time and (b) PV of air. Columns RRT1, RRT2, RRT3, and RRT4 used flow rates of 1.3 PV/min, 2.7 PV/min, 5 PV/min, and 10 PV/min, respectively.

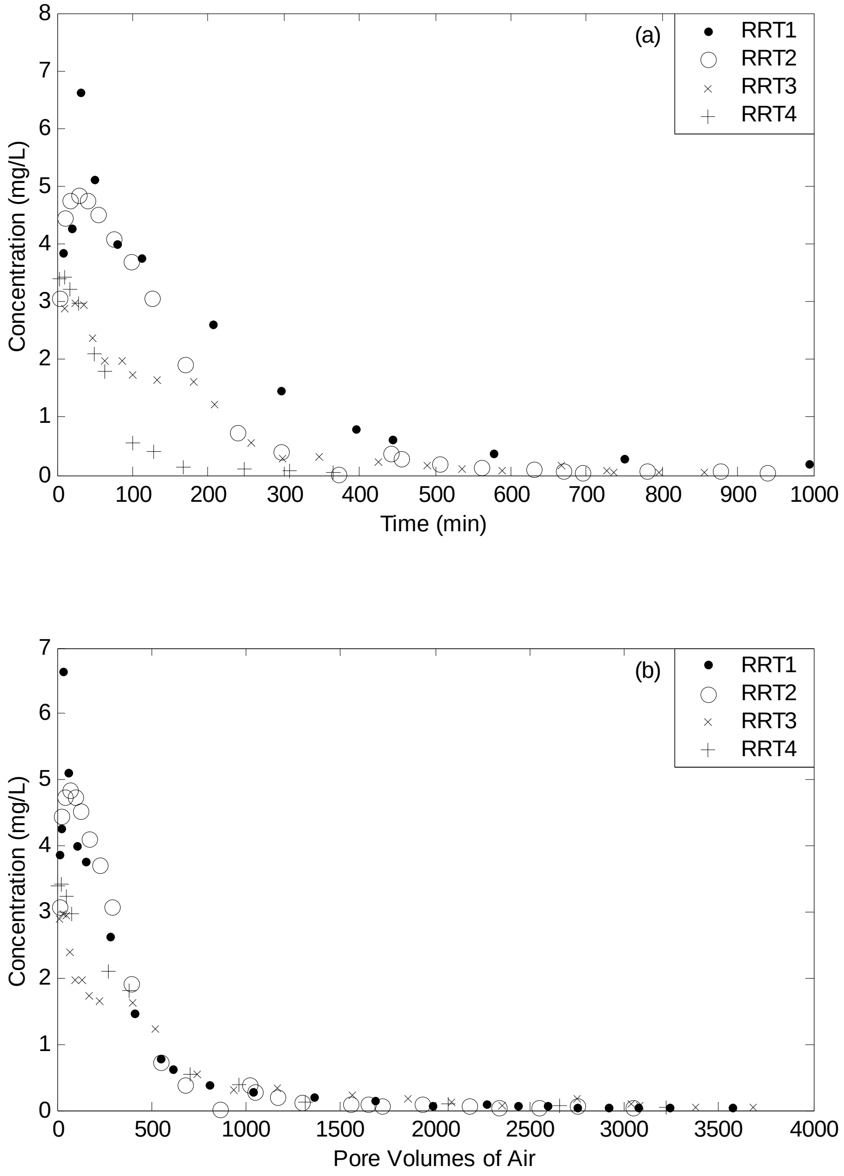

Figure A- 7. Toluene regeneration at four different airflow rates as a function of (a) time and (b) PV of air. Columns RRT1, RRT2, RRT3, and RRT4 used flow rates of 1.3 PV/min, 2.7 PV/min, 5 PV/min, and 10 PV/min, respectively.

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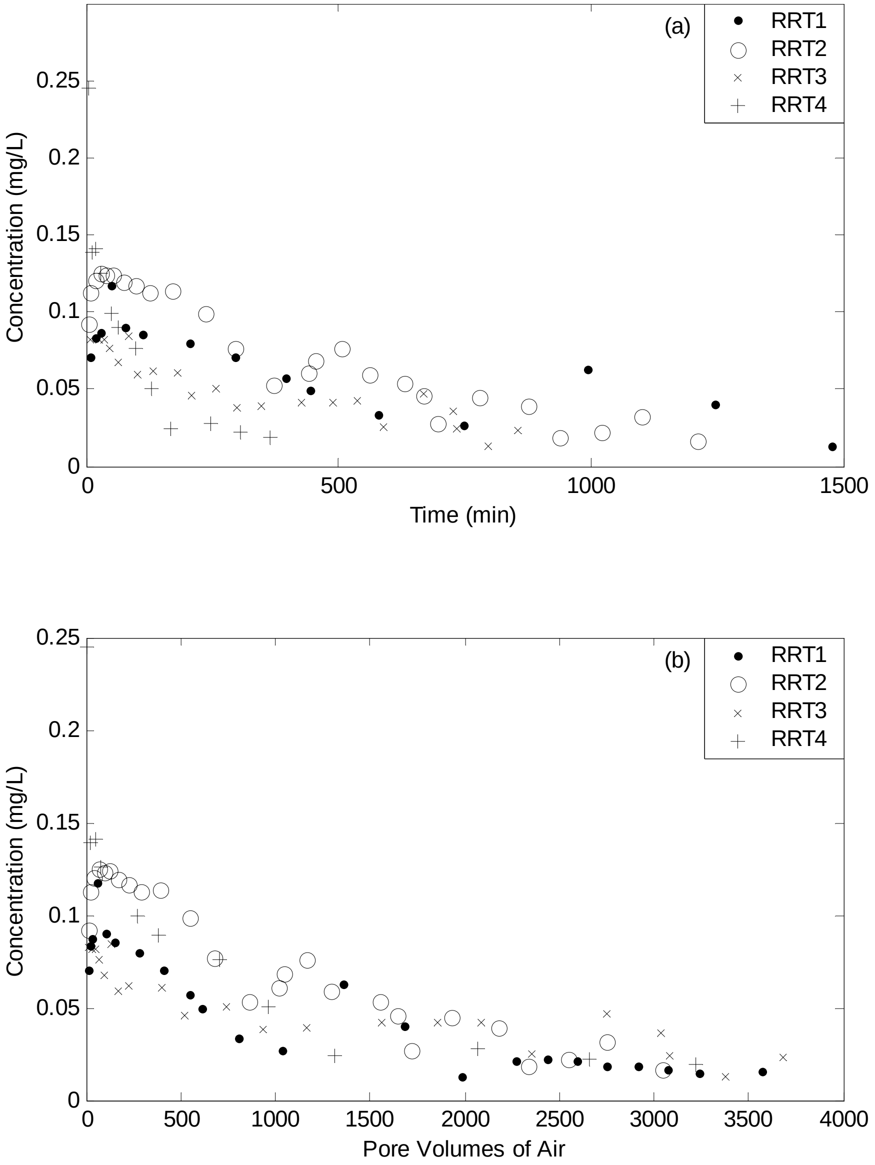

Figure A- 8. Ethylbenzene regeneration at four different airflow rates as a function of (a) time and (b) PV of air. Columns RRT1, RRT2, RRT3, and RRT4 used flow rates of 1.3 PV/min, 2.7 PV/min, 5 PV/min, and 10 PV/min, respectively.

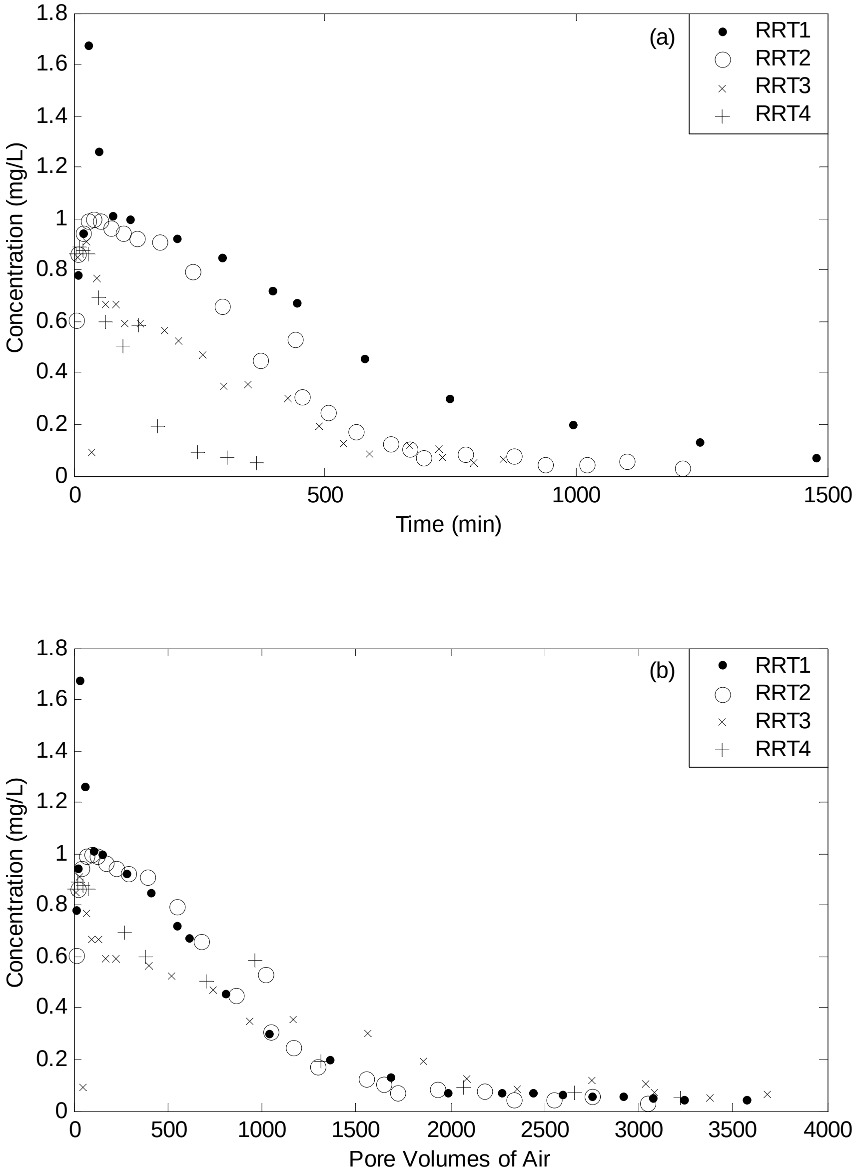

Figure A- 9. *p*- and *m*-xylene regeneration at four different airflow rates as a function of (a) time and (b) PV of air. Columns RRT1, RRT2, RRT3, and RRT4 used flow rates of 1.3 PV/min, 2.7 PV/min, 5 PV/min, and 10 PV/min, respectively.

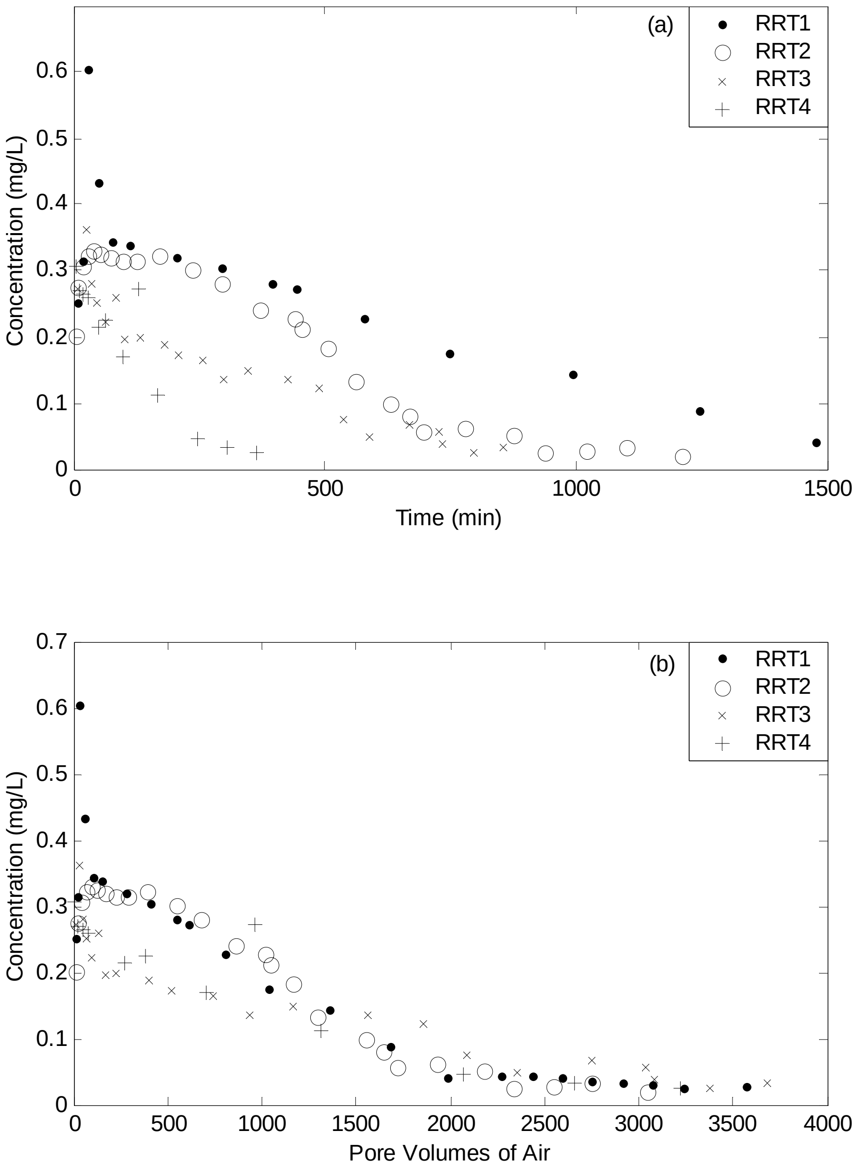

Figure A- 10. ***o*****-xylene regeneration at four different airflow rates as a function of (a) time and (b) PV of air. Columns RRT1, RRT2, RRT3, and RRT4 used flow rates of 1.3 PV/min, 2.7 PV/min, 5 PV/min, and 10 PV/min, respectively.**

APPENDIX B. TRITIUM TRACER TEST RESULTS FOR THE LONG-TERM STABILITY TESTS

This appendix contains information on the tritium tracer tests conducted on the LST columns. Appendix Tables B-1 and B-2 give the observed and fitted data for the tritium tests, presented as normalized concentration (C/C_0) as a function of PV of tritiated water. The fitted data used the equilibrium model from CXTFIT2.1. Figures B-1a through B-1c show observed and fitted tritium BTCs on column LST2 for the virgin column, after the 25th regeneration cycle, and after the 50th regeneration cycle, respectively. Figure 4 in the manuscript shows similar data for column LST1.

Table B- 1. Observed and fitted values for C/C_0 for tritium tracer tests conducted on column LST1

		Virgin SMZ		After 25th cycle		After 50th cycle	
Sample	Pore Volumes	Obs C/Co	Fit C/Co	Obs C/Co	Fit C/Co	Obs C/Co	Fit C/Co
1	0.069	0.001	0.000	0.001	0.000	0.001	0.000
2	0.205	0.002	0.003	0.002	0.012	0.001	0.002
3	0.342	0.007	0.045	0.021	0.085	0.013	0.032
4	0.479	0.090	0.147	0.110	0.199	0.089	0.117
5	0.616	0.230	0.276	0.220	0.318	0.204	0.234
6	0.753	0.359	0.404	0.350	0.427	0.335	0.357
7	0.890	0.475	0.519	0.474	0.520	0.460	0.471
8	1.027	0.594	0.616	0.621	0.599	0.537	0.570
9	1.164	0.684	0.695	0.724	0.664	0.621	0.653
10	1.301	0.779	0.759	0.781	0.719	0.686	0.722
11	1.438	0.850	0.809	0.860	0.764	0.739	0.777
12	1.575	0.857	0.850	0.933	0.801	0.801	0.822
13	1.712	0.924	0.881	0.942	0.832	0.851	0.857
14	1.849	0.915	0.906	0.929	0.858	0.913	0.886
15	1.986	0.963	0.926	0.934	0.880	0.969	0.909
16	2.123	0.999	0.941	0.942	0.898	0.949	0.927
17	2.260	0.994	0.953	0.961	0.913	0.999	0.941
18	2.396	0.970	0.963	0.950	0.926	0.915	0.937
19	2.533	0.992	0.964	0.913	0.937	0.869	0.879
20	2.670	0.879	0.915	0.864	0.941	0.757	0.777
21	2.807	0.743	0.810	0.766	0.893	0.653	0.660
22	2.944	0.619	0.683	0.640	0.792	0.486	0.546
23	3.081	0.535	0.559	0.599	0.678	0.397	0.446
24	3.218	0.446	0.450	0.549	0.570	0.350	0.360
25	3.355	0.351	0.359	0.495	0.477	0.293	0.290
26	3.492	0.286	0.285	0.429	0.398	0.212	0.232
27	3.629	0.215	0.225	0.386	0.332	0.167	0.186
28	3.766	0.172	0.178	0.335	0.278	0.138	0.148
29	3.903	0.115	0.140	0.301	0.233	0.108	0.119
30	4.040	0.142	0.111	0.258	0.196	0.089	0.095
31	4.177	0.107	0.088	0.189	0.165	0.075	0.076
32	4.314	0.094	0.069	0.163	0.139	0.059	0.061
33	4.451	0.077	0.055	0.150	0.118	0.052	0.049
34	4.588	0.070	0.043	0.131	0.100	0.043	0.039
35	4.724	0.061	0.034	0.120	0.085	0.034	0.031
36	4.861	0.052	0.027	0.093	0.072	0.032	0.025
37	4.998	0.045	0.022	0.087	0.061	0.028	0.020
38	5.135	0.042	0.017	0.077	0.053	0.023	0.016
39	5.272	0.035	0.014	0.061	0.045	0.019	0.013
40	5.409	0.035	0.011	0.039	0.039	0.018	0.011
41	5.546	0.032	0.009	0.033	0.033	0.014	0.009
42	5.683	0.024	0.007	0.028	0.028	0.012	0.007
43	5.820	0.020	0.006	0.017	0.024	0.012	0.006
44	5.957	0.016	0.005	0.013	0.021	0.010	0.005
45	6.094	0.015	0.004	0.010	0.018	0.008	0.004
46	6.231	0.014	0.003	0.009	0.016	0.009	0.003
47	6.368	0.016	0.002	0.008	0.014	0.007	0.002
48	6.505	0.012	0.002	0.007	0.012	0.005	0.002
49	6.642	0.013	0.002	0.007	0.010	0.004	0.002
50	6.779	0.011	0.001	0.006	0.009	0.004	0.001

Table B- 2. Observed and fitted values for C/C_0 for tritium tracer tests conducted on column LT2

		Virgin SMZ		After 25th cycle		After 50th cycle	
Sample	Pore Volumes	Obs C/Co	Fit C/Co	Obs C/Co	Fit C/Co	Obs C/Co	Fit C/Co
1	0.069	0.002	0.000	0.002	0.000	0.001	0.000
2	0.205	0.002	0.000	0.002	0.001	0.001	0.002
3	0.342	0.006	0.004	0.008	0.019	0.004	0.037
4	0.479	0.030	0.037	0.053	0.085	0.056	0.131
5	0.616	0.103	0.119	0.149	0.190	0.155	0.257
6	0.753	0.158	0.237	0.259	0.309	0.272	0.387
7	0.890	0.298	0.368	0.386	0.426	0.420	0.505
8	1.027	0.461	0.494	0.494	0.531	0.518	0.606
9	1.164	0.565	0.605	0.600	0.621	0.636	0.688
10	1.301	0.686	0.697	0.694	0.696	0.727	0.754
11	1.438	0.788	0.770	0.778	0.757	0.816	0.807
12	1.575	0.850	0.828	0.811	0.806	0.876	0.849
13	1.712	0.905	0.872	0.855	0.846	0.937	0.882
14	1.849	0.969	0.905	0.898	0.878	0.997	0.907
15	1.986	0.975	0.930	0.924	0.903	1.004	0.927
16	2.123	0.941	0.948	0.961	0.923	1.007	0.943
17	2.260	0.958	0.962	0.957	0.935	0.975	0.955
18	2.396	0.902	0.960	0.910	0.912	0.944	0.963
19	2.533	0.904	0.916	0.792	0.838	0.879	0.940
20	2.670	0.789	0.823	0.700	0.733	0.753	0.855
21	2.807	0.663	0.701	0.581	0.619	0.628	0.734
22	2.944	0.526	0.573	0.486	0.511	0.528	0.607
23	3.081	0.398	0.454	0.383	0.416	0.404	0.491
24	3.218	0.329	0.352	0.317	0.335	0.342	0.392
25	3.355	0.245	0.269	0.257	0.269	0.279	0.310
26	3.492	0.203	0.203	0.209	0.214	0.226	0.244
27	3.629	0.162	0.152	0.172	0.171	0.179	0.192
28	3.766	0.128	0.113	0.138	0.136	0.146	0.150
29	3.903	0.096	0.084	0.111	0.108	0.118	0.118
30	4.040	0.083	0.062	0.088	0.086	0.089	0.092
31	4.177	0.072	0.045	0.081	0.068	0.075	0.072
32	4.314	0.056	0.033	0.061	0.054	0.064	0.057
33	4.451	0.046	0.024	0.053	0.043	0.053	0.045
34	4.588	0.038	0.018	0.047	0.034	0.048	0.035
35	4.724	0.033	0.013	0.035	0.027	0.036	0.028
36	4.861	0.028	0.010	0.031	0.022	0.028	0.022
37	4.998	0.024	0.007	0.027	0.017	0.026	0.017
38	5.135	0.019	0.005	0.024	0.014	0.023	0.014
39	5.272	0.015	0.004	0.021	0.011	0.019	0.011
40	5.409	0.013	0.003	0.020	0.009	0.015	0.008
41	5.546	0.011	0.002	0.016	0.007	0.013	0.007
42	5.683	0.010	0.001	0.015	0.006	0.011	0.005
43	5.820	0.010	0.001	0.014	0.004	0.009	0.004
44	5.957	0.007	0.001	0.011	0.004	0.009	0.003
45	6.094	0.007	0.001	0.009	0.003	0.005	0.003
46	6.231	0.006	0.000	0.009	0.002	0.005	0.002
47	6.368	0.005	0.000	0.007	0.002	0.005	0.002
48	6.505	0.004	0.000	0.007	0.002	0.004	0.001
49	6.642	0.004	0.000	0.005	0.001	0.004	0.001
50	6.779	0.004	0.000	0.005	0.001	0.005	0.001

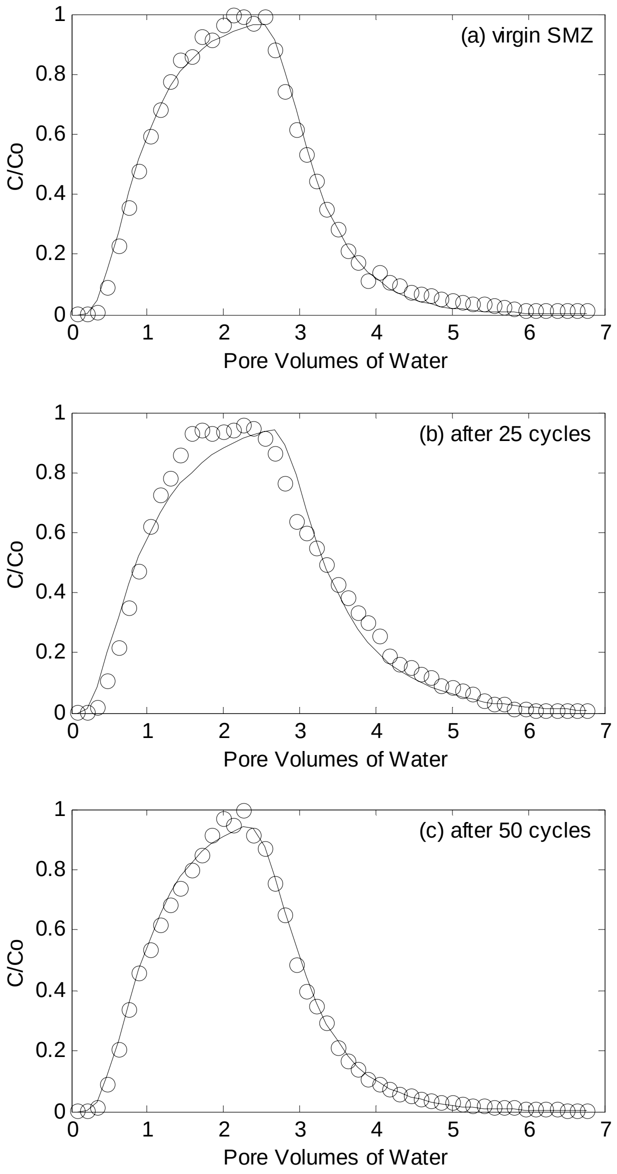

Figure B- 1. BTCs of tritiated water in column LST1 for (a) virgin SMZ and (b) after the 25th regeneration cycle and (c) after the 50th regeneration cycle. Solid lines represent fitted values using an equilibrium advection-dispersion equation.

APPENDIX C. LONG-TERM STABILITY TEST SORPTION AND REGENERATION RESULTS

Appendix C presents laboratory data for the LTS experiments. Tables C-1 through C-11 contain relative BTEX concentrations (C/C_0) as a function of PV of produced water for all of the analyzed sorption cycles on column LST1. Tables C-12 through C-22 contain off-gas BTEX concentrations and total mass removed for each of the analyzed regeneration cycles on column LST1. Likewise, Tables C-23 through C-33 contain BTEX sorption data for column LST2 and Tables C-34 through C-44 contain BTEX regeneration data for column LST2. Tables C-45 and C-46 show the total mass of BTEX sorbed and removed during each analyzed cycle on columns LST1 and LST2, respectively. Table C-47 gives K_d values caluculated from fitted the R of each compound. Observed trends in K_d's are discussed within the manuscript.

Figures C-1 through C-3 show BTCs for toluene, ethylbenzene, and *o*-xylene for every analyzed cycle of the LST experiments. Figures C-4 through C-8 show regeneration curves for each BTEX compound for column LST1. Figures C-9 through C-13 show BTEX BTCs for column LST2. Figures C-14 through C-18 show curves for each BTEX compound for column LST2. Figures C-19 through C-28 show the Kd values calculated for each compound from each measured cycles and linear regressions fit to these values.

Table C- 1. Data for BTEX BTCs from the 1st sorption cycle on column LST1

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	2.1	0.055	0.000	0.000	0.000	0.000
2	6.2	0.441	0.101	0.000	0.000	0.000
3	11.5	0.543	0.201	0.000	0.046	0.000
4	16.7	0.737	0.314	0.119	0.081	0.160
5	21.8	0.738	0.390	0.161	0.105	0.175
6	28.3	0.901	0.508	0.249	0.170	0.228
7	36.6	0.838	0.572	0.277	0.217	0.275
8	46.0	0.842	0.641	0.353	0.268	0.321
9	61.6	0.964	0.780	0.415	0.386	0.455
10	87.5	0.887	0.774	0.561	0.455	0.527
11	101.1	0.902	0.788	0.599	0.558	0.563

Table C- 2. Data for BTEX BTCs from the 5th sorption cycle on column LST1

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	2.9	0.108	0.000	0.000	0.000	0.000
2	8.0	0.519	0.089	0.000	0.000	0.000
3	12.9	0.543	0.192	0.087	0.053	0.117
4	19.4	0.696	0.314	0.159	0.110	0.192
5	26.1	0.685	0.435	0.177	0.097	0.191
6	30.9	0.831	0.535	0.287	0.164	0.216
7	37.6	0.897	0.619	0.303	0.235	0.313
8	49.5	0.862	0.677	0.377	0.298	0.382
9	61.6	0.930	0.755	0.441	0.377	0.487
10	88.5	0.966	0.807	0.520	0.527	0.561
11	99.6	0.952	0.893	0.551	0.592	0.585

Table C- 3. Data for BTEX BTCs from the 10th sorption cycle on column LST1

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	4.6	0.106	0.025	0.000	0.000	0.000
2	9.6	0.503	0.089	0.085	0.036	0.071
3	23.1	0.728	0.346	0.188	0.064	0.154
4	29.8	0.813	0.493	0.303	0.129	0.214
5	36.7	0.807	0.592	0.240	0.180	0.269
6	45.0	0.851	0.634	0.353	0.241	0.341
7	53.4	0.878	0.728	0.414	0.312	0.377
8	59.6	0.865	0.830	0.487	0.368	0.464
9	87.8	0.941	0.828	0.541	0.515	0.543
10	96.6	0.926	0.897	0.579	0.686	0.607

Table C- 4. Data for BTEX BTCs from the 15th sorption cycle on column LST1

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	3.8	0.101	0.000	0.000	0.000	0.000
2	7.2	0.354	0.063	0.000	0.000	0.000
3	13.0	0.512	0.143	0.000	0.032	0.088
4	17.2	0.568	0.258	0.126	0.048	0.154
5	25.9	0.674	0.370	0.185	0.099	0.182
6	35.3	0.863	0.481	0.221	0.115	0.302
7	44.6	0.857	0.603	0.265	0.217	0.306
8	52.9	0.911	0.670	0.380	0.238	0.378
9	61.8	0.916	0.725	0.443	0.375	0.386
10	66.1	0.989	0.747	0.464	0.447	0.501
11	82.9	0.978	0.768	0.508	0.446	0.521
12	93.5	0.951	0.811	0.555	0.515	0.546

Table C- 5. Data for BTEX BTCs from the 20th sorption cycle on column LST1

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	5.5	0.072	0.000	0.000	0.000	0.000
2	10.9	0.505	0.072	0.000	0.053	0.100
3	17.4	0.561	0.221	0.145	0.052	0.149
4	23.0	0.686	0.339	0.189	0.089	0.188
5	29.4	0.756	0.425	0.231	0.161	0.228
6	37.7	0.772	0.556	0.276	0.185	0.267
7	46.4	0.841	0.668	0.353	0.242	0.332
8	57.9	0.952	0.736	0.389	0.329	0.398
9	63.3	1.014	0.772	0.412	0.391	0.474
10	70.9	0.998	0.854	0.480	0.462	0.519
11	81.4	0.913	0.802	0.548	0.500	0.541
12	91.1	0.972	0.856	0.584	0.496	0.540
13	97.9	0.953	0.867	0.619	0.519	0.550

Table C- 6. Data for BTEX BTCs from the 25th sorption cycle on column LST1

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	3.4	0.044	0.012	0.000	0.000	0.000
2	8.5	0.264	0.022	0.000	0.023	0.076
3	15.5	0.458	0.139	0.119	0.030	0.090
4	24.3	0.633	0.307	0.127	0.048	0.144
5	31.6	0.706	0.398	0.164	0.073	0.170
6	40.8	0.780	0.493	0.245	0.148	0.227
7	51.0	0.833	0.594	0.319	0.260	0.292
8	69.1	0.855	0.724	0.388	0.327	0.409
9	92.2	0.918	0.816	0.480	0.498	0.468
10	104.2	0.978	0.879	0.520	0.560	0.539

Table C- 7. Data for BTEX BTCs from the 30th sorption cycle on column LST1

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	4.8	0.072	0.047	0.000	0.000	0.000
2	9.6	0.384	0.065	0.099	0.021	0.000
3	16.9	0.668	0.263	0.124	0.061	0.136
4	22.7	0.697	0.305	0.206	0.076	0.176
5	29.3	0.821	0.447	0.262	0.150	0.217
6	36.5	0.840	0.555	0.274	0.236	0.289
7	44.3	0.902	0.575	0.343	0.255	0.342
8	52.7	0.912	0.659	0.392	0.356	0.388
9	60.3	0.889	0.695	0.371	0.413	0.425
10	73.1	0.932	0.755	0.448	0.481	0.513
11	86.3	1.014	0.802	0.503	0.515	0.590
12	96.5	0.978	0.866	0.544	0.572	0.613

Table C- 8. Data for BTEX BTCs from the 35th sorption cycle on column LST1

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	5.3	0.061	0.056	0.088	0.000	0.000
2	10.5	0.423	0.173	0.104	0.000	0.082
3	16.0	0.588	0.257	0.144	0.046	0.154
4	23.5	0.774	0.408	0.196	0.099	0.222
5	30.1	0.805	0.486	0.231	0.165	0.267
6	35.1	0.858	0.560	0.254	0.251	0.291
7	45.1	0.962	0.654	0.314	0.283	0.316
8	54.3	0.997	0.735	0.415	0.347	0.399
9	60.0	1.042	0.782	0.462	0.402	0.473
10	68.6	0.989	0.858	0.469	0.429	0.535
11	78.2	0.997	0.841	0.483	0.458	0.623
12	86.2	1.023	0.879	0.568	0.512	0.630
13	97.9	1.059	0.876	0.548	0.596	0.713

Table C- 9. Data for BTEX BTCs from the 40th sorption cycle on column LST1

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	5.3	0.086	0.080	0.000	0.000	0.000
2	10.6	0.459	0.153	0.093	0.031	0.000
3	21.8	0.702	0.327	0.123	0.109	0.134
4	32.3	0.812	0.513	0.251	0.163	0.230
5	44.6	0.917	0.623	0.302	0.265	0.277
6	52.1	0.966	0.744	0.412	0.292	0.343
7	63.4	0.949	0.757	0.483	0.380	0.449
8	79.9	0.984	0.839	0.487	0.504	0.560
9	94.8	1.006	0.917	0.540	0.564	0.596
10	102.6	0.970	0.878	0.614	0.612	0.668

Table C- 10. Data for BTEX BTCs from the 45th sorption cycle on column LST1

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	5.6	0.130	0.000	0.000	0.024	0.000
2	11.0	0.514	0.116	0.117	0.041	0.000
3	20.1	0.691	0.275	0.137	0.085	0.193
4	29.5	0.839	0.449	0.266	0.177	0.266
5	37.7	0.865	0.629	0.320	0.253	0.294
6	47.6	0.926	0.728	0.417	0.306	0.395
7	54.6	0.953	0.756	0.426	0.359	0.456
8	65.0	0.984	0.826	0.477	0.464	0.534
9	77.6	1.041	0.840	0.531	0.491	0.555
10	86.3	1.007	0.839	0.621	0.548	0.611
11	92.9	0.977	0.881	0.609	0.583	0.665
12	101.7	0.996	0.874	0.589	0.643	0.771

Table C- 11. Data for BTEX BTCs from the 50th sorption cycle on column LST1

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	5.2	0.129	0.062	0.000	0.000	0.000
2	10.6	0.451	0.203	0.102	0.066	0.083
3	19.0	0.685	0.341	0.190	0.098	0.153
4	27.2	0.781	0.468	0.225	0.196	0.205
5	37.9	0.864	0.571	0.275	0.208	0.228
6	48.0	0.947	0.667	0.332	0.262	0.360
7	59.7	0.954	0.749	0.434	0.391	0.433
8	70.9	0.987	0.783	0.549	0.426	0.549
9	82.4	0.987	0.820	0.567	0.498	0.620
10	90.6	1.031	0.900	0.632	0.529	0.670
11	101.5	1.047	0.855	0.631	0.614	0.724

Table C- 12. Data for BTEX removal from the 1st regeneration cycle on column LST1

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	88.8	0.0337	0.4202	0.0314	0.1389	0.1019	0.088	1.090	0.082	0.360	0.264
2	205.4	0.0752	0.2455	0.0215	0.0956	0.0791	0.273	2.224	0.172	0.760	0.573
3	322.0	0.0598	0.1559	0.0170	0.0733	0.0670	0.503	2.907	0.237	1.047	0.821
4	438.6	0.0227	0.1043	0.0128	0.0570	0.0533	0.643	3.350	0.288	1.269	1.026
5	555.2	0.0145	0.0715	0.0102	0.0456	0.0440	0.707	3.649	0.327	1.444	1.192
6	671.7	0.0124	0.0566	0.0089	0.0386	0.0391	0.752	3.868	0.360	1.587	1.333
7	788.3	0.0064	0.0248	0.0052	0.0179	0.0196	0.785	4.006	0.384	1.683	1.433
8	904.9	0.0050	0.0251	0.0062	0.0240	0.0270	0.804	4.091	0.403	1.755	1.513
9	1021.5	0.0038	0.0202	0.0054	0.0200	0.0225	0.819	4.168	0.423	1.829	1.597
10	1138.1	0.0031	0.0161	0.0048	0.0172	0.0202	0.830	4.230	0.440	1.893	1.670
11	1254.7	0.0027	0.0125	0.0040	0.0149	0.0171	0.840	4.279	0.455	1.948	1.733
12	1371.2	0.0022	0.0095	0.0037	0.0123	0.0157	0.849	4.316	0.468	1.994	1.789
13	1487.8	0.0020	0.0084	0.0036	0.0109	0.0147	0.856	4.347	0.481	2.033	1.840
14	1604.4	0.0018	0.0076	0.0034	0.0101	0.0133	0.862	4.374	0.493	2.069	1.888

Table C- 13. Data for BTEX removal from the 5th regeneration cycle on column LST1

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	76.4	0.0590	0.3858	0.0368	0.1482	0.1213	0.132	0.861	0.082	0.331	0.271
2	189.9	0.0639	0.2280	0.0231	0.1046	0.0876	0.335	1.879	0.181	0.750	0.617
3	303.5	0.0598	0.1579	0.0162	0.0807	0.0754	0.540	2.519	0.247	1.057	0.888
4	417.0	0.0236	0.1036	0.0124	0.0697	0.0618	0.679	2.952	0.294	1.307	1.115
5	530.5	0.0166	0.0734	0.0103	0.0565	0.0506	0.746	3.246	0.332	1.516	1.302
6	644.0	0.0118	0.0524	0.0088	0.0439	0.0442	0.793	3.454	0.363	1.682	1.459
7	757.5	0.0064	0.0332	0.0076	0.0325	0.0355	0.823	3.596	0.391	1.809	1.591
8	871.0	0.0044	0.0245	0.0060	0.0258	0.0302	0.841	3.692	0.413	1.906	1.700
9	984.6	0.0034	0.0172	0.0052	0.0216	0.0248	0.854	3.761	0.432	1.984	1.791
10	1098.1	0.0024	0.0136	0.0044	0.0183	0.0198	0.863	3.812	0.448	2.051	1.865
11	1211.6	0.0020	0.0129	0.0039	0.0161	0.0163	0.870	3.856	0.461	2.108	1.925
12	1325.1	0.0016	0.0083	0.0032	0.0114	0.0138	0.876	3.891	0.473	2.153	1.975
13	1438.6	0.0015	0.0054	0.0030	0.0109	0.0126	0.882	3.914	0.483	2.190	2.019
14	1552.1	0.0013	0.0045	0.0028	0.0096	0.0112	0.886	3.930	0.493	2.224	2.059

Table C- 14. Data for BTEX removal from the 10th regeneration cycle on column LST1

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	73.4	0.0633	0.4208	0.0311	0.1419	0.0962	0.136	0.902	0.067	0.304	0.206
2	181.2	0.0654	0.2325	0.0211	0.0891	0.0775	0.338	1.931	0.149	0.668	0.480
3	297.8	0.0529	0.1383	0.0138	0.0751	0.0617	0.540	2.562	0.208	0.948	0.717
4	414.4	0.0304	0.0889	0.0105	0.0556	0.0457	0.682	2.949	0.250	1.170	0.899
5	531.0	0.0162	0.0662	0.0083	0.0461	0.0379	0.761	3.213	0.282	1.343	1.042
6	647.5	0.0119	0.0551	0.0066	0.0348	0.0322	0.809	3.420	0.307	1.481	1.161
7	764.1	0.0073	0.0371	0.0056	0.0291	0.0288	0.842	3.577	0.328	1.590	1.265
8	880.7	0.0047	0.0241	0.0044	0.0223	0.0227	0.862	3.681	0.345	1.677	1.353
9	997.3	0.0032	0.0182	0.0038	0.0203	0.0172	0.876	3.753	0.359	1.750	1.421
10	1113.9	0.0029	0.0149	0.0033	0.0158	0.0155	0.886	3.809	0.370	1.812	1.476
11	1230.5	0.0027	0.0120	0.0033	0.0127	0.0141	0.895	3.855	0.382	1.860	1.527
12	1347.0	0.0023	0.0095	0.0026	0.0095	0.0120	0.904	3.892	0.392	1.898	1.571
13	1463.6	0.0022	0.0077	0.0024	0.0086	0.0112	0.912	3.921	0.400	1.929	1.611
14	1580.2	0.0022	0.0070	0.0025	0.0078	0.0106	0.919	3.946	0.409	1.957	1.648

Table C- 15. Data for BTEX removal from the 15th regeneration cycle on column LST1

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	73.4	0.0537	0.4934	0.0400	0.1467	0.1101	0.115	1.057	0.086	0.314	0.236
2	178.6	0.0647	0.2726	0.0271	0.0921	0.0887	0.297	2.234	0.189	0.681	0.541
3	295.2	0.0604	0.1622	0.0178	0.0777	0.0706	0.510	2.975	0.265	0.970	0.813
4	411.7	0.0357	0.1042	0.0134	0.0575	0.0523	0.674	3.428	0.318	1.200	1.022
5	525.3	0.0176	0.0776	0.0106	0.0476	0.0434	0.762	3.730	0.358	1.375	1.181
6	638.8	0.0105	0.0646	0.0085	0.0359	0.0369	0.809	3.965	0.390	1.513	1.314
7	752.3	0.0065	0.0435	0.0072	0.0301	0.0330	0.837	4.145	0.416	1.623	1.430
8	865.8	0.0054	0.0283	0.0056	0.0231	0.0260	0.856	4.264	0.437	1.711	1.528
9	979.3	0.0050	0.0214	0.0048	0.0210	0.0197	0.874	4.346	0.455	1.784	1.603
10	1092.8	0.0032	0.0174	0.0042	0.0163	0.0177	0.887	4.410	0.469	1.846	1.665
11	1206.3	0.0023	0.0141	0.0042	0.0131	0.0162	0.896	4.462	0.483	1.895	1.722
12	1319.9	0.0018	0.0112	0.0033	0.0098	0.0137	0.903	4.504	0.496	1.933	1.771
13	1433.4	0.0011	0.0090	0.0031	0.0089	0.0128	0.908	4.538	0.507	1.964	1.815
14	1546.9	0.0011	0.0082	0.0032	0.0080	0.0121	0.911	4.566	0.517	1.992	1.856

Table C- 16. Data for BTEX removal from the 20th regeneration cycle on column LST1

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	88.0	0.0508	0.4036	0.0412	0.1604	0.1087	0.131	1.038	0.106	0.413	0.279
2	186.1	0.0634	0.2230	0.0279	0.1007	0.0875	0.294	1.935	0.205	0.786	0.560
3	296.7	0.0547	0.1327	0.0183	0.0849	0.0697	0.485	2.510	0.279	1.086	0.814
4	410.2	0.0404	0.0852	0.0138	0.0629	0.0517	0.643	2.871	0.332	1.331	1.016
5	526.8	0.0138	0.0635	0.0109	0.0521	0.0428	0.735	3.124	0.374	1.527	1.176
6	643.4	0.0122	0.0528	0.0087	0.0393	0.0364	0.779	3.322	0.408	1.683	1.311
7	759.9	0.0090	0.0356	0.0074	0.0329	0.0326	0.816	3.473	0.435	1.806	1.429
8	876.5	0.0065	0.0232	0.0058	0.0253	0.0257	0.842	3.573	0.458	1.905	1.528
9	993.1	0.0049	0.0175	0.0050	0.0230	0.0194	0.861	3.642	0.476	1.987	1.605
10	1109.7	0.0033	0.0143	0.0043	0.0179	0.0175	0.875	3.696	0.492	2.057	1.668
11	1226.3	0.0021	0.0115	0.0044	0.0144	0.0159	0.885	3.740	0.507	2.111	1.725
12	1342.9	0.0019	0.0091	0.0034	0.0107	0.0135	0.891	3.775	0.520	2.154	1.775
13	1459.4	0.0016	0.0074	0.0032	0.0098	0.0127	0.897	3.803	0.531	2.189	1.819
14	1576.0	0.0015	0.0067	0.0033	0.0088	0.0120	0.902	3.827	0.542	2.221	1.861

Table C- 17. Data for BTEX removal from the 25th regeneration cycle on column LST1

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	225.0	0.0817	0.2743	0.0217	0.1038	0.0718	0.537	1.802	0.142	0.682	0.472
2	348.2	0.0426	0.1864	0.0172	0.0851	0.0627	0.761	2.632	0.212	1.022	0.714
3	456.1	0.0227	0.1367	0.0132	0.0670	0.0514	0.864	3.140	0.260	1.262	0.894
4	566.7	0.0135	0.0953	0.0111	0.0572	0.0458	0.922	3.515	0.300	1.462	1.050
5	683.2	0.0081	0.0680	0.0094	0.0458	0.0379	0.959	3.793	0.335	1.638	1.193
6	799.8	0.0049	0.0468	0.0075	0.0368	0.0306	0.981	3.989	0.363	1.778	1.309
7	916.4	0.0034	0.0349	0.0060	0.0297	0.0261	0.995	4.128	0.386	1.892	1.406
8	1033.0	0.0023	0.0252	0.0050	0.0247	0.0225	1.005	4.230	0.405	1.984	1.489
9	1149.6	0.0017	0.0186	0.0043	0.0199	0.0189	1.011	4.305	0.421	2.060	1.559
10	1266.2	0.0014	0.0143	0.0035	0.0172	0.0169	1.017	4.361	0.434	2.123	1.620
11	1382.7	0.0011	0.0107	0.0031	0.0145	0.0142	1.021	4.403	0.445	2.177	1.673
12	1499.3	0.0009	0.0084	0.0027	0.0125	0.0126	1.024	4.436	0.455	2.223	1.719
13	1615.9	0.0009	0.0066	0.0025	0.0104	0.0114	1.028	4.461	0.464	2.262	1.760
14	1732.5	0.0009	0.0025	0.0022	0.0096	0.0096	1.031	4.477	0.472	2.296	1.795

Table C- 18. Data for BTEX removal from the 30th regeneration cycle on column LST1

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	75.1	0.0573	0.4165	0.0304	0.1507	0.1073	0.126	0.914	0.067	0.331	0.236
2	183.0	0.0738	0.2817	0.0212	0.1151	0.0897	0.332	2.014	0.148	0.749	0.546
3	293.6	0.0525	0.1987	0.0154	0.0914	0.0707	0.536	2.790	0.207	1.083	0.805
4	407.1	0.0310	0.1273	0.0121	0.0709	0.0595	0.675	3.331	0.253	1.352	1.021
5	520.6	0.0171	0.0844	0.0099	0.0543	0.0495	0.755	3.681	0.289	1.559	1.201
6	634.1	0.0120	0.0576	0.0085	0.0436	0.0422	0.803	3.917	0.320	1.722	1.354
7	747.7	0.0090	0.0450	0.0066	0.0348	0.0366	0.838	4.087	0.345	1.851	1.484
8	861.2	0.0077	0.0357	0.0057	0.0294	0.0305	0.866	4.221	0.365	1.958	1.596
9	974.7	0.0058	0.0247	0.0049	0.0260	0.0253	0.888	4.321	0.383	2.050	1.688
10	1088.2	0.0042	0.0186	0.0037	0.0195	0.0227	0.905	4.393	0.397	2.125	1.768
11	1201.7	0.0020	0.0109	0.0031	0.0181	0.0195	0.915	4.441	0.408	2.188	1.838
12	1315.2	0.0009	0.0093	0.0030	0.0153	0.0162	0.920	4.475	0.418	2.243	1.897
13	1428.7	0.0006	0.0061	0.0028	0.0132	0.0126	0.922	4.500	0.428	2.290	1.945
14	1542.3	0.0005	0.0044	0.0025	0.0108	0.0093	0.924	4.518	0.437	2.330	1.981

Table C- 19. Data for BTEX removal from the 35th regeneration cycle on column LST1

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	80.4	0.0527	0.4032	0.0380	0.1476	0.1130	0.124	0.947	0.089	0.347	0.265
2	180.7	0.0712	0.2765	0.0283	0.0979	0.0798	0.305	1.942	0.186	0.706	0.548
3	300.5	0.0461	0.1829	0.0179	0.0783	0.0675	0.510	2.746	0.267	1.015	0.805
4	420.3	0.0184	0.1070	0.0144	0.0660	0.0530	0.623	3.253	0.324	1.267	1.016
5	540.2	0.0119	0.0777	0.0118	0.0550	0.0426	0.676	3.577	0.370	1.479	1.184
6	660.0	0.0094	0.0581	0.0103	0.0461	0.0388	0.714	3.814	0.408	1.656	1.326
7	776.6	0.0077	0.0450	0.0080	0.0348	0.0318	0.743	3.990	0.439	1.794	1.446
8	893.1	0.0069	0.0335	0.0070	0.0303	0.0245	0.768	4.123	0.465	1.905	1.542
9	1009.7	0.0054	0.0204	0.0067	0.0256	0.0210	0.789	4.215	0.488	2.000	1.620
10	1126.3	0.0034	0.0133	0.0058	0.0181	0.0182	0.804	4.273	0.510	2.074	1.686
11	1242.9	0.0024	0.0072	0.0049	0.0148	0.0159	0.814	4.308	0.528	2.130	1.744
12	1359.5	0.0011	0.0059	0.0045	0.0115	0.0122	0.820	4.330	0.544	2.175	1.792
13	1476.1	0.0007	0.0044	0.0039	0.0110	0.0116	0.823	4.348	0.558	2.213	1.833
14	1592.6	0.0006	0.0031	0.0035	0.0070	0.0106	0.825	4.360	0.571	2.244	1.871

Table C- 20. Data for BTEX removal from the 40th regeneration cycle on column LST1

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	94.8	0.0685	0.3121	0.0408	0.1302	0.1019	0.190	0.864	0.113	0.360	0.282
2	208.3	0.0725	0.2488	0.0270	0.0874	0.0756	0.423	1.794	0.225	0.721	0.577
3	321.8	0.0462	0.1691	0.0187	0.0736	0.0619	0.620	2.487	0.301	0.988	0.804
4	435.4	0.0263	0.1150	0.0128	0.0588	0.0510	0.740	2.958	0.353	1.208	0.992
5	548.9	0.0145	0.0696	0.0098	0.0529	0.0430	0.808	3.264	0.391	1.393	1.147
6	662.4	0.0101	0.0490	0.0074	0.0374	0.0340	0.849	3.461	0.419	1.542	1.275
7	775.9	0.0067	0.0389	0.0061	0.0348	0.0287	0.876	3.606	0.442	1.662	1.379
8	889.4	0.0058	0.0299	0.0054	0.0267	0.0233	0.897	3.720	0.461	1.764	1.465
9	1002.9	0.0050	0.0206	0.0045	0.0202	0.0189	0.915	3.804	0.477	1.841	1.535
10	1116.4	0.0034	0.0158	0.0038	0.0174	0.0181	0.929	3.865	0.491	1.904	1.596
11	1230.0	0.0015	0.0083	0.0036	0.0125	0.0153	0.937	3.905	0.503	1.953	1.652
12	1343.5	0.0011	0.0072	0.0033	0.0097	0.0136	0.941	3.930	0.515	1.990	1.700
13	1457.0	0.0008	0.0047	0.0031	0.0073	0.0115	0.944	3.950	0.526	2.019	1.741
14	1570.5	0.0006	0.0031	0.0029	0.0069	0.0094	0.947	3.963	0.535	2.042	1.776

Table C- 21. Data for BTEX removal from the 45th regeneration cycle on column LST1

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	92.4	0.0412	0.3522	0.0299	0.1323	0.0889	0.111	0.951	0.081	0.357	0.240
2	219.3	0.0540	0.2383	0.0173	0.0964	0.0693	0.288	2.045	0.168	0.781	0.533
3	342.5	0.0411	0.1462	0.0132	0.0736	0.0558	0.459	2.737	0.223	1.087	0.759
4	459.1	0.0290	0.0983	0.0096	0.0573	0.0453	0.578	3.154	0.262	1.310	0.931
5	572.6	0.0207	0.0610	0.0078	0.0497	0.0370	0.661	3.418	0.291	1.487	1.067
6	689.2	0.0125	0.0523	0.0068	0.0397	0.0337	0.717	3.611	0.316	1.640	1.188
7	805.8	0.0092	0.0346	0.0056	0.0313	0.0257	0.754	3.759	0.337	1.761	1.289
8	922.4	0.0059	0.0251	0.0048	0.0257	0.0217	0.780	3.860	0.355	1.857	1.370
9	1039.0	0.0040	0.0176	0.0044	0.0209	0.0185	0.797	3.933	0.370	1.937	1.438
10	1155.6	0.0033	0.0114	0.0036	0.0177	0.0151	0.809	3.982	0.384	2.002	1.495
11	1272.2	0.0022	0.0065	0.0030	0.0165	0.0146	0.819	4.013	0.395	2.060	1.546
12	1388.7	0.0010	0.0058	0.0031	0.0148	0.0126	0.824	4.034	0.406	2.114	1.592
13	1505.3	0.0009	0.0043	0.0026	0.0119	0.0096	0.828	4.051	0.415	2.159	1.630
14	1621.9	0.0005	0.0025	0.0027	0.0080	0.0091	0.830	4.063	0.424	2.193	1.662

Table C- 22. Data for BTEX removal from the 50^{h} regeneration cycle on column LST1

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	88.0	0.0543	0.4025	0.0351	0.1302	0.1095	0.140	1.035	0.090	0.335	0.282
2	186.1	0.0624	0.2994	0.0206	0.0990	0.0844	0.307	2.040	0.170	0.663	0.559
3	296.7	0.0562	0.1800	0.0163	0.0800	0.0705	0.498	2.814	0.230	0.952	0.809
4	410.2	0.0350	0.1053	0.0131	0.0679	0.0600	0.649	3.287	0.278	1.197	1.026
5	526.8	0.0228	0.0716	0.0087	0.0563	0.0506	0.748	3.588	0.316	1.409	1.214
6	643.4	0.0124	0.0602	0.0081	0.0466	0.0408	0.808	3.813	0.344	1.584	1.370
7	759.9	0.0084	0.0413	0.0077	0.0376	0.0333	0.843	3.985	0.371	1.727	1.496
8	876.5	0.0038	0.0325	0.0062	0.0276	0.0289	0.864	4.111	0.395	1.838	1.602
9	993.1	0.0032	0.0243	0.0053	0.0236	0.0240	0.876	4.208	0.414	1.925	1.692
10	1109.7	0.0022	0.0147	0.0047	0.0174	0.0201	0.885	4.274	0.431	1.995	1.767
11	1226.3	0.0018	0.0090	0.0042	0.0149	0.0183	0.892	4.315	0.447	2.050	1.832
12	1342.9	0.0012	0.0078	0.0037	0.0138	0.0155	0.897	4.343	0.460	2.099	1.889
13	1459.4	0.0008	0.0063	0.0035	0.0130	0.0142	0.901	4.367	0.472	2.145	1.940
14	1576.0	0.0005	0.0031	0.0032	0.0084	0.0126	0.903	4.383	0.484	2.181	1.986

Table C- 23. Data for BTEX BTCs from the 1st sorption cycle on column LST2

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	3.4	0.030	0.030	0.000	0.000	0.000
2	8.5	0.079	0.083	0.114	0.000	0.000
3	15.5	0.396	0.135	0.149	0.063	0.079
4	24.3	0.657	0.218	0.186	0.084	0.113
5	31.6	0.730	0.354	0.256	0.153	0.156
6	40.8	0.821	0.483	0.336	0.202	0.231
7	51.0	0.888	0.592	0.395	0.282	0.315
8	69.1	0.985	0.739	0.506	0.423	0.423
9	79.6	0.999	0.795	0.498	0.484	0.460
10	96.7	0.996	0.810	0.590	0.528	0.543

Table C- 24. Data for BTEX BTCs from the 5th sorption cycle on column LST2

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	8.2	0.116	0.017	0.000	0.000	0.000
2	8.1	0.421	0.072	0.000	0.023	0.000
3	8.0	0.577	0.222	0.124	0.063	0.116
4	7.9	0.722	0.315	0.212	0.092	0.196
5	7.9	0.787	0.435	0.233	0.143	0.268
6	7.9	0.839	0.564	0.276	0.196	0.288
7	8.0	0.919	0.624	0.353	0.288	0.386
8	7.7	0.873	0.679	0.440	0.335	0.426
9	7.8	0.961	0.736	0.489	0.441	0.487
10	7.6	0.931	0.772	0.556	0.503	0.577
11	7.6	0.973	0.825	0.546	0.564	0.569

Table C- 25. Data for BTEX BTCs from the 10th sorption cycle on column LST2

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	5.3	0.054	0.000	0.000	0.000	0.000
2	10.9	0.306	0.092	0.073	0.023	0.072
3	18.3	0.556	0.265	0.109	0.043	0.088
4	25.5	0.628	0.284	0.164	0.067	0.160
5	32.9	0.832	0.409	0.199	0.128	0.198
6	41.4	0.879	0.524	0.246	0.168	0.262
7	49.2	0.925	0.626	0.275	0.230	0.308
8	58.2	0.976	0.702	0.362	0.297	0.394
9	67.1	0.975	0.746	0.424	0.385	0.443
10	77.7	0.955	0.834	0.481	0.455	0.479
11	91.1	1.003	0.812	0.581	0.482	0.511
12	101.8	0.988	0.843	0.648	0.544	0.560

Table C- 26. Data for BTEX BTCs from the 15th sorption cycle on column LST2

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	5.9	0.104	0.036	0.000	0.000	0.000
2	11.4	0.366	0.119	0.000	0.026	0.000
3	19.0	0.559	0.245	0.163	0.029	0.159
4	28.6	0.689	0.370	0.186	0.087	0.225
5	36.6	0.776	0.536	0.229	0.167	0.265
6	45.2	0.821	0.622	0.287	0.229	0.324
7	53.0	0.855	0.652	0.355	0.271	0.410
8	64.2	0.958	0.771	0.392	0.409	0.427
9	70.9	0.942	0.814	0.514	0.424	0.521
10	80.2	0.998	0.832	0.537	0.502	0.522
11	91.2	0.943	0.911	0.615	0.540	0.641
12	101.7	0.979	0.972	0.615	0.611	0.585

Table C- 27. Data for BTEX BTCs from the 20th sorption cycle on column LST2

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	5.4	0.162	0.049	0.000	0.000	0.000
2	10.6	0.287	0.139	0.107	0.026	0.068
3	17.4	0.476	0.253	0.130	0.059	0.150
4	22.7	0.670	0.368	0.147	0.072	0.161
5	30.9	0.777	0.395	0.185	0.145	0.235
6	40.2	0.813	0.612	0.224	0.234	0.319
7	49.0	0.856	0.705	0.230	0.329	0.386
8	57.5	0.921	0.702	0.273	0.367	0.428
9	65.8	0.944	0.782	0.364	0.448	0.531
10	77.9	0.980	0.883	0.442	0.523	0.559
11	89.7	1.032	0.966	0.510	0.565	0.584
12	100.8	1.028	0.924	0.582	0.594	0.666

Table C- 28. Data for BTEX BTCs from the 25th sorption cycle on column LST2

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	5.5	0.082	0.000	0.000	0.000	0.000
2	11.8	0.241	0.145	0.100	0.047	0.000
3	22.3	0.557	0.284	0.146	0.103	0.110
4	29.5	0.709	0.471	0.197	0.147	0.163
5	36.3	0.855	0.582	0.265	0.256	0.239
6	46.2	0.880	0.623	0.308	0.256	0.309
7	56.1	0.840	0.658	0.358	0.346	0.346
8	65.1	0.921	0.784	0.397	0.453	0.404
9	73.8	0.960	0.782	0.455	0.471	0.468
10	81.2	1.017	0.829	0.555	0.576	0.534
11	91.4	1.062	0.887	0.516	0.626	0.570
12	102.1	1.012	0.948	0.568	0.633	0.591

Table C- 29. Data for BTEX BTCs from the 30th sorption cycle on column LST2

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	5.0	0.073	0.000	0.000	0.000	0.000
2	10.4	0.273	0.063	0.072	0.023	0.079
3	17.7	0.425	0.196	0.112	0.041	0.119
4	22.8	0.619	0.351	0.163	0.061	0.138
5	30.8	0.664	0.488	0.260	0.113	0.181
6	39.6	0.755	0.589	0.299	0.139	0.247
7	49.0	0.880	0.681	0.314	0.233	0.355
8	60.2	0.856	0.824	0.346	0.325	0.451
9	69.7	0.898	0.784	0.460	0.424	0.573
10	82.0	0.938	0.912	0.449	0.467	0.554
11	91.6	0.959	0.891	0.580	0.501	0.616
12	102.6	1.018	0.947	0.665	0.576	0.616

Table C- 30. Data for BTEX BTCs from the 35th sorption cycle on column LST2

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	6.0	0.044	0.024	0.000	0.000	0.000
2	11.9	0.280	0.094	0.086	0.026	0.000
3	18.6	0.368	0.247	0.183	0.053	0.115
4	26.7	0.696	0.377	0.194	0.124	0.141
5	34.6	0.743	0.465	0.248	0.176	0.286
6	42.7	0.777	0.566	0.308	0.221	0.318
7	51.2	0.881	0.634	0.305	0.314	0.418
8	60.2	0.925	0.728	0.423	0.413	0.427
9	73.0	1.002	0.817	0.510	0.486	0.554
10	79.6	1.025	0.913	0.609	0.568	0.522
11	89.2	0.997	0.873	0.616	0.578	0.563
12	102.2	0.964	0.949	0.674	0.614	0.617

Table C- 31. Data for BTEX BTCs from the 40th sorption cycle on column LST2

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	5.3	0.064	0.000	0.000	0.000	0.000
2	10.3	0.341	0.109	0.111	0.065	0.000
3	17.2	0.559	0.159	0.198	0.096	0.139
4	24.9	0.704	0.284	0.245	0.117	0.183
5	32.9	0.796	0.474	0.308	0.186	0.213
6	41.0	0.885	0.604	0.353	0.289	0.285
7	49.0	0.893	0.727	0.398	0.349	0.333
8	57.1	0.920	0.766	0.434	0.396	0.417
9	69.1	0.986	0.800	0.506	0.482	0.469
10	78.6	0.942	0.824	0.523	0.594	0.524
11	89.9	0.975	0.874	0.644	0.630	0.571
12	100.2	1.022	0.898	0.701	0.650	0.609

Table C- 32. Data for BTEX BTCs from the 45th sorption cycle on column LST2

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	5.9	0.146	0.061	0.000	0.000	0.000
2	12.0	0.393	0.169	0.103	0.037	0.091
3	17.6	0.604	0.284	0.145	0.078	0.102
4	23.2	0.720	0.370	0.189	0.090	0.126
5	30.0	0.763	0.437	0.192	0.118	0.197
6	38.1	0.809	0.612	0.257	0.177	0.254
7	46.1	0.904	0.663	0.324	0.232	0.355
8	54.4	1.005	0.786	0.366	0.414	0.393
9	63.6	0.947	0.826	0.440	0.415	0.431
10	74.9	0.985	0.872	0.527	0.501	0.498
11	87.2	1.087	0.908	0.538	0.586	0.558
12	101.5	1.055	0.937	0.608	0.606	0.622

Table C- 33. Data for BTEX BTCs from the 50th sorption cycle on column LST2

		C/Co				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	5.5	0.213	0.000	0.000	0.000	0.000
2	11.1	0.340	0.163	0.080	0.022	0.124
3	18.9	0.510	0.259	0.171	0.068	0.144
4	26.6	0.694	0.394	0.205	0.150	0.204
5	33.3	0.794	0.523	0.236	0.178	0.234
6	44.1	0.881	0.704	0.291	0.227	0.322
7	52.9	0.928	0.686	0.320	0.315	0.390
8	61.4	0.993	0.798	0.384	0.410	0.454
9	71.3	0.990	0.872	0.451	0.449	0.499
10	79.6	0.985	0.904	0.563	0.489	0.598
11	89.1	1.038	0.865	0.628	0.578	0.597
12	100.7	1.029	0.966	0.657	0.644	0.668

Table C- 34. Data for BTEX removal from the 1st regeneration cycle on column LST2

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	72.5	0.1012	0.5819	0.0346	0.1304	0.1359	0.217	1.247	0.074	0.279	0.291
2	167.3	0.1115	0.3250	0.0231	0.0995	0.1068	0.529	2.157	0.139	0.558	0.590
3	274.0	0.0805	0.2166	0.0178	0.0750	0.0911	0.782	2.839	0.195	0.794	0.877
4	383.3	0.0530	0.1506	0.0136	0.0613	0.0782	0.954	3.326	0.239	0.992	1.130
5	495.6	0.0366	0.1200	0.0101	0.0499	0.0642	1.075	3.723	0.273	1.158	1.343
6	607.8	0.0227	0.0869	0.0082	0.0412	0.0546	1.150	4.012	0.300	1.294	1.524
7	720.1	0.0159	0.0659	0.0068	0.0342	0.0473	1.203	4.230	0.322	1.408	1.681
8	832.3	0.0116	0.0510	0.0061	0.0278	0.0395	1.242	4.399	0.342	1.500	1.812
9	944.6	0.0093	0.0408	0.0049	0.0220	0.0335	1.273	4.535	0.359	1.573	1.923
10	1056.8	0.0076	0.0332	0.0041	0.0177	0.0284	1.298	4.645	0.372	1.631	2.017
11	1169.1	0.0060	0.0246	0.0037	0.0156	0.0242	1.318	4.726	0.385	1.683	2.097
12	1281.3	0.0036	0.0193	0.0031	0.0137	0.0209	1.329	4.790	0.395	1.728	2.167
13	1393.6	0.0020	0.0115	0.0025	0.0113	0.0180	1.336	4.828	0.403	1.766	2.226
14	1505.8	0.0011	0.0069	0.0021	0.0090	0.0160	1.340	4.851	0.410	1.796	2.279

Table C- 35. Data for BTEX removal from the 5th regeneration cycle on column LST2

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	79.5	0.1149	0.6869	0.0412	0.1537	0.0992	0.270	1.613	0.097	0.361	0.233
2	198.0	0.1344	0.3605	0.0281	0.1045	0.0787	0.740	2.875	0.195	0.727	0.508
3	316.4	0.0712	0.2203	0.0208	0.0770	0.0641	0.990	3.646	0.268	0.996	0.732
4	431.7	0.0478	0.1401	0.0159	0.0629	0.0541	1.152	4.123	0.322	1.210	0.916
5	544.0	0.0354	0.1123	0.0125	0.0498	0.0446	1.270	4.495	0.364	1.375	1.064
6	656.2	0.0246	0.0781	0.0102	0.0412	0.0389	1.351	4.754	0.397	1.512	1.193
7	768.5	0.0197	0.0667	0.0084	0.0342	0.0340	1.417	4.975	0.425	1.625	1.306
8	880.7	0.0147	0.0520	0.0070	0.0293	0.0287	1.466	5.147	0.448	1.722	1.401
9	993.0	0.0111	0.0363	0.0063	0.0231	0.0240	1.502	5.268	0.469	1.799	1.481
10	1105.2	0.0094	0.0265	0.0054	0.0201	0.0205	1.534	5.356	0.487	1.866	1.549
11	1217.5	0.0066	0.0193	0.0050	0.0173	0.0178	1.556	5.420	0.504	1.923	1.608
12	1329.7	0.0040	0.0136	0.0047	0.0156	0.0158	1.569	5.465	0.519	1.975	1.660
13	1442.0	0.0018	0.0077	0.0039	0.0137	0.0140	1.575	5.491	0.532	2.020	1.706
14	1554.2	0.0013	0.0064	0.0037	0.0120	0.0131	1.579	5.512	0.545	2.060	1.750

Table C- 36. Data for BTEX removal from the 10th regeneration cycle on column LST2

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	86.3	0.0896	0.4318	0.0516	0.1547	0.1253	0.229	1.101	0.132	0.395	0.320
2	185.5	0.1178	0.2087	0.0385	0.1126	0.1059	0.574	1.713	0.244	0.724	0.630
3	294.9	0.0925	0.1622	0.0289	0.0910	0.0855	0.873	2.237	0.338	1.018	0.906
4	410.2	0.0589	0.1271	0.0217	0.0728	0.0719	1.073	2.670	0.412	1.266	1.151
5	522.4	0.0357	0.0985	0.0175	0.0598	0.0601	1.192	2.996	0.470	1.465	1.350
6	634.7	0.0253	0.0733	0.0139	0.0479	0.0493	1.275	3.239	0.516	1.623	1.514
7	746.9	0.0169	0.0608	0.0113	0.0405	0.0418	1.331	3.441	0.554	1.758	1.652
8	859.2	0.0126	0.0518	0.0099	0.0334	0.0351	1.373	3.613	0.587	1.868	1.768
9	971.4	0.0087	0.0379	0.0087	0.0254	0.0293	1.402	3.738	0.616	1.953	1.866
10	1083.7	0.0059	0.0306	0.0074	0.0233	0.0245	1.421	3.840	0.640	2.030	1.947
11	1195.9	0.0037	0.0240	0.0063	0.0206	0.0200	1.434	3.919	0.661	2.098	2.013
12	1308.1	0.0033	0.0166	0.0054	0.0187	0.0177	1.444	3.974	0.679	2.160	2.072
13	1420.4	0.0019	0.0149	0.0046	0.0162	0.0144	1.451	4.024	0.694	2.214	2.120
14	1532.6	0.0012	0.0054	0.0037	0.0147	0.0103	1.455	4.042	0.707	2.262	2.154

Table C- 37. Data for BTEX removal from the 15th regeneration cycle on column LST2

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	84.6	0.0939	0.5073	0.0333	0.1598	0.0903	0.235	1.268	0.083	0.399	0.226
2	186.2	0.1016	0.2730	0.0235	0.1138	0.0717	0.540	2.087	0.154	0.741	0.441
3	292.8	0.0689	0.1387	0.0163	0.0878	0.0605	0.757	2.524	0.205	1.017	0.631
4	402.2	0.0434	0.1034	0.0131	0.0703	0.0512	0.897	2.858	0.247	1.245	0.797
5	517.5	0.0339	0.0815	0.0107	0.0582	0.0416	1.012	3.136	0.283	1.443	0.939
6	632.8	0.0215	0.0631	0.0087	0.0467	0.0335	1.085	3.351	0.313	1.602	1.053
7	748.0	0.0159	0.0438	0.0070	0.0392	0.0275	1.139	3.500	0.337	1.735	1.146
8	863.3	0.0107	0.0378	0.0059	0.0323	0.0233	1.176	3.629	0.357	1.845	1.226
9	978.6	0.0067	0.0265	0.0054	0.0255	0.0180	1.199	3.719	0.375	1.932	1.287
10	1093.9	0.0061	0.0166	0.0045	0.0200	0.0143	1.219	3.775	0.390	2.000	1.336
11	1209.2	0.0037	0.0128	0.0036	0.0166	0.0127	1.232	3.819	0.403	2.057	1.379
12	1324.4	0.0024	0.0090	0.0035	0.0152	0.0117	1.240	3.850	0.414	2.108	1.419
13	1439.7	0.0015	0.0064	0.0031	0.0124	0.0107	1.245	3.872	0.425	2.151	1.455
14	1555.0	0.0010	0.0044	0.0030	0.0107	0.0088	1.248	3.887	0.435	2.187	1.486

Table C- 38. Data for BTEX removal from the 20th regeneration cycle on column LST2

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	72.9	0.0675	0.4460	0.0411	0.1636	0.0965	0.145	0.961	0.089	0.352	0.208
2	185.2	0.0729	0.2637	0.0279	0.1065	0.0763	0.387	1.835	0.181	0.706	0.461
3	297.4	0.0566	0.1709	0.0205	0.0828	0.0619	0.575	2.401	0.249	0.980	0.666
4	409.7	0.0318	0.0976	0.0164	0.0653	0.0547	0.680	2.725	0.303	1.197	0.847
5	521.9	0.0233	0.0834	0.0128	0.0553	0.0467	0.757	3.002	0.346	1.380	1.002
6	634.2	0.0148	0.0560	0.0101	0.0474	0.0384	0.806	3.187	0.379	1.537	1.130
7	746.4	0.0090	0.0456	0.0088	0.0403	0.0327	0.836	3.339	0.409	1.671	1.238
8	858.6	0.0078	0.0359	0.0078	0.0341	0.0289	0.862	3.458	0.434	1.784	1.334
9	970.9	0.0059	0.0282	0.0067	0.0283	0.0245	0.882	3.552	0.457	1.878	1.415
10	1083.1	0.0044	0.0195	0.0061	0.0248	0.0207	0.896	3.616	0.477	1.960	1.484
11	1195.4	0.0029	0.0138	0.0053	0.0205	0.0160	0.906	3.662	0.495	2.028	1.537
12	1307.6	0.0022	0.0114	0.0047	0.0165	0.0137	0.913	3.700	0.510	2.083	1.582
13	1419.9	0.0012	0.0077	0.0037	0.0158	0.0119	0.917	3.725	0.522	2.135	1.622
14	1532.1	0.0007	0.0047	0.0035	0.0129	0.0103	0.919	3.741	0.534	2.178	1.656

Table C- 39. Data for BTEX removal from the 25th regeneration cycle on column LST2

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	63.5	0.0769	0.3582	0.0378	0.1471	0.0940	0.144	0.672	0.071	0.276	0.176
2	165.0	0.0878	0.2556	0.0289	0.1082	0.0768	0.408	1.439	0.158	0.600	0.407
3	277.3	0.0741	0.1801	0.0215	0.0847	0.0637	0.653	2.036	0.229	0.881	0.618
4	389.5	0.0448	0.1138	0.0172	0.0658	0.0539	0.802	2.413	0.286	1.099	0.797
5	504.8	0.0339	0.0892	0.0137	0.0526	0.0439	0.918	2.717	0.333	1.279	0.946
6	620.1	0.0250	0.0678	0.0104	0.0407	0.0365	1.003	2.948	0.368	1.417	1.071
7	735.4	0.0168	0.0513	0.0085	0.0338	0.0303	1.060	3.123	0.397	1.533	1.174
8	850.6	0.0132	0.0405	0.0075	0.0279	0.0241	1.105	3.261	0.423	1.627	1.256
9	965.9	0.0096	0.0354	0.0065	0.0238	0.0195	1.138	3.381	0.445	1.709	1.322
10	1081.2	0.0065	0.0267	0.0055	0.0221	0.0163	1.160	3.472	0.463	1.784	1.378
11	1196.5	0.0053	0.0218	0.0045	0.0195	0.0144	1.178	3.546	0.479	1.850	1.427
12	1311.8	0.0032	0.0160	0.0038	0.0179	0.0122	1.189	3.601	0.492	1.911	1.469
13	1427.1	0.0020	0.0087	0.0037	0.0158	0.0105	1.196	3.630	0.504	1.965	1.505
14	1542.3	0.0011	0.0056	0.0033	0.0136	0.0087	1.200	3.649	0.516	2.011	1.534

Table C- 40. Data for BTEX removal from the 30th regeneration cycle on column LST2

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	77.4	0.1313	0.4544	0.0451	0.1758	0.1125	0.300	1.039	0.103	0.402	0.257
2	184.0	0.1672	0.2765	0.0327	0.1321	0.0929	0.827	1.910	0.206	0.818	0.550
3	290.6	0.1097	0.1966	0.0253	0.1015	0.0757	1.172	2.529	0.286	1.138	0.788
4	400.0	0.0754	0.1204	0.0194	0.0830	0.0667	1.416	2.918	0.349	1.406	1.004
5	512.3	0.0419	0.0852	0.0157	0.0707	0.0543	1.555	3.200	0.400	1.640	1.184
6	624.5	0.0267	0.0751	0.0128	0.0600	0.0456	1.643	3.449	0.443	1.839	1.335
7	736.8	0.0212	0.0523	0.0108	0.0512	0.0377	1.713	3.623	0.479	2.009	1.460
8	849.0	0.0159	0.0443	0.0085	0.0414	0.0321	1.766	3.770	0.507	2.146	1.567
9	961.3	0.0118	0.0342	0.0073	0.0340	0.0264	1.805	3.883	0.531	2.259	1.654
10	1073.5	0.0074	0.0282	0.0061	0.0302	0.0216	1.830	3.977	0.551	2.359	1.726
11	1185.7	0.0063	0.0175	0.0058	0.0251	0.0170	1.851	4.034	0.570	2.442	1.782
12	1298.0	0.0031	0.0110	0.0054	0.0217	0.0155	1.861	4.071	0.588	2.514	1.834
13	1410.2	0.0021	0.0091	0.0047	0.0187	0.0127	1.868	4.101	0.604	2.576	1.876
14	1522.5	0.0015	0.0070	0.0044	0.0179	0.0098	1.873	4.124	0.619	2.636	1.908

Table C- 41. Data for BTEX removal from the 35th regeneration cycle on column LST2

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	91.9	0.0729	0.4224	0.0451	0.1727	0.1014	0.198	1.146	0.122	0.469	0.275
2	210.4	0.0909	0.2358	0.0331	0.1185	0.0819	0.516	1.972	0.238	0.884	0.562
3	328.9	0.0659	0.1684	0.0249	0.0930	0.0658	0.746	2.561	0.325	1.209	0.792
4	444.1	0.0428	0.1079	0.0204	0.0743	0.0574	0.892	2.929	0.395	1.462	0.988
5	559.4	0.0282	0.0801	0.0160	0.0557	0.0485	0.988	3.201	0.449	1.652	1.153
6	674.7	0.0208	0.0627	0.0128	0.0441	0.0427	1.059	3.415	0.493	1.802	1.298
7	790.0	0.0130	0.0473	0.0102	0.0362	0.0362	1.103	3.576	0.528	1.925	1.421
8	905.3	0.0080	0.0355	0.0082	0.0292	0.0311	1.130	3.697	0.556	2.025	1.527
9	1020.5	0.0043	0.0261	0.0069	0.0256	0.0257	1.145	3.785	0.579	2.112	1.615
10	1135.8	0.0037	0.0208	0.0060	0.0229	0.0209	1.158	3.856	0.600	2.190	1.686
11	1251.1	0.0025	0.0182	0.0056	0.0194	0.0173	1.166	3.918	0.619	2.256	1.745
12	1366.4	0.0022	0.0123	0.0052	0.0153	0.0148	1.174	3.960	0.636	2.308	1.795
13	1481.7	0.0015	0.0096	0.0048	0.0129	0.0130	1.179	3.993	0.653	2.352	1.840
14	1596.9	0.0008	0.0063	0.0042	0.0106	0.0113	1.182	4.014	0.667	2.388	1.878

Table C- 42. Data for BTEX removal from the 40th regeneration cycle on column LST2

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	77.4	0.0667	0.4503	0.0438	0.1114	0.1131	0.153	1.029	0.100	0.255	0.258
2	178.9	0.0763	0.2285	0.0304	0.0836	0.0971	0.381	1.715	0.191	0.506	0.550
3	288.3	0.0704	0.1628	0.0219	0.0659	0.0805	0.609	2.241	0.262	0.719	0.810
4	400.6	0.0466	0.1155	0.0154	0.0521	0.0678	0.764	2.624	0.313	0.891	1.035
5	512.8	0.0346	0.0920	0.0118	0.0425	0.0572	0.879	2.929	0.353	1.032	1.224
6	625.0	0.0263	0.0768	0.0092	0.0338	0.0489	0.966	3.183	0.383	1.144	1.387
7	737.3	0.0169	0.0592	0.0070	0.0296	0.0401	1.022	3.380	0.406	1.242	1.520
8	849.5	0.0140	0.0484	0.0062	0.0237	0.0343	1.068	3.540	0.427	1.321	1.633
9	961.8	0.0101	0.0276	0.0051	0.0188	0.0281	1.102	3.632	0.444	1.383	1.726
10	1074.0	0.0084	0.0250	0.0042	0.0158	0.0218	1.130	3.714	0.458	1.436	1.799
11	1186.3	0.0058	0.0185	0.0042	0.0124	0.0179	1.149	3.776	0.471	1.476	1.858
12	1298.5	0.0046	0.0146	0.0037	0.0115	0.0156	1.164	3.824	0.484	1.515	1.910
13	1410.8	0.0026	0.0104	0.0036	0.0097	0.0119	1.173	3.859	0.496	1.547	1.949
14	1523.0	0.0012	0.0092	0.0035	0.0075	0.0118	1.177	3.889	0.507	1.572	1.988

Table C- 43. Data for BTEX removal from the 45th regeneration cycle on column LST2

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	98.7	0.0696	0.3926	0.0375	0.1675	0.1187	0.203	1.144	0.109	0.488	0.346
2	205.3	0.0820	0.2073	0.0282	0.1236	0.0963	0.461	1.797	0.198	0.877	0.649
3	314.7	0.0607	0.1525	0.0225	0.0984	0.0793	0.657	2.290	0.271	1.195	0.906
4	424.0	0.0294	0.1101	0.0183	0.0748	0.0675	0.752	2.645	0.330	1.437	1.124
5	536.3	0.0205	0.0833	0.0144	0.0613	0.0589	0.820	2.922	0.378	1.640	1.319
6	648.5	0.0152	0.0630	0.0123	0.0513	0.0504	0.870	3.131	0.418	1.810	1.486
7	760.8	0.0116	0.0505	0.0101	0.0414	0.0439	0.909	3.298	0.452	1.947	1.632
8	873.0	0.0089	0.0429	0.0088	0.0331	0.0363	0.938	3.440	0.481	2.057	1.752
9	985.3	0.0067	0.0354	0.0075	0.0252	0.0292	0.961	3.557	0.506	2.141	1.849
10	1097.5	0.0049	0.0298	0.0060	0.0213	0.0247	0.977	3.656	0.526	2.211	1.930
11	1209.8	0.0026	0.0212	0.0054	0.0188	0.0198	0.985	3.727	0.544	2.274	1.996
12	1322.0	0.0024	0.0156	0.0045	0.0169	0.0167	0.993	3.778	0.559	2.330	2.052
13	1434.3	0.0015	0.0088	0.0043	0.0119	0.0145	0.998	3.808	0.573	2.369	2.100
14	1546.5	0.0009	0.0069	0.0037	0.0099	0.0124	1.001	3.831	0.585	2.402	2.141

Table C- 44. Data for BTEX removal from the 50^{h} regeneration cycle on column LS

		Concentration (mg/L)					Mass Removed (mg)				
Sample	Pore Volumes	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
1	69.2	0.0911	0.3984	0.0510	0.1662	0.1228	0.186	0.815	0.104	0.340	0.251
2	173.3	0.1170	0.2373	0.0374	0.1274	0.0991	0.546	1.544	0.219	0.732	0.556
3	291.8	0.0748	0.1595	0.0285	0.0963	0.0794	0.808	2.103	0.319	1.069	0.833
4	407.0	0.0380	0.1060	0.0197	0.0746	0.0676	0.937	2.464	0.386	1.323	1.064
5	519.3	0.0224	0.0821	0.0160	0.0589	0.0580	1.011	2.736	0.439	1.518	1.256
6	631.5	0.0166	0.0638	0.0129	0.0473	0.0492	1.066	2.948	0.482	1.675	1.419
7	743.8	0.0127	0.0480	0.0106	0.0348	0.0433	1.108	3.107	0.517	1.790	1.563
8	856.0	0.0087	0.0368	0.0090	0.0287	0.0366	1.137	3.229	0.547	1.885	1.684
9	968.3	0.0047	0.0259	0.0073	0.0244	0.0312	1.153	3.314	0.571	1.966	1.788
10	1080.5	0.0036	0.0192	0.0058	0.0220	0.0249	1.165	3.378	0.590	2.039	1.870
11	1192.8	0.0028	0.0152	0.0053	0.0187	0.0199	1.174	3.429	0.608	2.101	1.936
12	1305.0	0.0021	0.0110	0.0047	0.0163	0.0169	1.181	3.465	0.623	2.155	1.992
13	1417.3	0.0014	0.0081	0.0039	0.0118	0.0147	1.186	3.492	0.636	2.194	2.041
14	1529.5	0.0009	0.0040	0.0036	0.0108	0.0136	1.189	3.505	0.648	2.230	2.086

Table C- 45. Cumulative BTEX mass sorbed and removed from column LST1.

Cycle		Concentration (mg/L)					Mean % recovery (std. dev.)
		Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	
1	sorption	0.864	4.301	0.487	2.131	2.068	
	regeneration	0.862	4.374	0.493	2.069	1.888	
	% recovery	99.8	101.7	101.2	97.1	91.3	98.2 (4.2)
5	sorption	0.863	4.232	0.462	2.292	2.264	
	regeneration	0.886	3.930	0.493	2.224	2.059	
	% recovery	102.7	92.9	106.8	97.1	90.9	98.1 (6.7)
10	sorption	0.944	3.854	0.434	2.026	1.639	
	regeneration	0.919	3.946	0.409	1.957	1.648	
	% recovery	97.3	102.4	94.1	96.6	100.5	98.2 (3.3)
15	sorption	0.886	4.607	0.538	2.043	1.842	
	regeneration	0.911	4.566	0.517	1.992	1.856	
	% recovery	102.8	99.1	96.1	97.5	100.8	99.3 (2.6)
20	sorption	0.982	4.229	0.561	2.237	1.918	
	regeneration	0.902	3.827	0.542	2.221	1.861	
	% recovery	91.9	90.5	96.7	99.2	97.0	95.1 (3.7)
25	sorption	1.103	4.569	0.477	2.308	1.778	
	regeneration	1.031	4.477	0.472	2.296	1.795	
	% recovery	93.5	98.0	99.0	99.5	100.9	98.2 (2.8)
30	sorption	0.867	4.175	0.431	2.179	1.786	
	regeneration	0.924	4.518	0.437	2.330	1.981	
	% recovery	106.6	108.2	101.4	106.9	110.9	106.8 (3.4)
35	sorption	0.763	4.268	0.582	2.076	1.753	
	regeneration	0.825	4.360	0.571	2.244	1.871	
	% recovery	108.1	102.2	98.2	108.1	106.7	104.6 (4.3)
40	sorption	0.996	4.158	0.546	2.108	1.834	
	regeneration	0.947	3.963	0.535	2.042	1.776	
	% recovery	95.0	95.3	98.1	96.9	96.9	96.4 (1.3)
45	sorption	0.798	3.993	0.431	2.173	1.657	
	regeneration	0.830	4.063	0.424	2.193	1.662	
	% recovery	104.0	101.7	98.5	100.9	100.3	101.1 (2.0)
50	sorption	0.823	4.234	0.460	2.182	1.966	
	regeneration	0.903	4.383	0.484	2.181	1.986	
	% recovery	109.6	103.5	105.1	100.0	101.0	103.9 (3.8)
	Mean % recovery (std. dev.)	101.1 (6.0)	99.5 (5.1)	99.5 (3.8)	100.0 (4.0)	99.8 (5.9)	

Table C- 46. Cumulative BTEX mass sorbed and removed from column LST2.

		Concentration (mg/L)					Mean % recovery (std. dev.)
Cycle		Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene	
1	sorption	1.23	4.77	0.40	1.73	2.23	
	regeneration	1.34	4.85	0.41	1.80	2.28	
	% recovery	109.2	101.6	102.0	103.8	102.4	103.8 (3.1)
5	sorption	1.46	5.32	0.53	1.98	1.74	
	regeneration	1.58	5.51	0.54	2.06	1.75	
	% recovery	108.3	103.6	103.2	104.0	100.8	104.0 (2.7)
10	sorption	1.50	4.30	0.75	2.29	2.30	
	regeneration	1.45	4.04	0.71	2.26	2.15	
	% recovery	96.8	94.0	94.6	98.7	93.7	95.6 (2.2)
15	sorption	1.29	3.83	0.42	2.33	1.60	
	regeneration	1.25	3.89	0.44	2.19	1.49	
	% recovery	96.6	101.6	103.3	94.0	93.0	97.7 (4.6)
20	sorption	0.96	4.02	0.56	2.29	1.75	
	regeneration	0.92	3.74	0.53	2.18	1.66	
	% recovery	95.9	93.2	95.9	95.2	94.5	95.0 (1.2)
25	sorption	1.14	3.44	0.48	1.96	1.44	
	regeneration	1.20	3.65	0.52	2.01	1.53	
	% recovery	105.3	106.2	106.8	102.7	106.4	105.5 (1.6)
30	sorption	1.80	3.97	0.64	2.52	1.86	
	regeneration	1.87	4.12	0.62	2.64	1.91	
	% recovery	104.0	103.9	96.3	104.5	102.6	102.3 (3.4)
35	sorption	1.20	4.13	0.64	2.34	1.84	
	regeneration	1.18	4.01	0.67	2.39	1.88	
	% recovery	98.3	97.3	104.0	102.0	102.3	100.8 (2.8)
40	sorption	1.25	4.13	0.52	1.68	2.03	
	regeneration	1.18	3.89	0.51	1.57	1.99	
	% recovery	94.2	94.2	98.3	93.4	97.9	95.6 (2.3)
45	sorption	0.98	3.88	0.58	2.34	2.05	
	regeneration	1.00	3.83	0.59	2.40	2.14	
	% recovery	101.7	98.8	100.8	102.8	104.5	101.7 (2.1)
50	sorption	1.09	3.23	0.58	2.07	1.98	
	regeneration	1.19	3.51	0.65	2.23	2.09	
	% recovery	108.6	108.6	111.7	107.5	105.2	108.3 (2.4)
	Mean % recovery (std. dev.)	101.7 (5.6)	100.3 (5.2)	101.5 (5.1)	100.8 (4.7)	100.3 (4.8)	

Table C- 47. Calculated K_d values for BTEX from columns LST1 and LST2

Column	Cycle	K_d (l/kg)				
		Benzene	Toluene	Ethylbenzene	p- & m-xylene	o-xylene
Column LST1	1	12.6	35.2	70.4	77.0	75.5
	5	12.1	30.5	80.9	67.0	65.5
	10	15.9	29.5	66.1	60.1	62.2
	15	13.1	33.5	67.9	68.9	69.9
	20	13.9	31.2	65.1	69.8	66.8
	25	18.6	35.4	82.2	73.1	78.9
	30	13.2	33.3	57.8	60.5	73.3
	35	10.9	26.2	65.3	71.8	52.8
	40	11.9	27.4	66.8	66.0	60.5
	45	11.0	39.3	61.7	62.7	53.0
	50	11.3	28.6	59.1	67.6	52.6
Column LST2	1	15.8	34.0	62.5	67.1	68.4
	5	14.1	34.4	67.0	64.4	65.3
	10	13.7	32.2	61.6	71.6	68.3
	15	15.9	28.4	60.7	64.8	62.9
	20	14.1	26.6	70.2	66.4	56.0
	25	15.3	29.3	68.3	57.6	66.4
	30	17.5	27.1	64.7	66.7	56.3
	35	16.5	28.9	56.2	59.2	69.0
	40	13.6	31.6	56.5	54.3	62.8
	45	10.8	24.9	63.1	58.4	60.3
	50	13.3	25.6	59.1	60.1	55.9

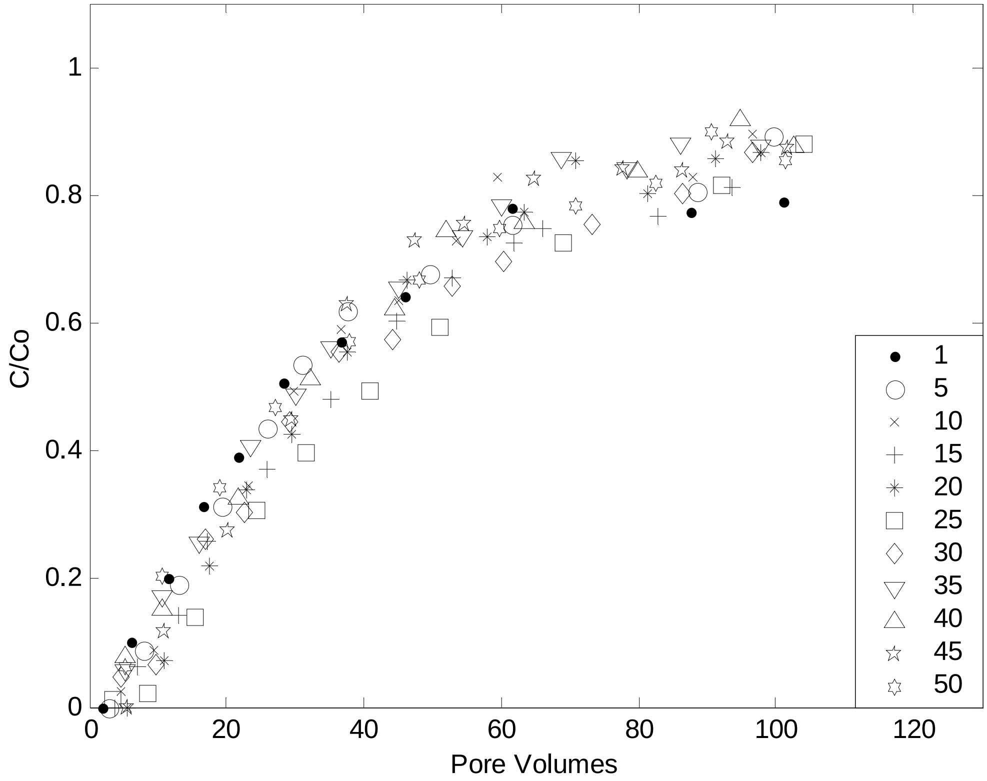

Figure C- 1. BTCs of toluene for every fifth sorption cycle on column LST1.

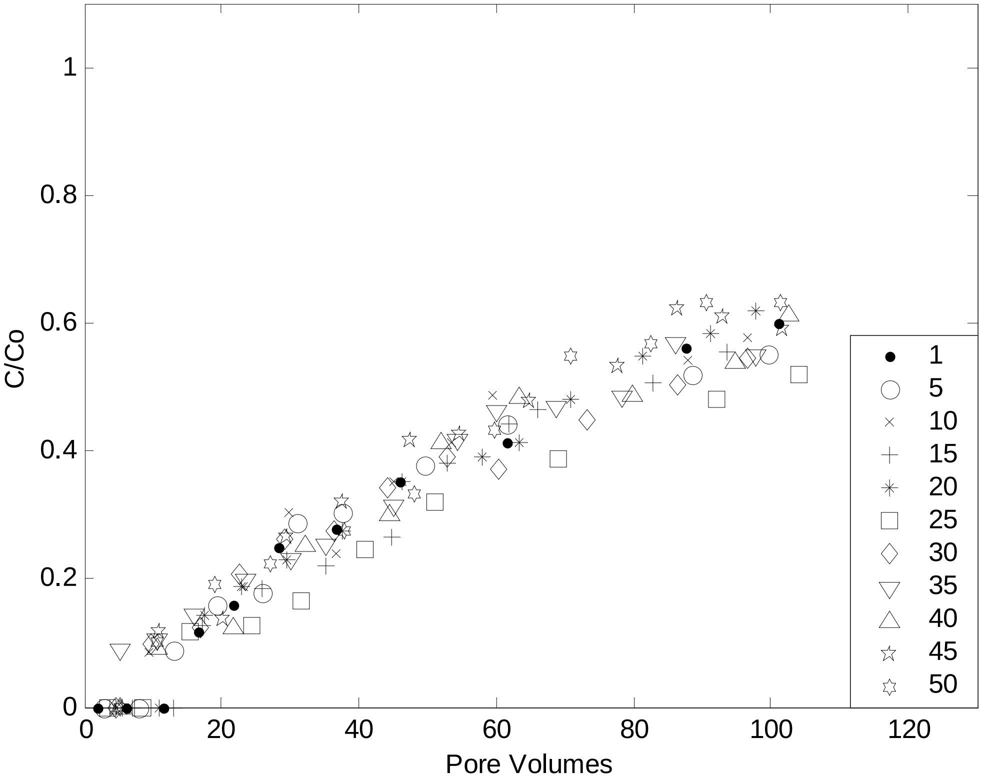

Figure C- 2. BTCs of ethylbenzene for every fifth sorption cycle on column LST1.

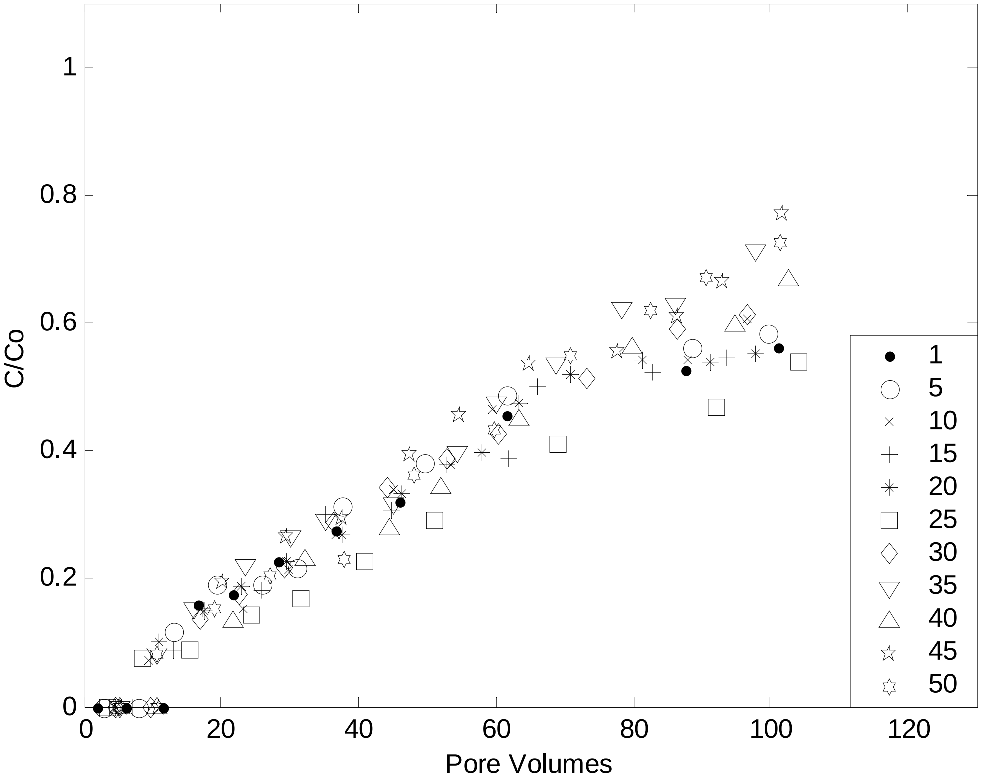

Figure C- 3. BTCs of o-xylene for every fifth sorption cycle on column LST1.

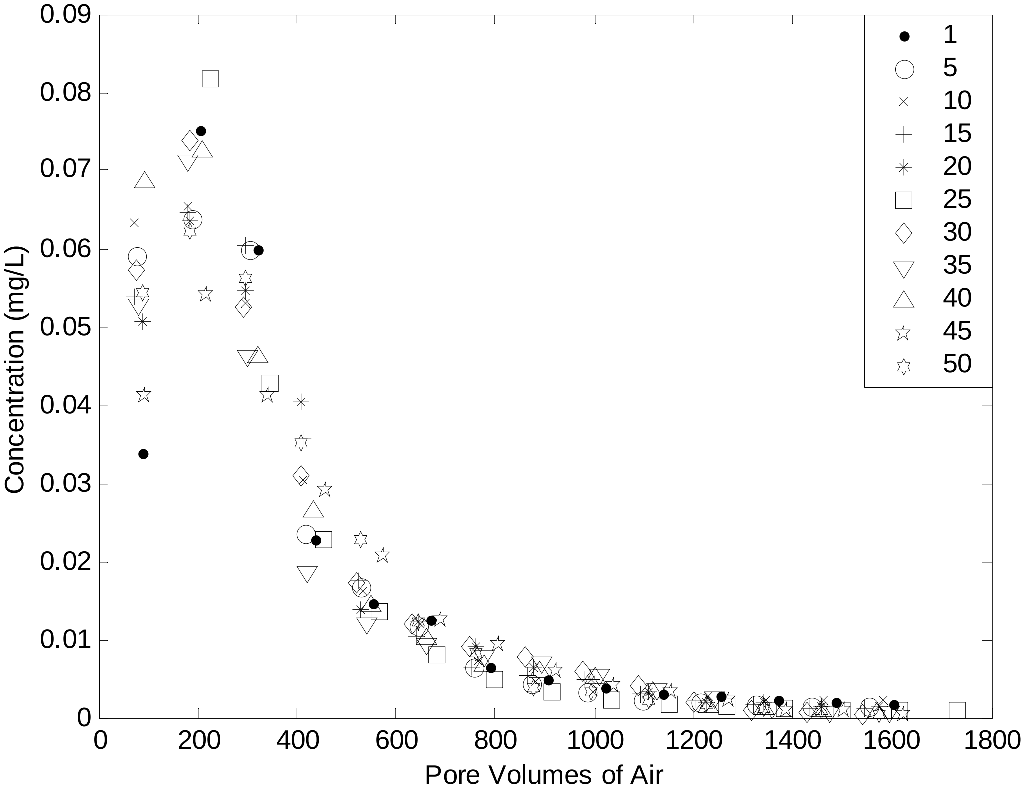

Figure C- 4. Benzene removal for every fifth regeneration cycle on column LST1.

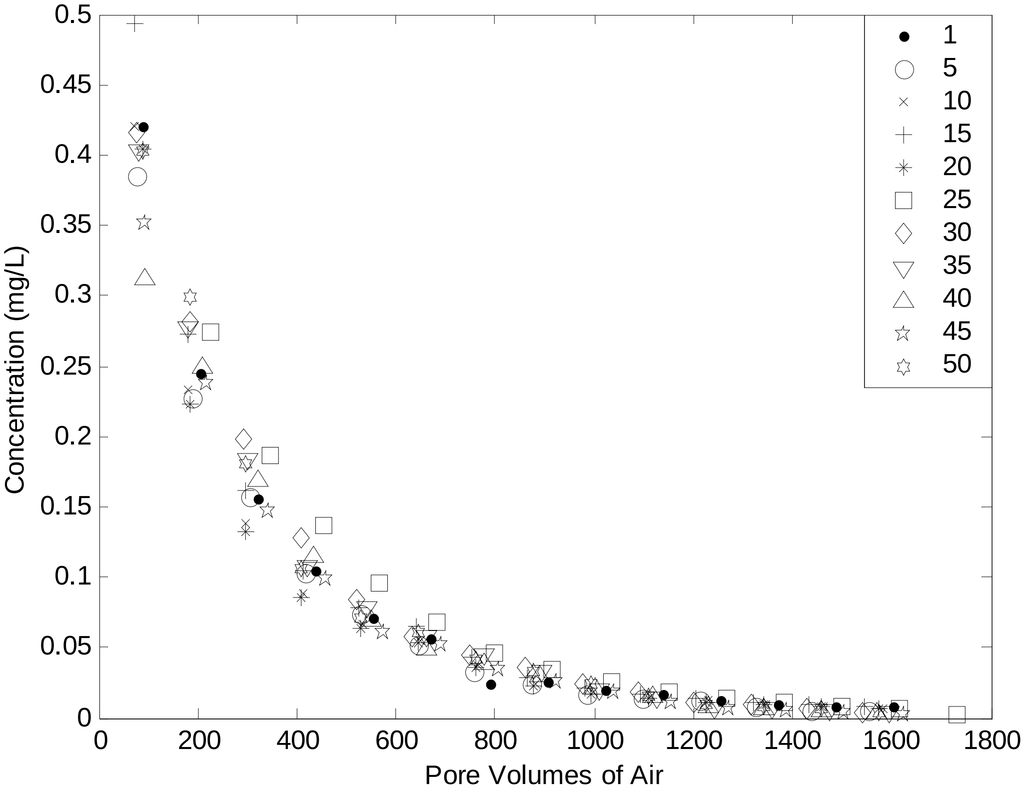

Figure C- 5. Toluene removal for every fifth regeneration cycle on column LST1.

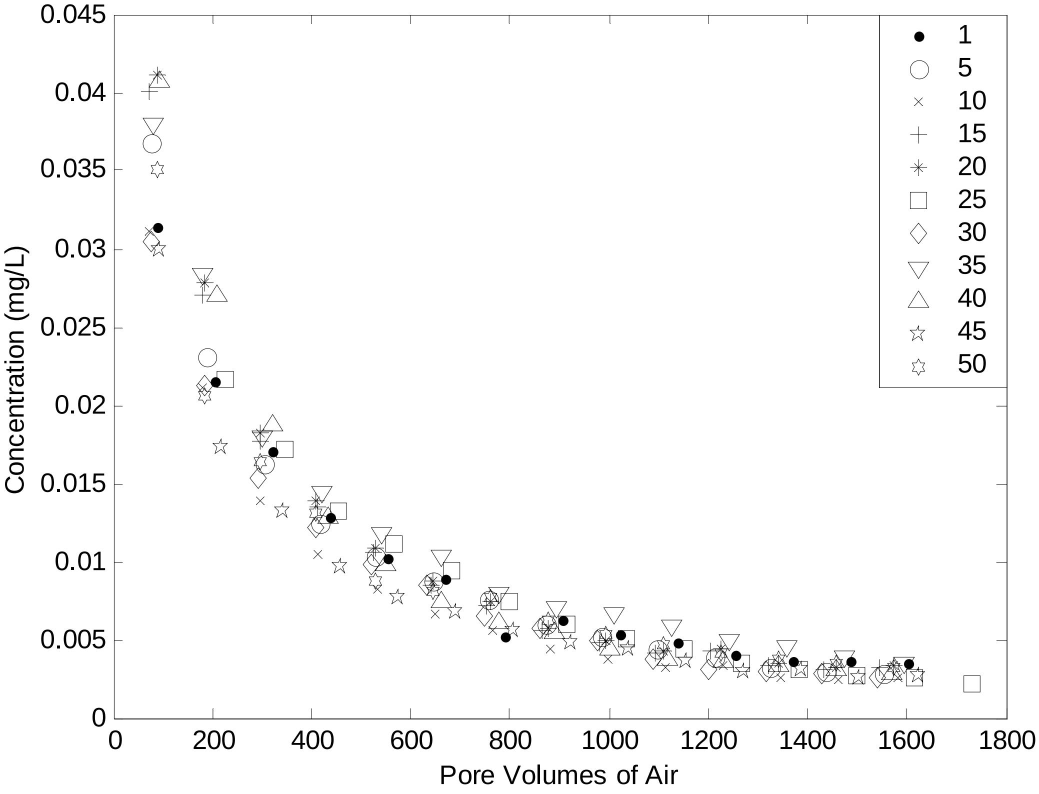

Figure C- 6. Ethylbenzene removal for every fifth regeneration cycle on column LST1.

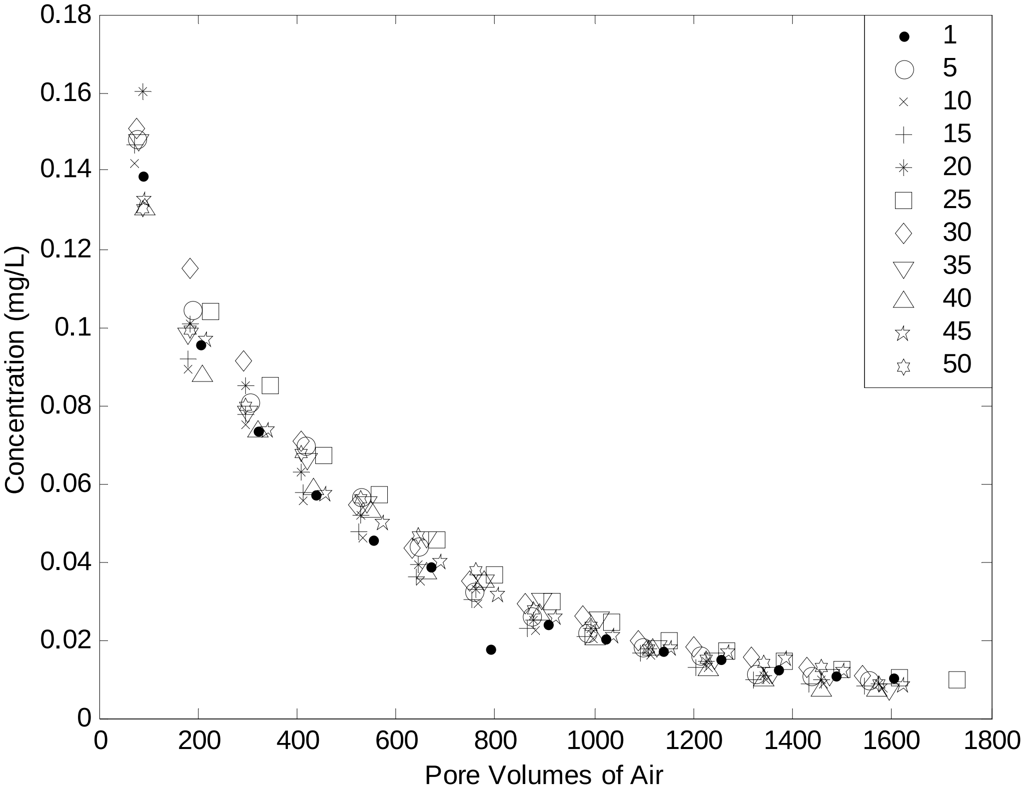

Figure C- 7. p- & m-xylene removal for every fifth regeneration cycle on column LST1.

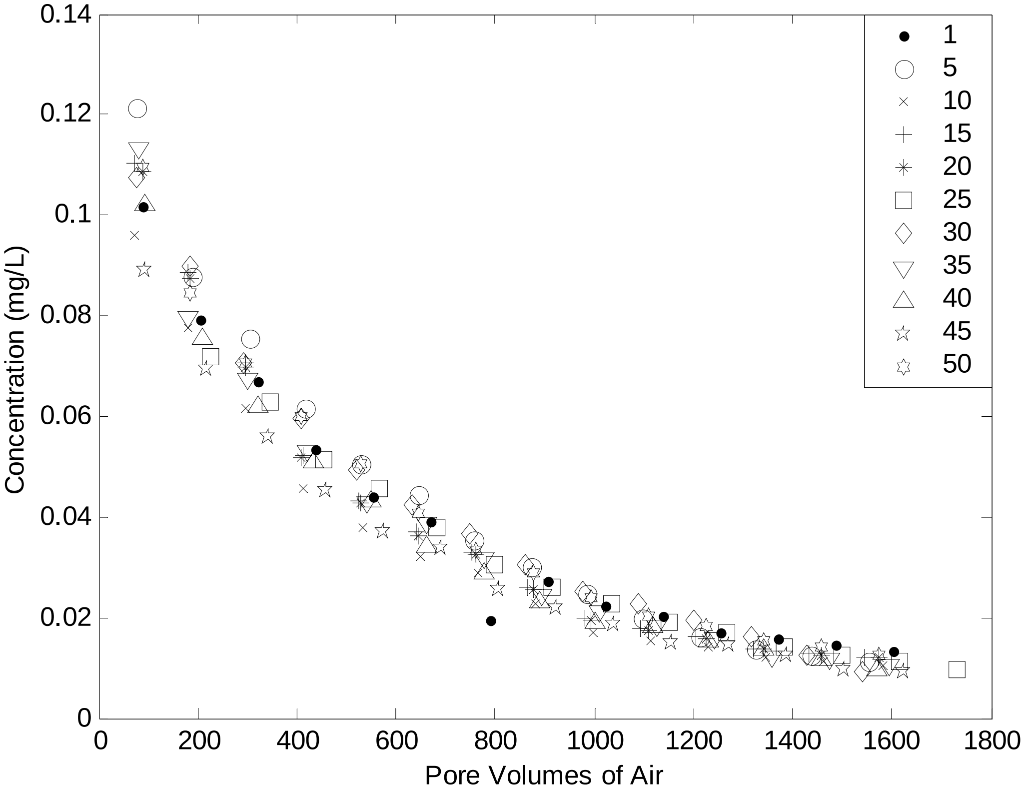

Figure C- 8. o-xylene removal for every fifth regeneration cycle on column LST1.

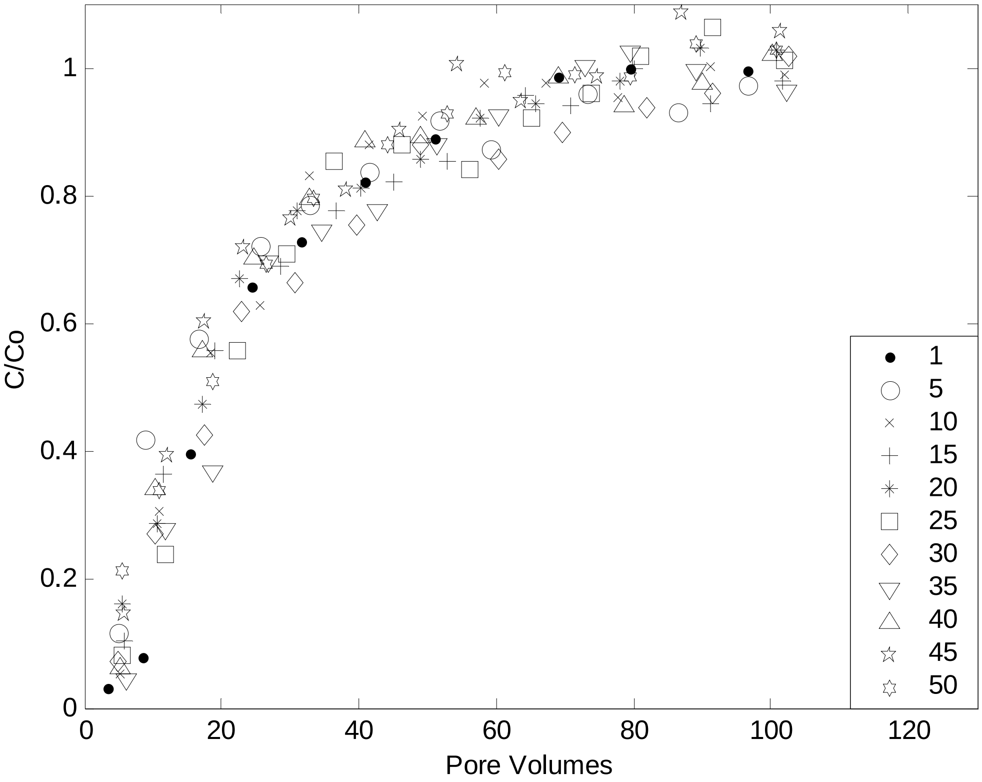

Figure C- 9. BTCs of benzene for every fifth sorption cycle on column LST2.

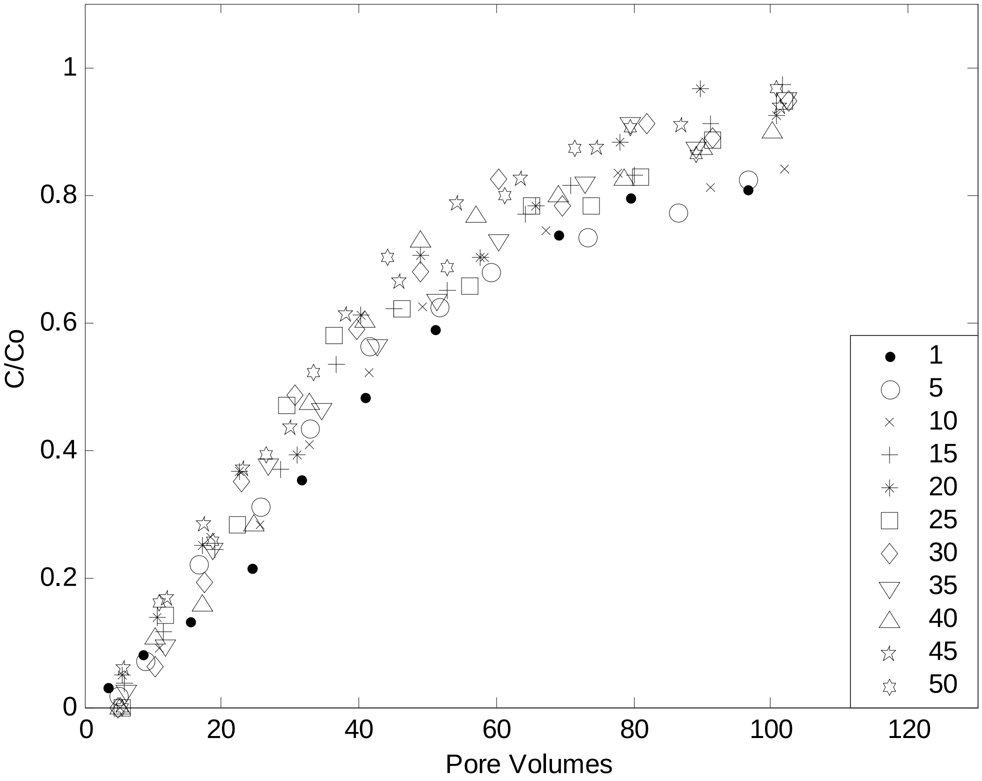

Figure C- 10. BTCs of toluene for every fifth sorption cycle on column LST2.

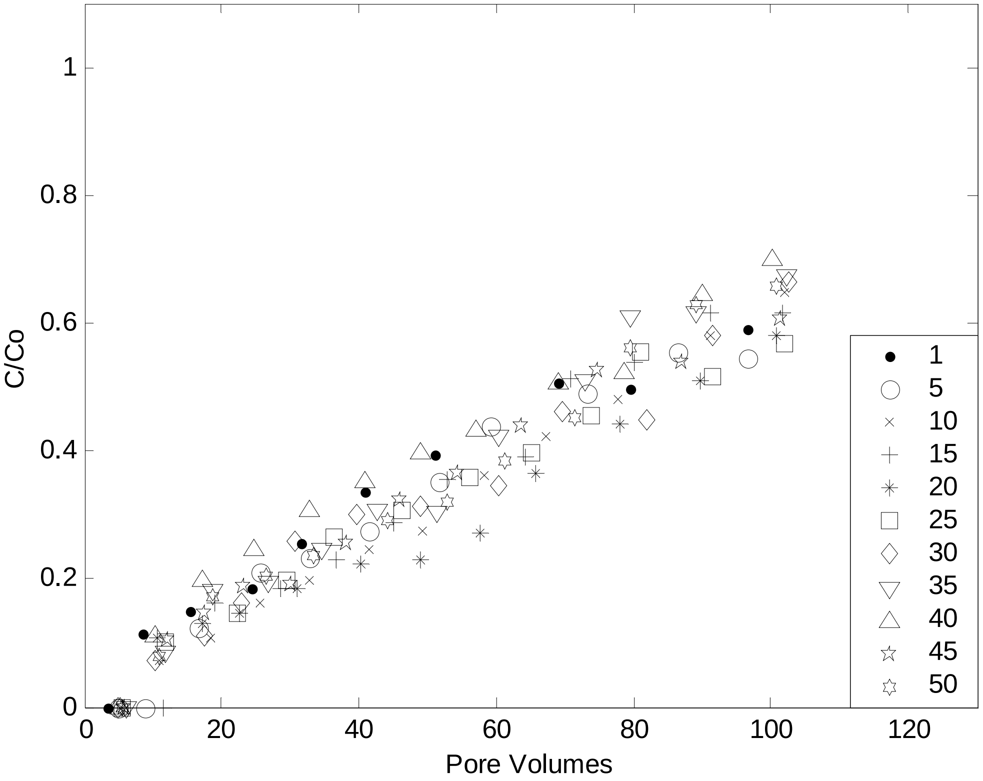

Figure C- 11. BTCs of ethylbenzene for every fifth sorption cycle on column LST2.

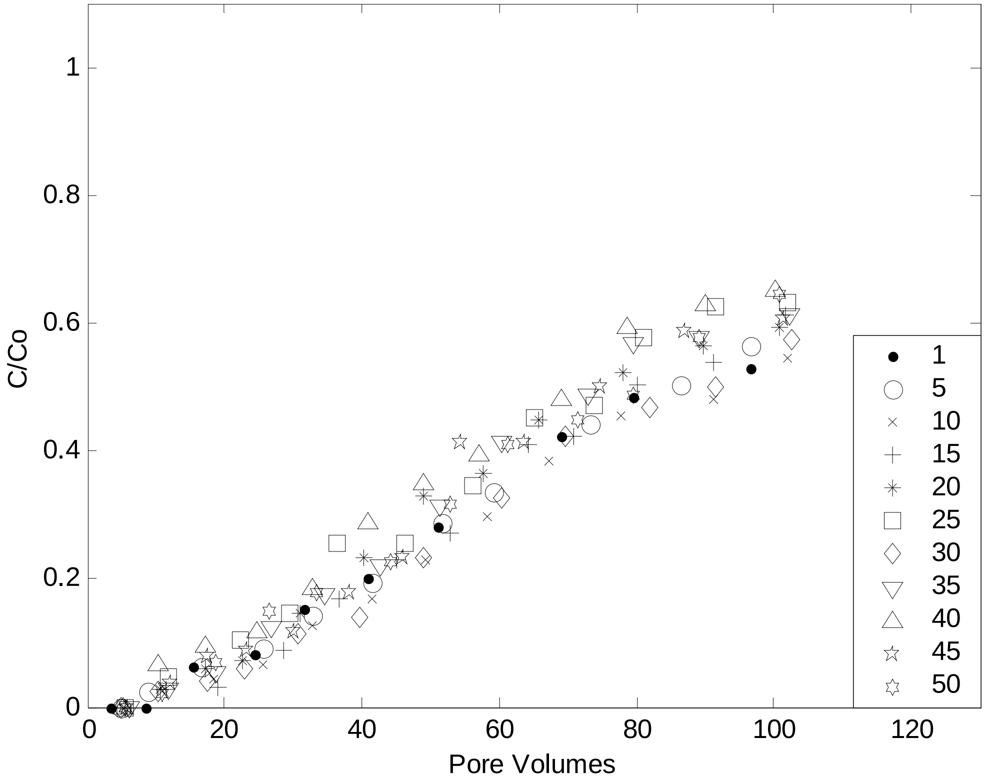

Figure C- 12. BTCs of p- & m-xylene for every fifth sorption cycle on column LST2.

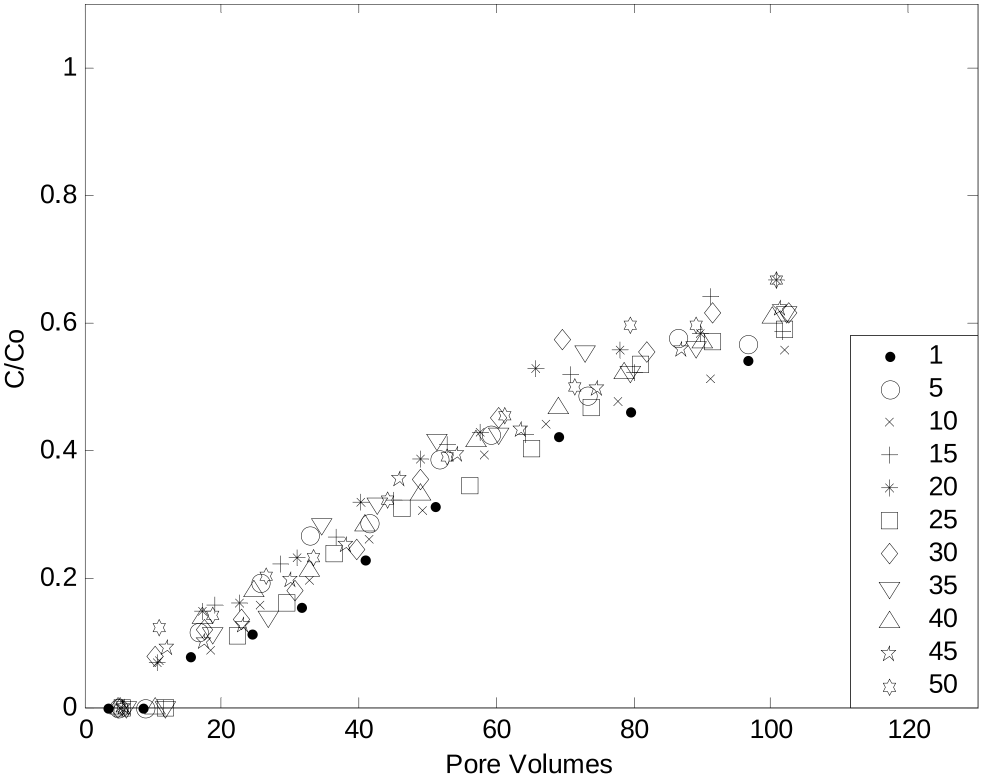

Figure C- 13. BTCs o-xylene for every fifth sorption cycle on column LST2.

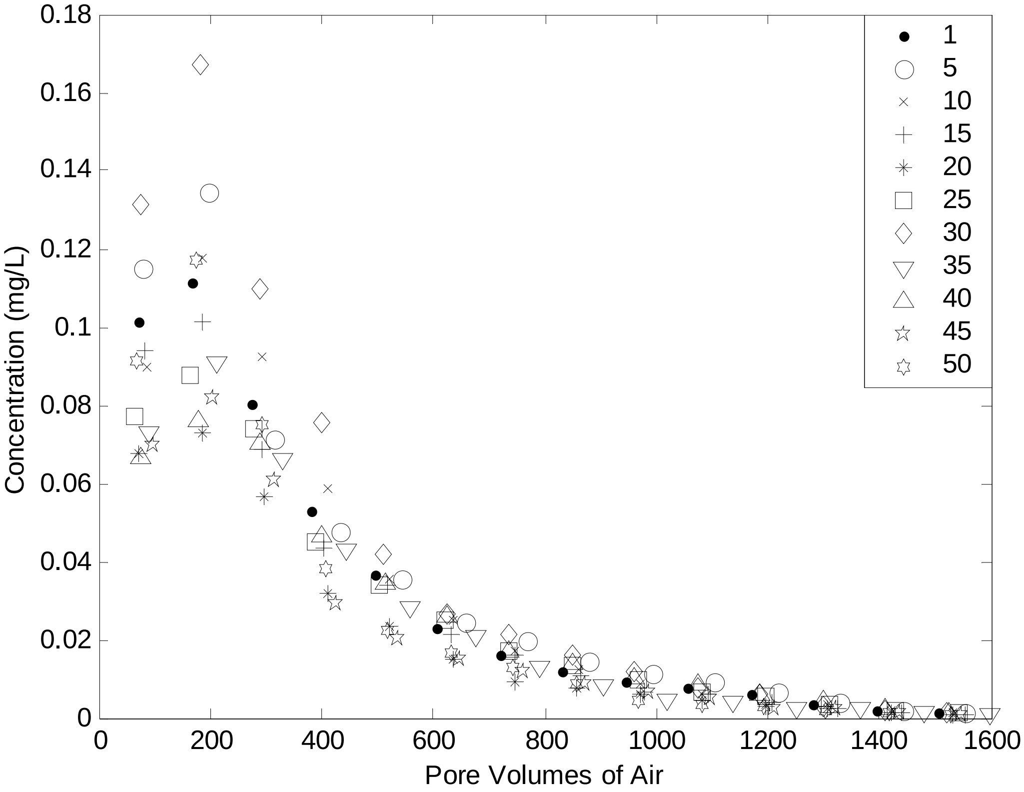

Figure C- 14. Benzene removal for every fifth regeneration cycle on column LST2

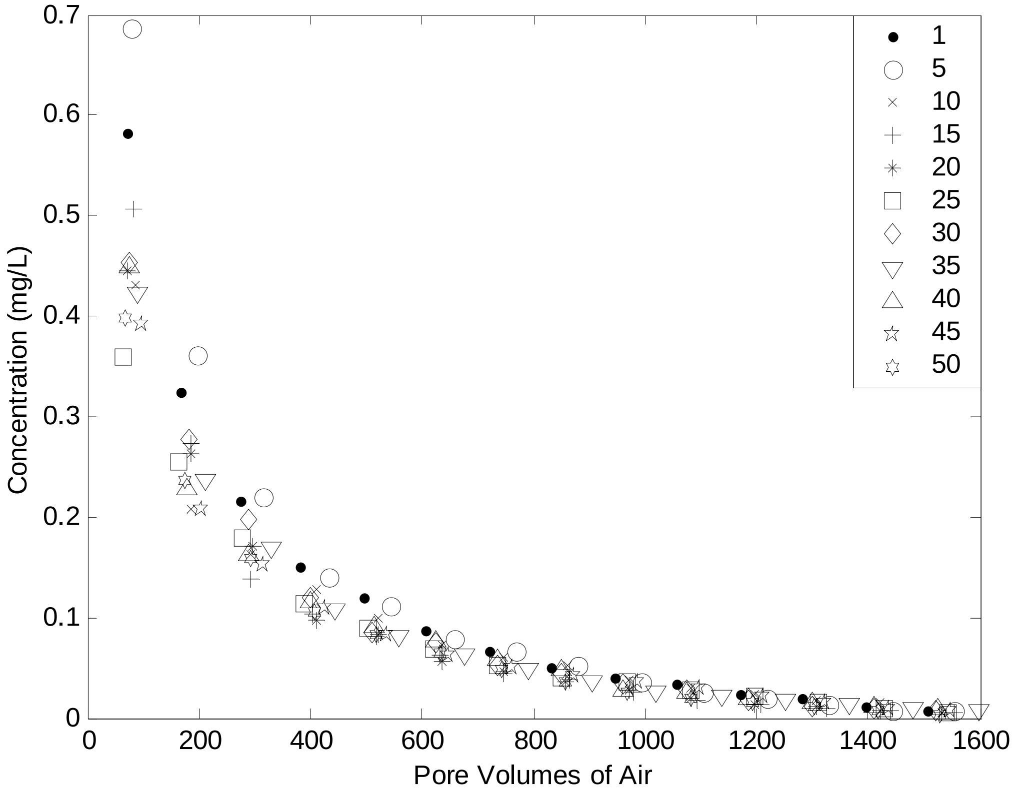

Figure C- 15. Toluene removal for every fifth regeneration cycle on column LST2

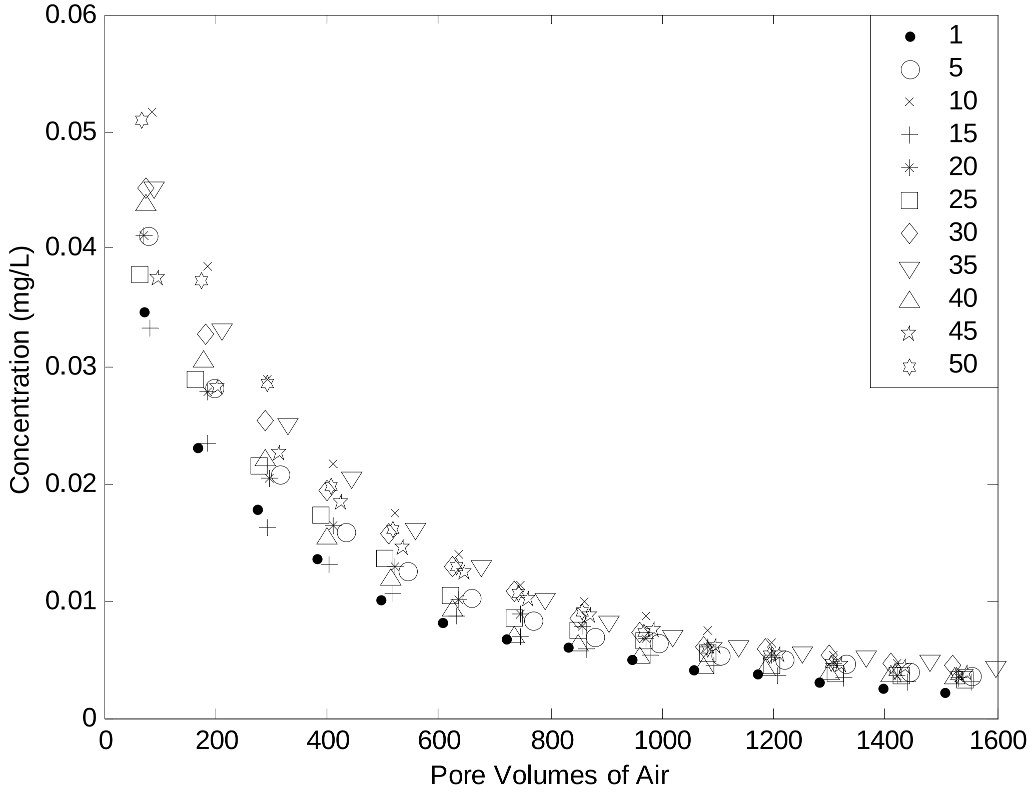

Figure C- 16. Ethylbenzene removal for every fifth regeneration cycle on column LST2

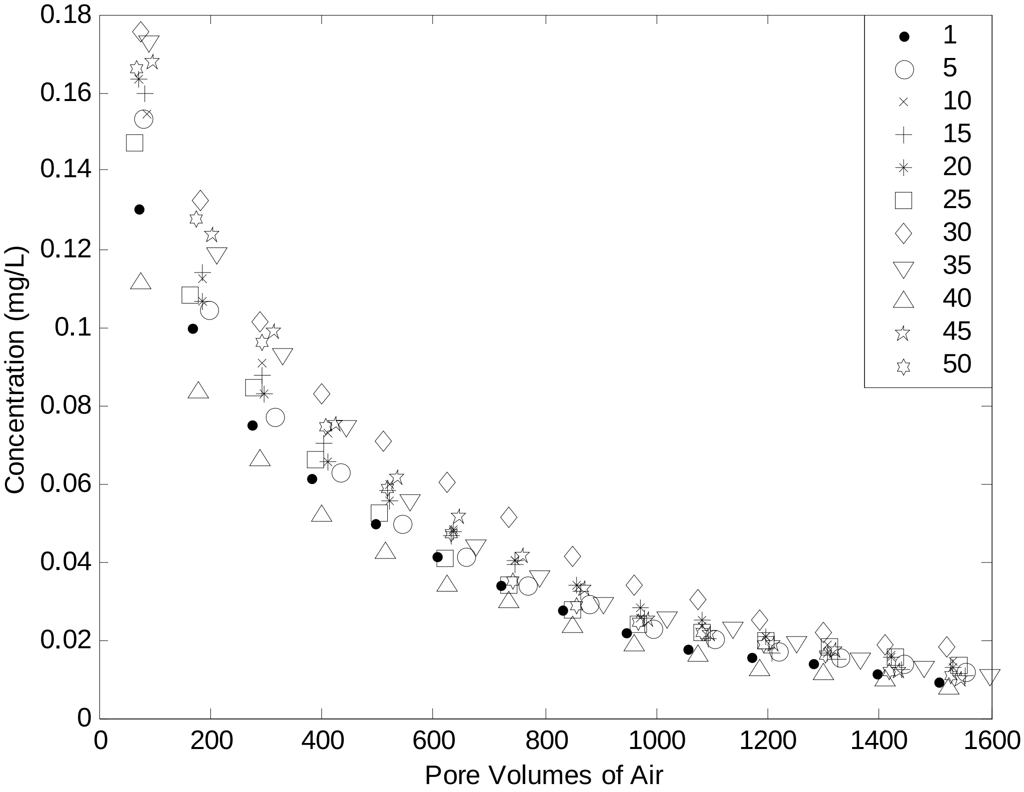

Figure C- 17. p- & m-xylene removal for every fifth regeneration cycle on column LST2

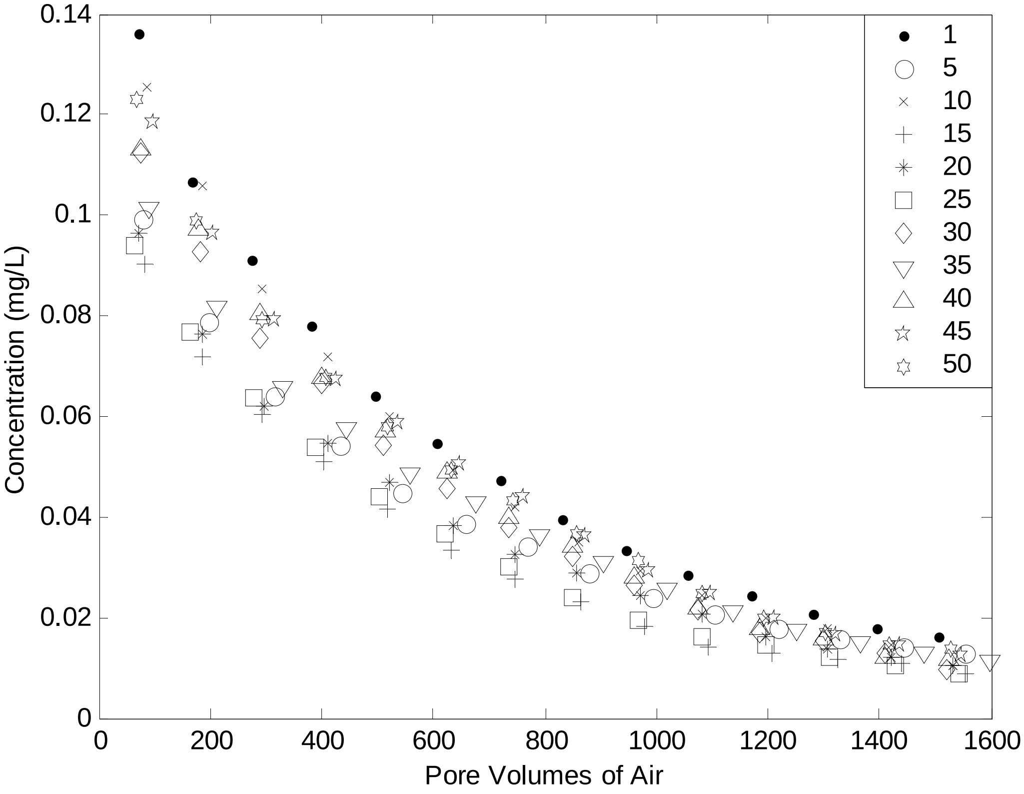

Figure C- 18. o-xylene removal for every fifth regeneration cycle on column LST2

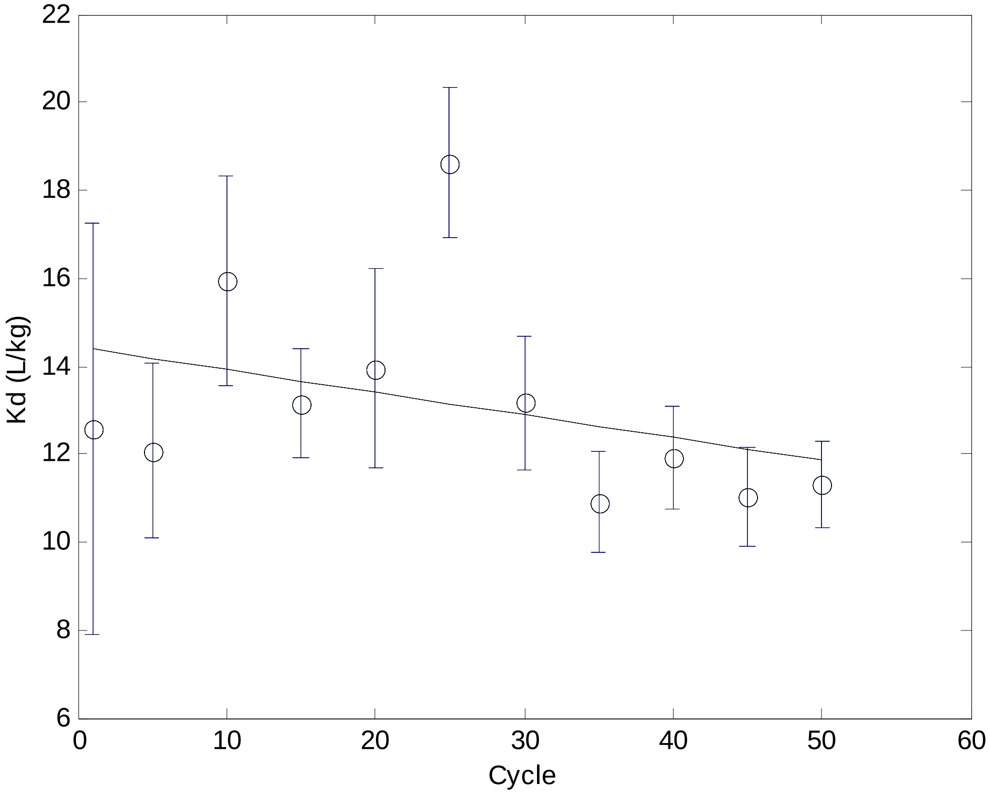

Figure C- 19. ***K**$_d$***’s and linear regression fit to the *K*$_d$ values for benzene from column LST1. Error bars represent the 95% confidence interval from the curve-fit process using CXTFIT.**

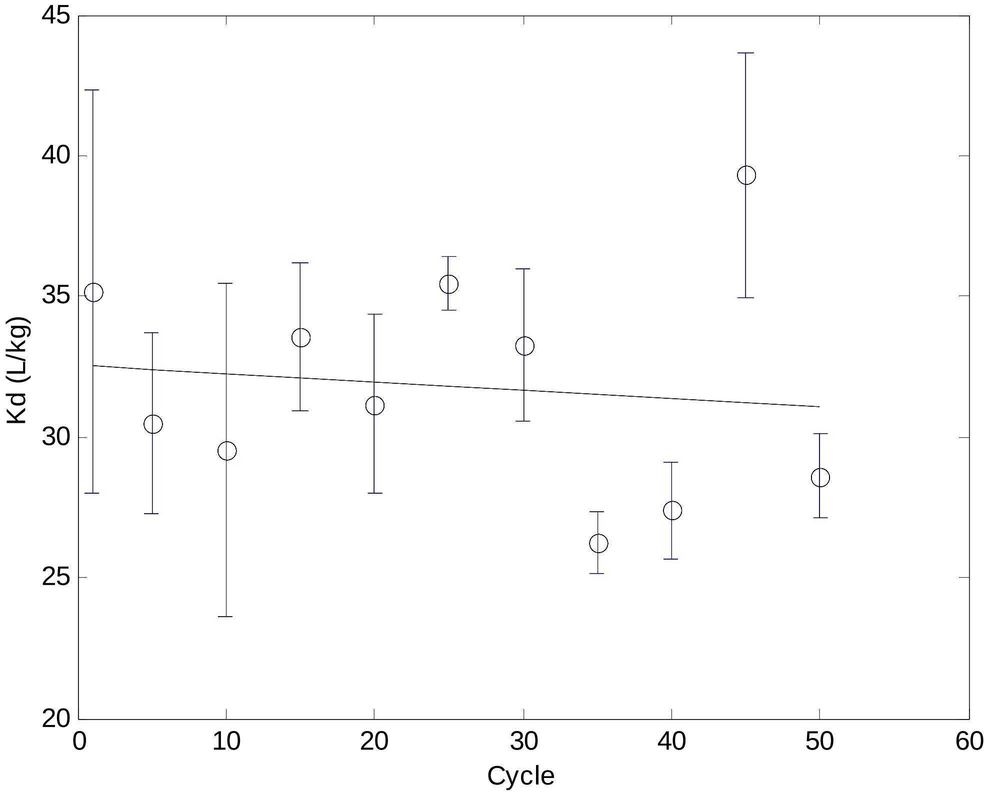

Figure C- 20. *K_d*'s and linear regression fit to the *K_d* values for toluene from column LST1. Error bars represent the 95% confidence interval from the curve-fit process using CXTFIT.

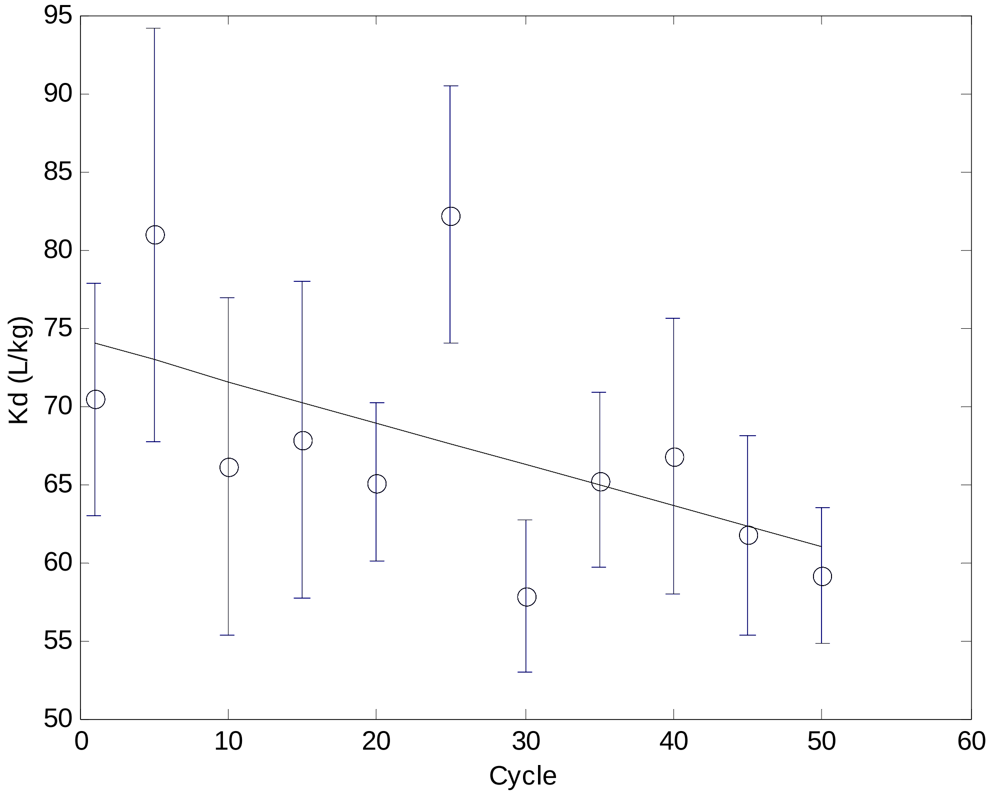

Figure C- 21. K_d's and linear regression fit to the K_d values for ethylbenzene from column LST1. Error bars represent the 95% confidence interval from the curve-fit process using CXTFIT.

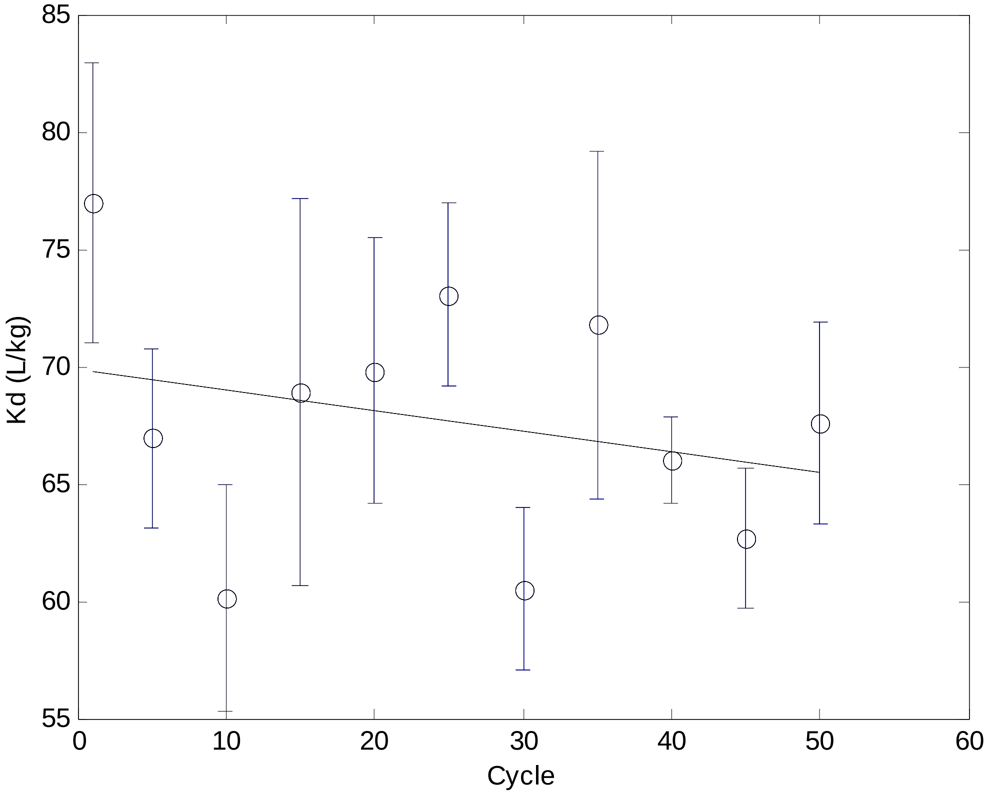

Figure C- 22. *K_d*'s and linear regression fit to the *K_d* values for *p*- & *m*-xylene from column LST1. Error bars represent the 95% confidence interval from the curve-fit process using CXTFIT.

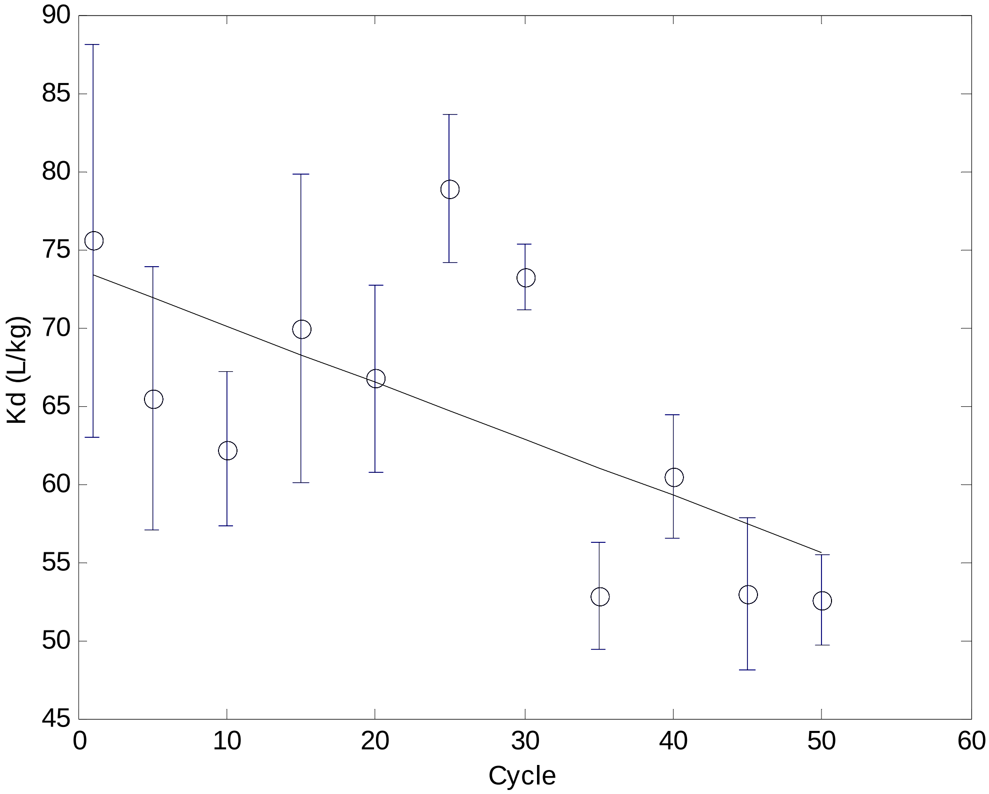

Figure C- 23. *K_d*'s and linear regression fit to the *K_d* values for *o*-xylene from column LST1. Error bars represent the 95% confidence interval from the curve-fit process using CXTFIT.

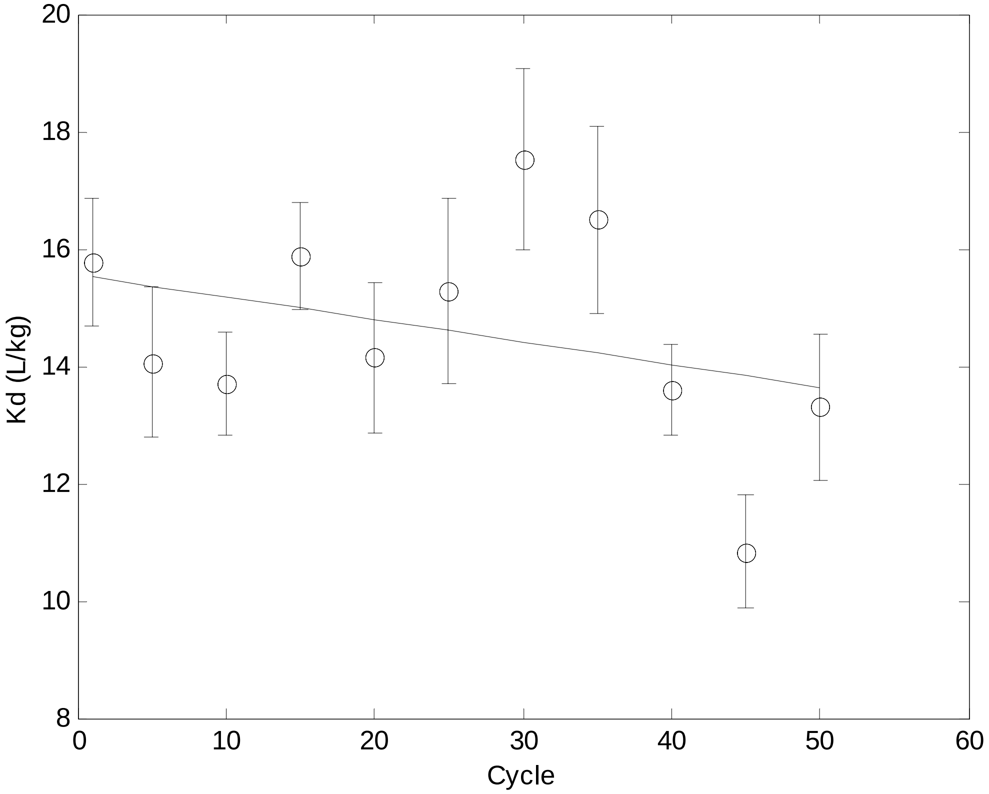

Figure C- 24. *K_d*'s and linear regression fit to the *K_d* values for benzene from column LST2. Error bars represent the 95% confidence interval from the curve-fit process using CXTFIT.

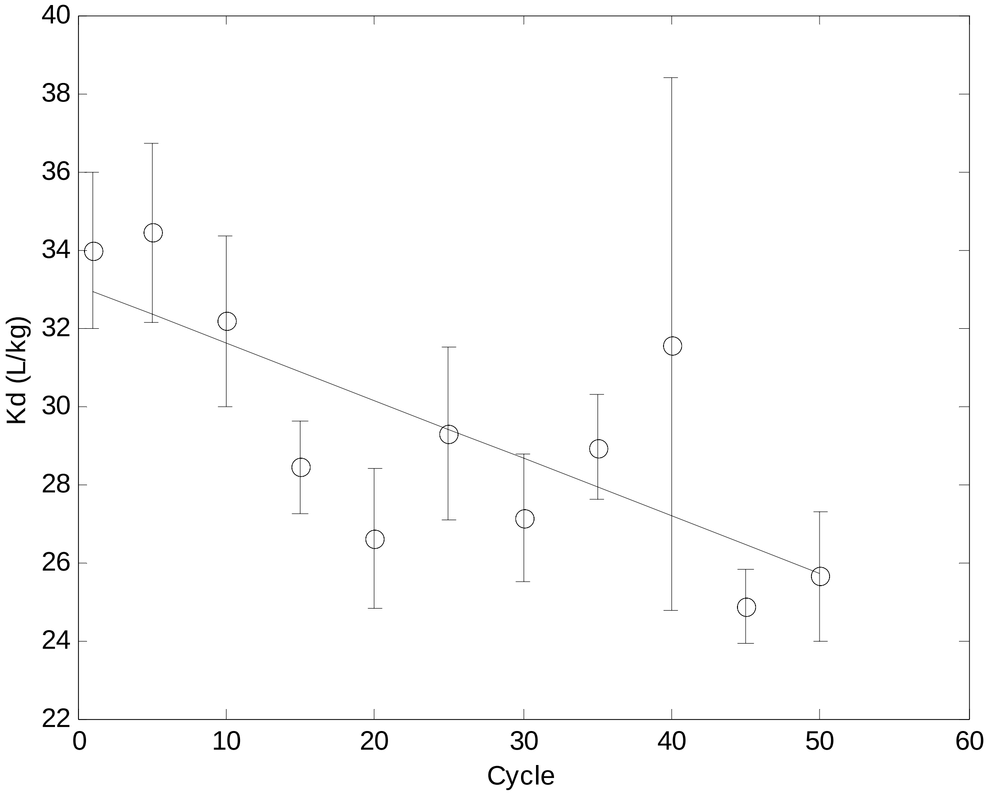

Figure C- 25. *K_d*'s and linear regression fit to the *K_d* values for toluene from column LST2. Error bars represent the 95% confidence interval from the curve-fit process using CXTFIT.

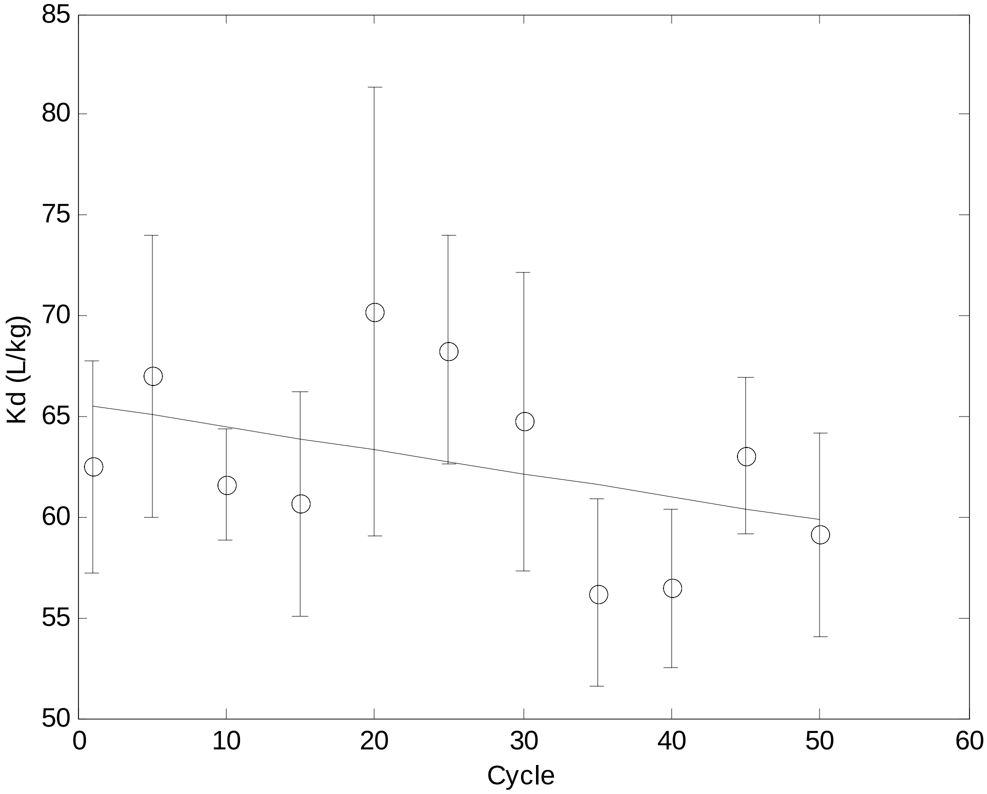

Figure C- 26. K_d's and linear regression fit to the K_d values for ethylbenzene from column LST2. Error bars represent the 95% confidence interval from the curve-fit process using CXTFIT.

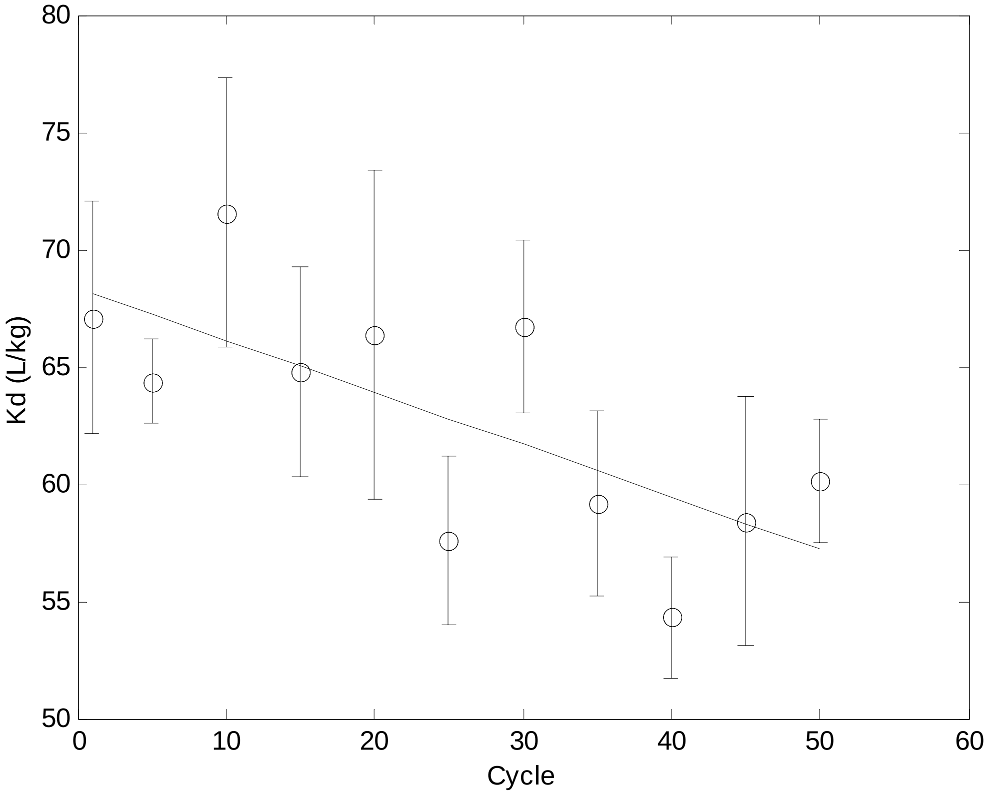

Figure C- 27. *K_d*'s and linear regression fit to the *K_d* values for *p*- & *m*-xylene from column LST2. Error bars represent the 95% confidence interval from the curve-fit process using CXTFIT.

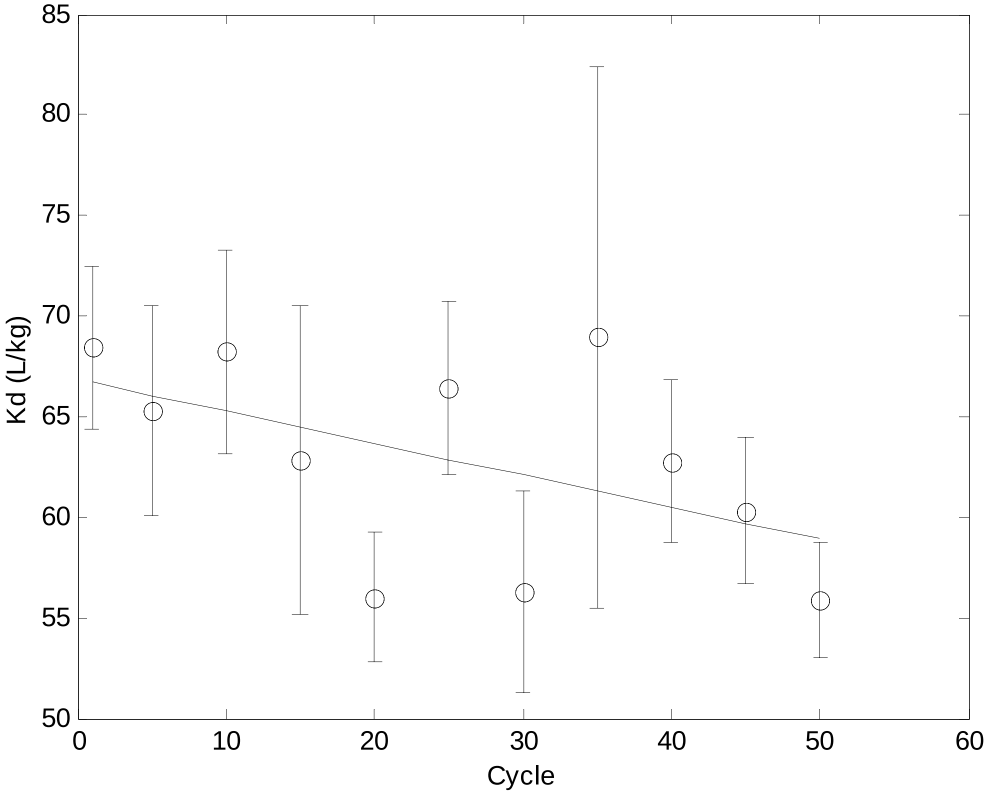

Figure C- 28. ***K_d*****'s and linear regression fit to the** ***K_d*** **values for** ***o*****-xylene from column LST2. Error bars represent the 95% confidence interval from the curve-fit process using CXTFIT.**

APPENDIX D. HYDRAULIC CONDUCTIVITY AND GRAIN SIZE MEASUREMENTS FOR THE LONG-TERM STABILITY EXPERIMENTS

Appendix D contains the results of hydraulic conductivity and grain size measurements for columns LST1 and LST2. Table D-1 contains all conductivity values recorded for the LST experiments as well as the conductivity of the used column with new frits in the end fittings. Discoloration of the used frits was noted during replacement, particularly for the influent frit. This indicates that some material either passed through the 0.45 μm syringe-tip filter or precipitated out of solution and accumulated on the frits. While clogging of the frits remains a concern for future laboratory experiments, the pilot-scale field tests mentioned in the manuscript did not use a similar type of frit.

Figures D-1 through D-3 show grain size distribution curves for virgin 14 – 40 mesh SMZ and used 14 – 40 mesh SMZ from columns LST1, LST2, respectively. As noted in the manuscript, the percentage of material finer than 0.075 mm increased from 1.83% for virgin SMZ to 13.68% for column LST1 and 17.84% for column LST2. This increase in fine material most likely led to the observed loss in hydraulic conductivity. Biofouling was eliminated as a possibility for the observed conductivity loss, as discussed in the results section of the manuscript.

Table D- 1. **Hydraulic conductivity measurements made after every fifth cycle on columns LST1 and LT2**

Cycles	K (cm/min)	
	LST1	LST2
virgin	2.49	2.19
5	2.36	1.91
10	2.27	2.11
15	1.97	2.03
20	0.62	1.52
25	0.06	0.67
30	0.06	0.09
35	0.06	0.05
40	0.05	0.04
45	0.05	0.05
50	0.03	0.04
50 + new frits	1.67	1.46

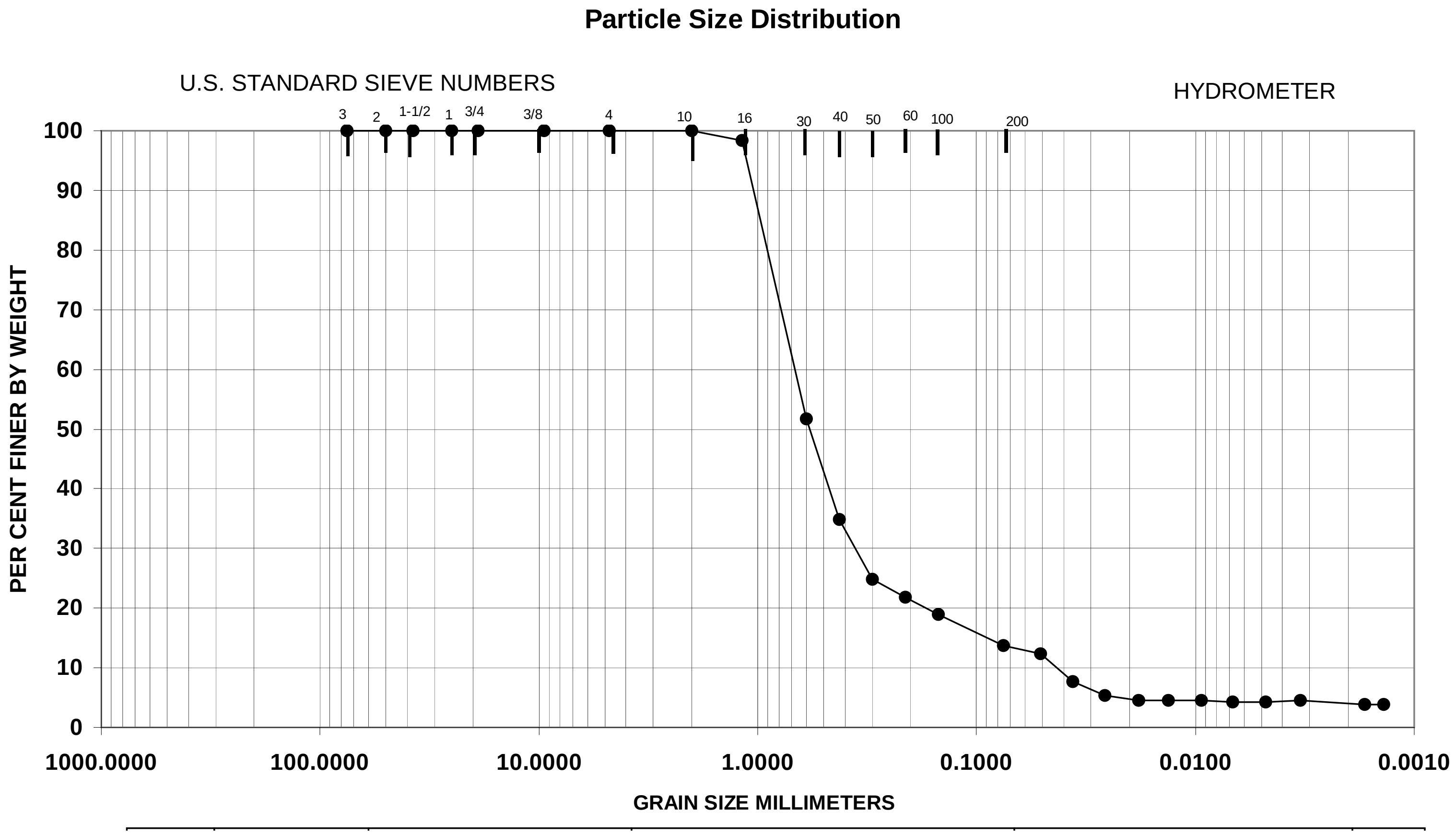

Figure D- 1. Grain size distribution for used 14 – 40 mesh SMZ from column LST1

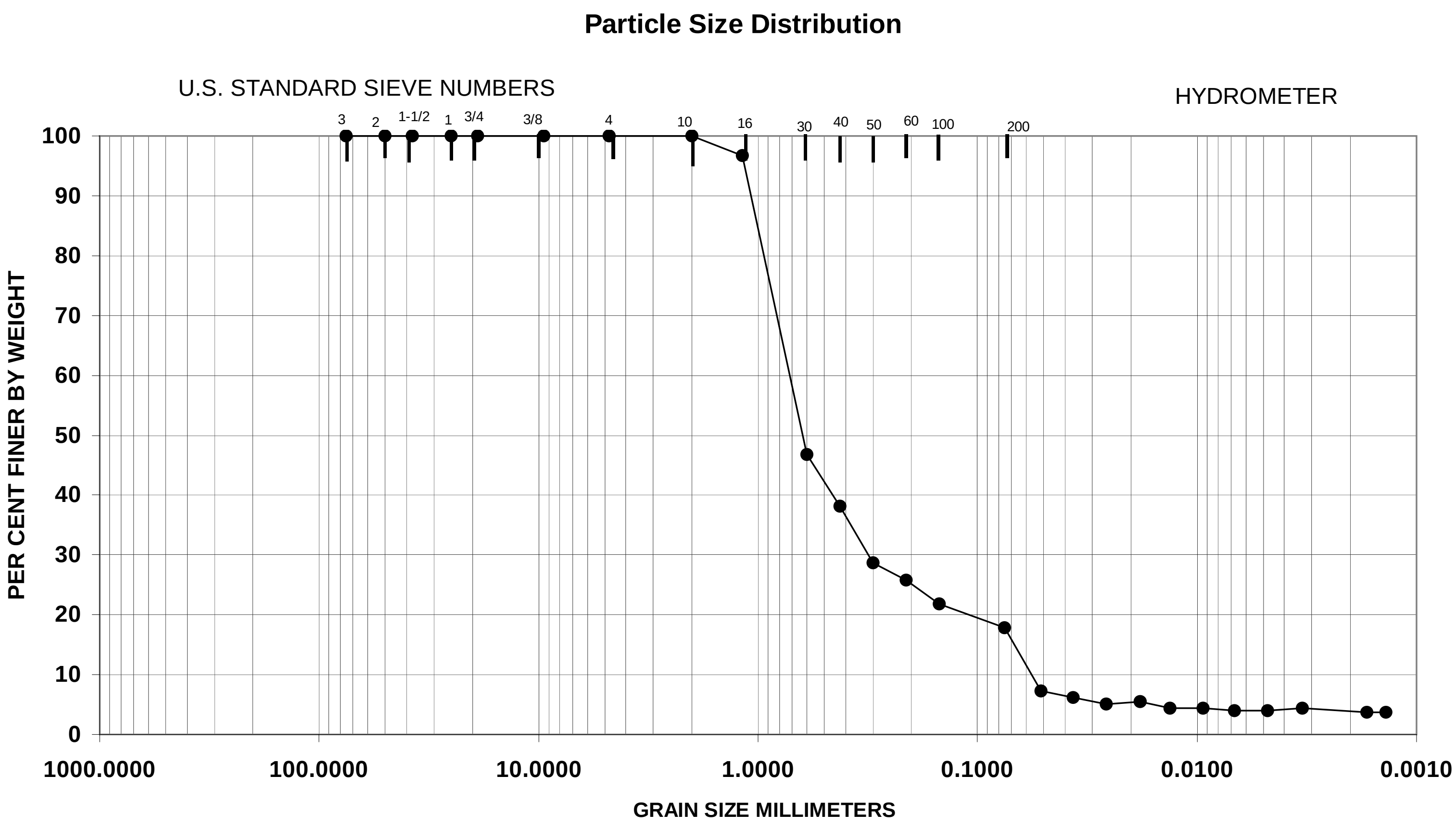

Figure D- 2. Grain size distribution for used 14 – 40 mesh SMZ from column LST2

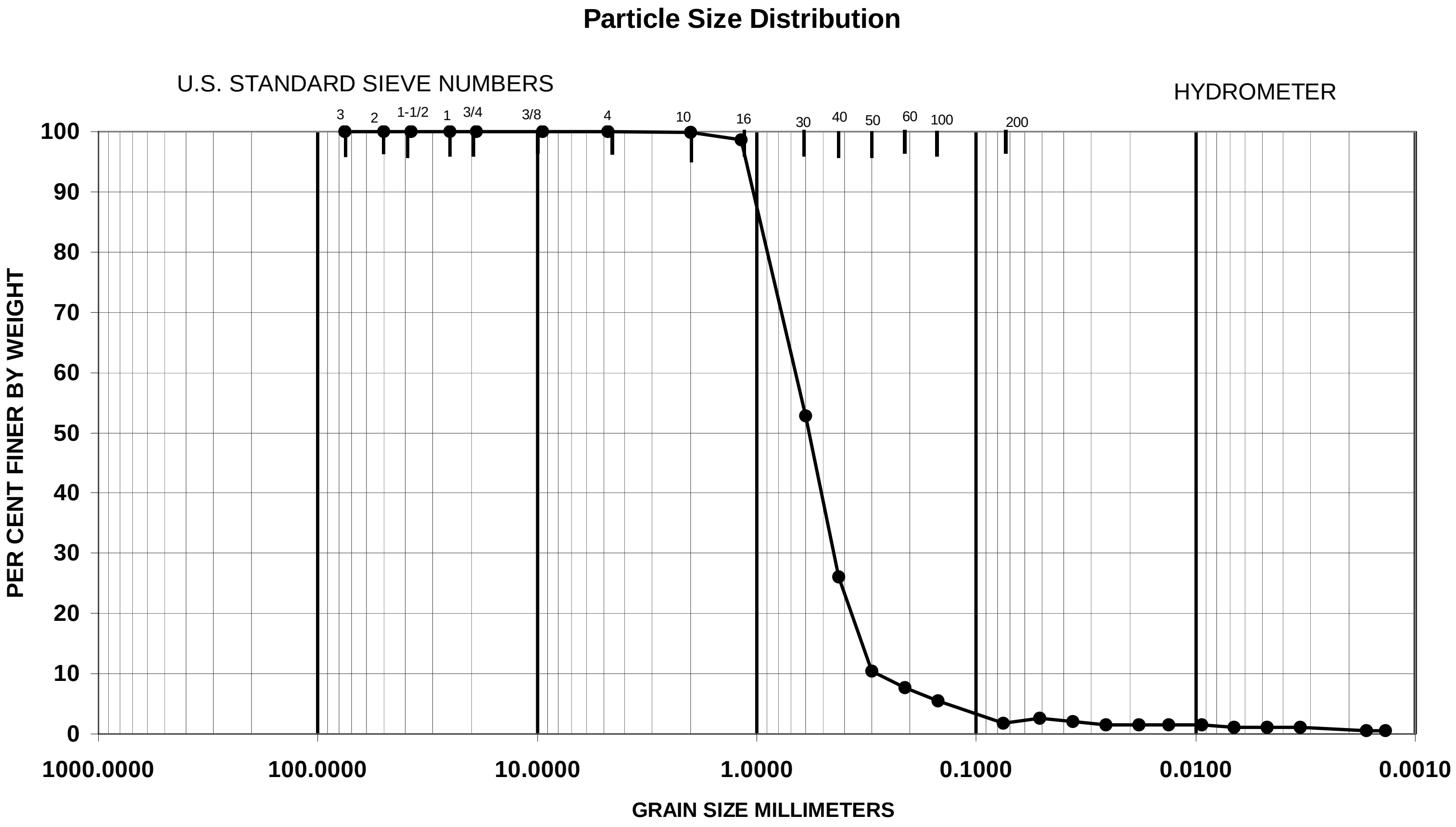

Figure D- 3. Grain size distribution for virgin 14 – 40 mesh SMZ

APPENDIX E. SEM IMAGES, CHEMICAL ANALYSIS, AND CHEMICAL DISTRIBUTION MAPS OF SMZ FROM LONG-TERM STABILITY EXPERIMENTS

Appendix E contains images taken from the scanning electron microscope (SEM) and x-ray maps for chemical distribution of used SMZ from the LST experiments. We thank Dr. Nelia Dunbar, of the New Mexico Bureau of Geology, for her help in preparing and interpreting these images.

Figures E-1 through E-3 show backscattered electron SEM images for virgin SMZ and used SMZ from columns LST1 and LST2, respectively. Additional SEM images are presented and discussed in the manuscript.

Table E-1 presents the results of a chemical analysis for iron and manganese on used and virgin SMZ.

Figures E-4 through E-9 show the results of microprobe analysis of SMZ particles. Part (a) of each figure is a backscattered image of the SMZ surface while part (b) is an iron distribution map, where lighter colors represent higher amounts of iron. The images were prepared by mounting the particles with epoxy and polishing the mount to a smooth surface for analysis. The polishing step removed the outer surfaces of the SMZ and chemical distribution maps were made for the inside of each particle. This process inherently prevented analysis of surface coatings on the SMZ grains. Iron is present around the interior void spaces on both used and virgin SMZ. No distinct trends were noted from these images with regards to increased iron presence on used SMZ.

Additional chemical distribution maps (not shown here) showed that essentially no mangansese was present on used or virgin SMZ.

Table E- 1. Total iron and manganese for used SMZ from columns LST1 and LST2 and for virgin SMZ. Units are mg of analyte per kg of SMZ

	Fe (mg/kg)	Mn (mg/kg)
LST1	9090	6816
LST2	9867	6828
virgin SMZ	7981	7758
virgin SMZ (duplicate)	9278	7841

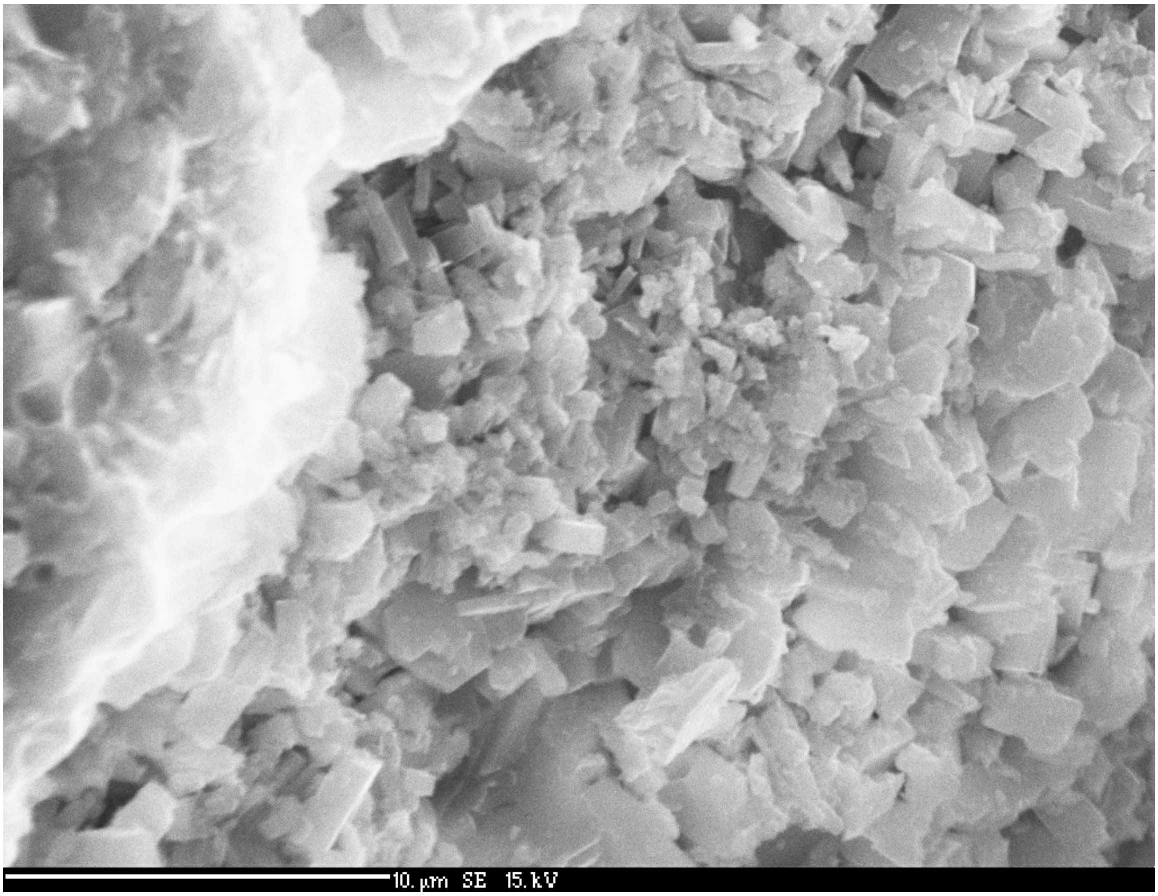

Figure E- 1. Backscattered SEM image of a virgin SMZ grain.

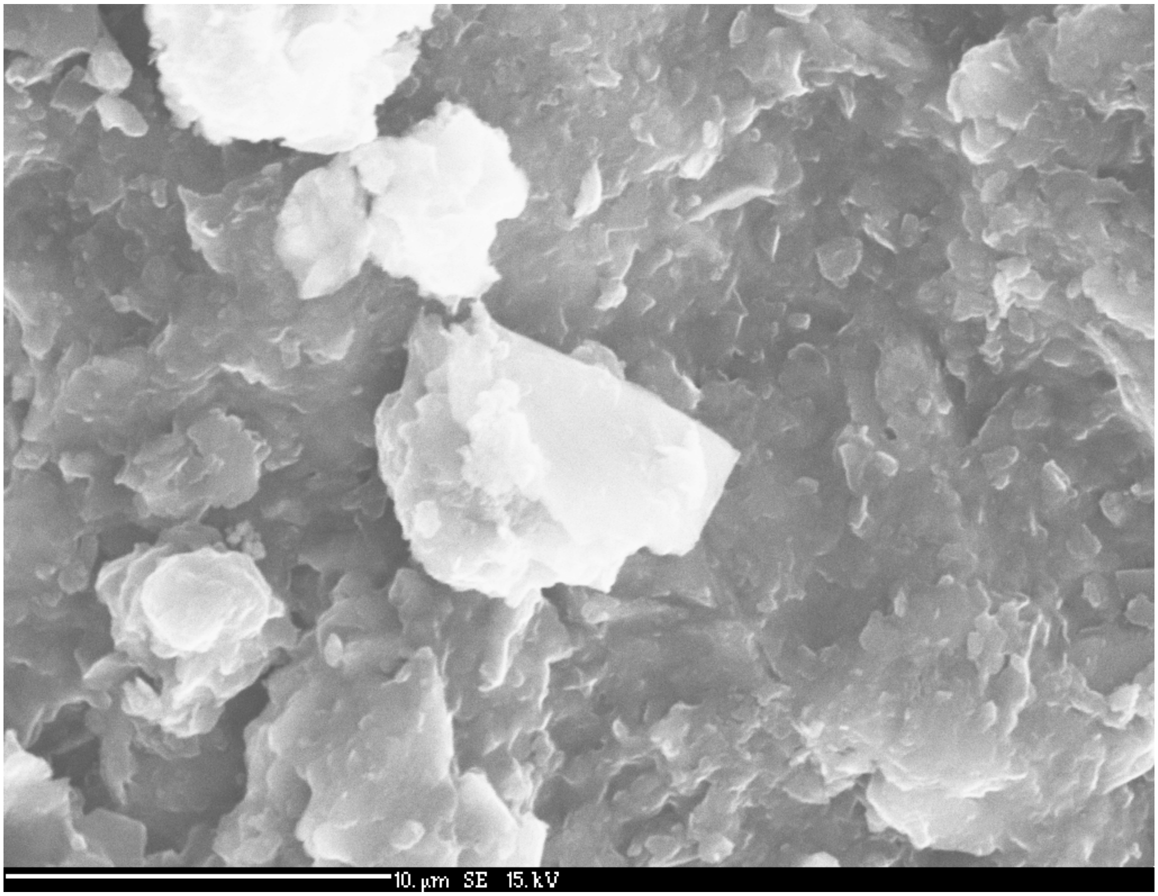

Figure E- 2. Backscattered SEM image of a used SMZ grain from column LST1.

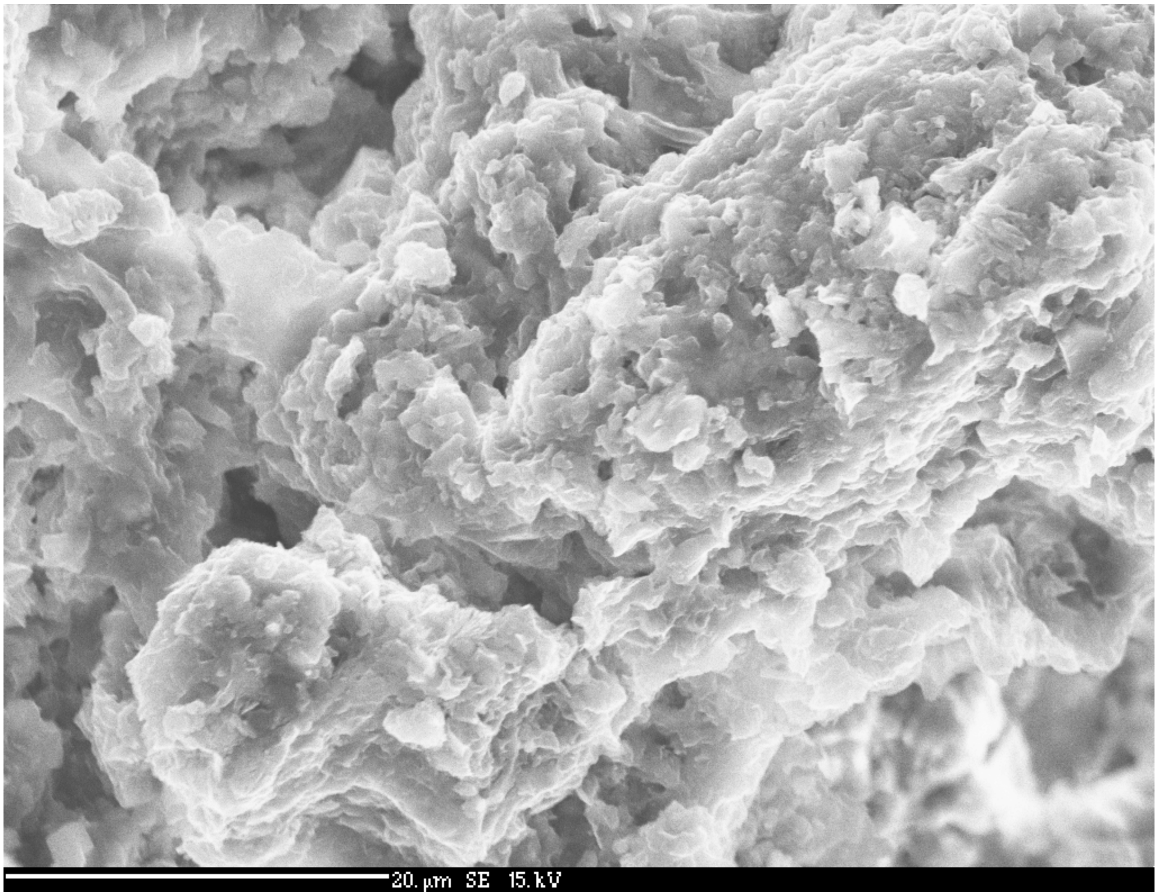

Figure E- 3. Backscattered SEM image of a used SMZ grain from column LST2.

(a)

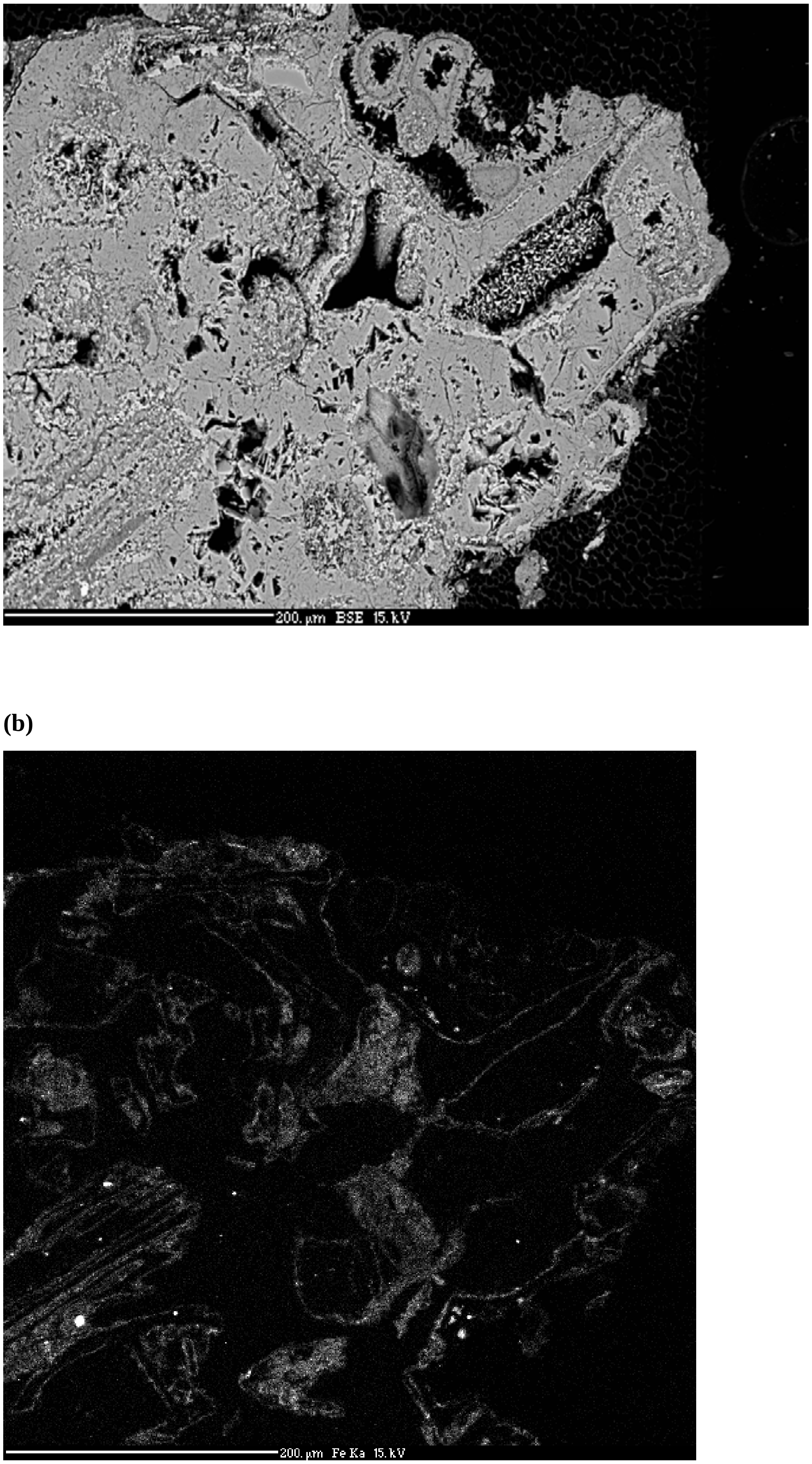

Figure E- 4. (a) Backscattered electron image and (b) iron distribution map of a virgin SMZ grain.

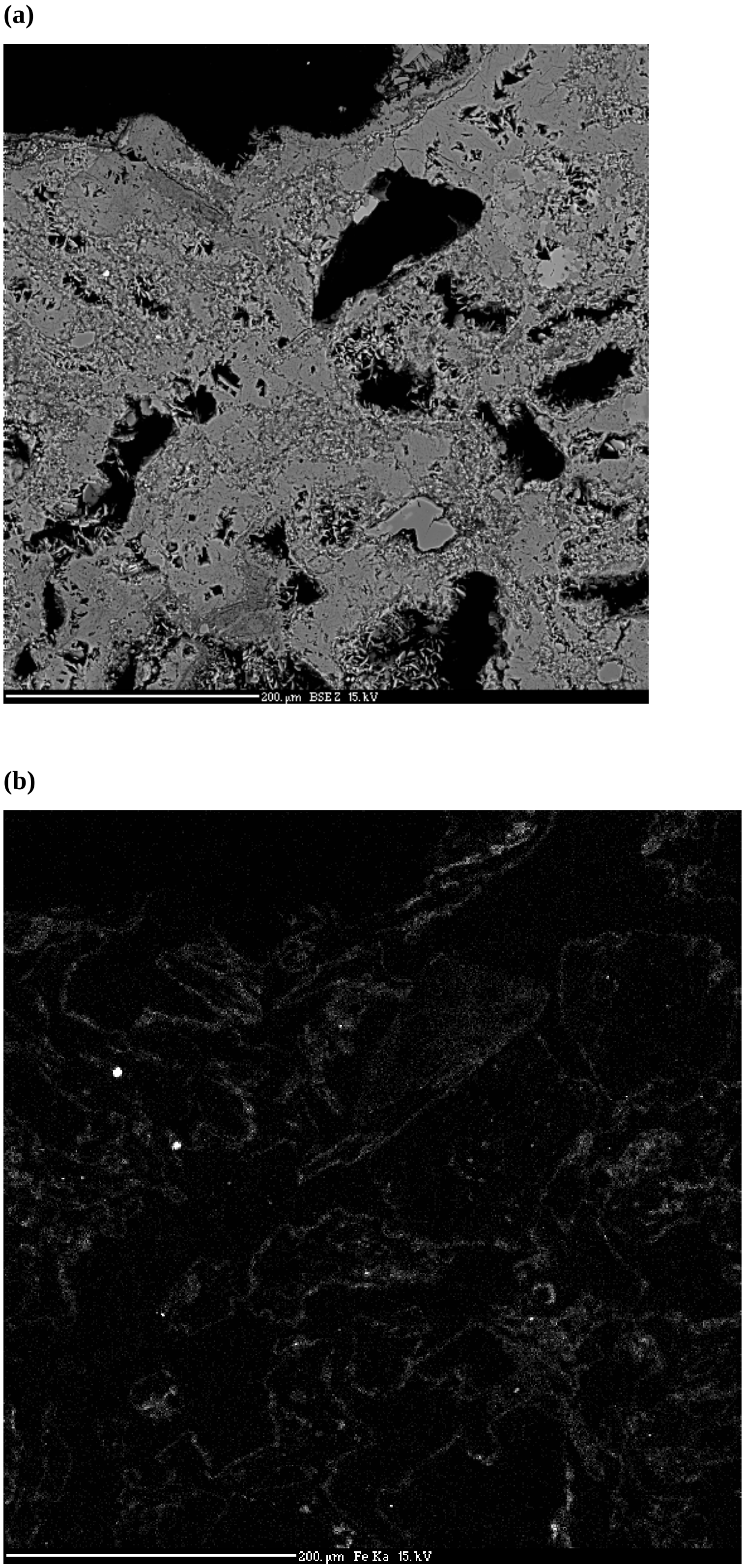

Figure E- 5. (a) Backscattered electron image and (b) iron distribution map of a virgin SMZ grain

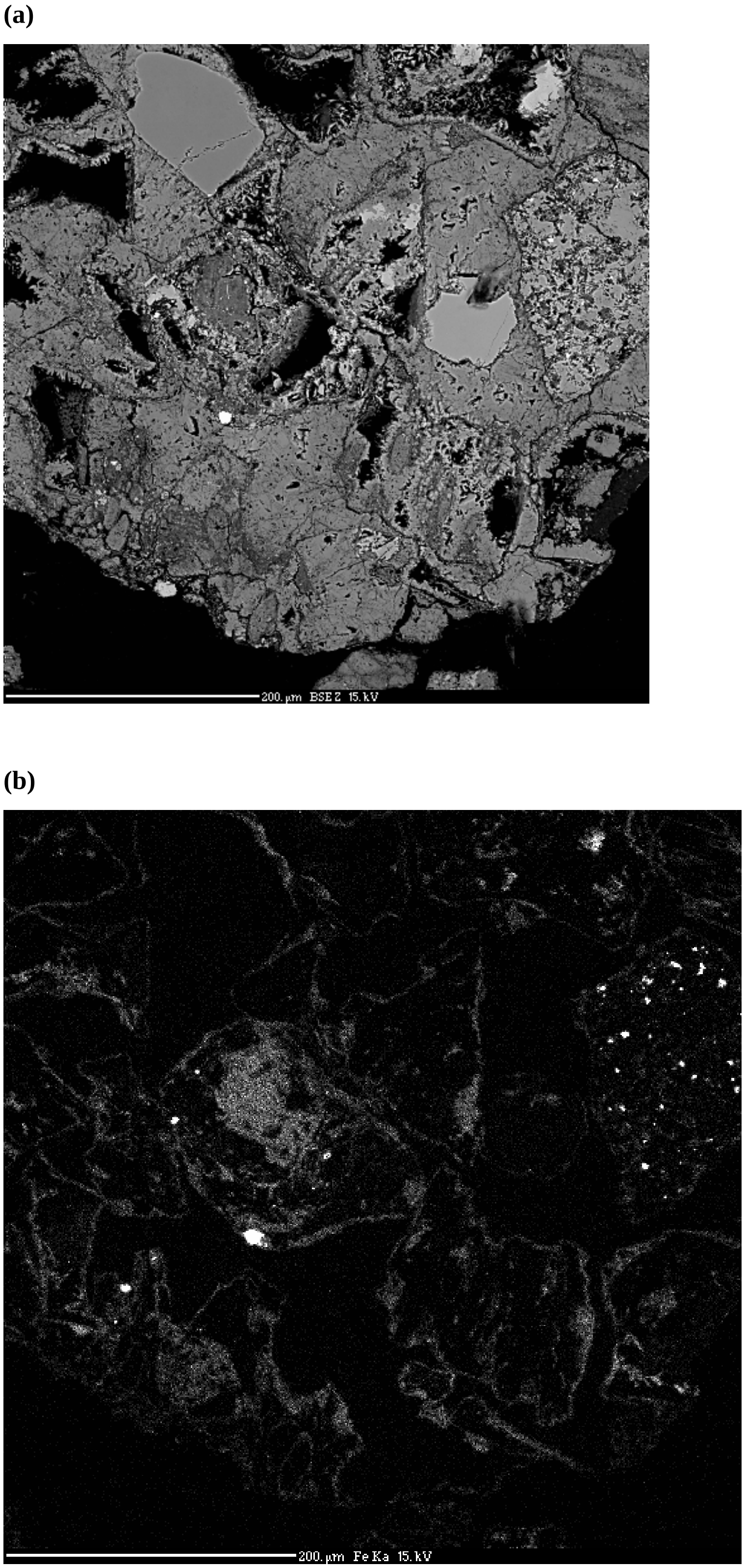

Figure E- 6. (a) Backscattered electron image and (b) iron distribution map of a used SMZ grain from column LST1

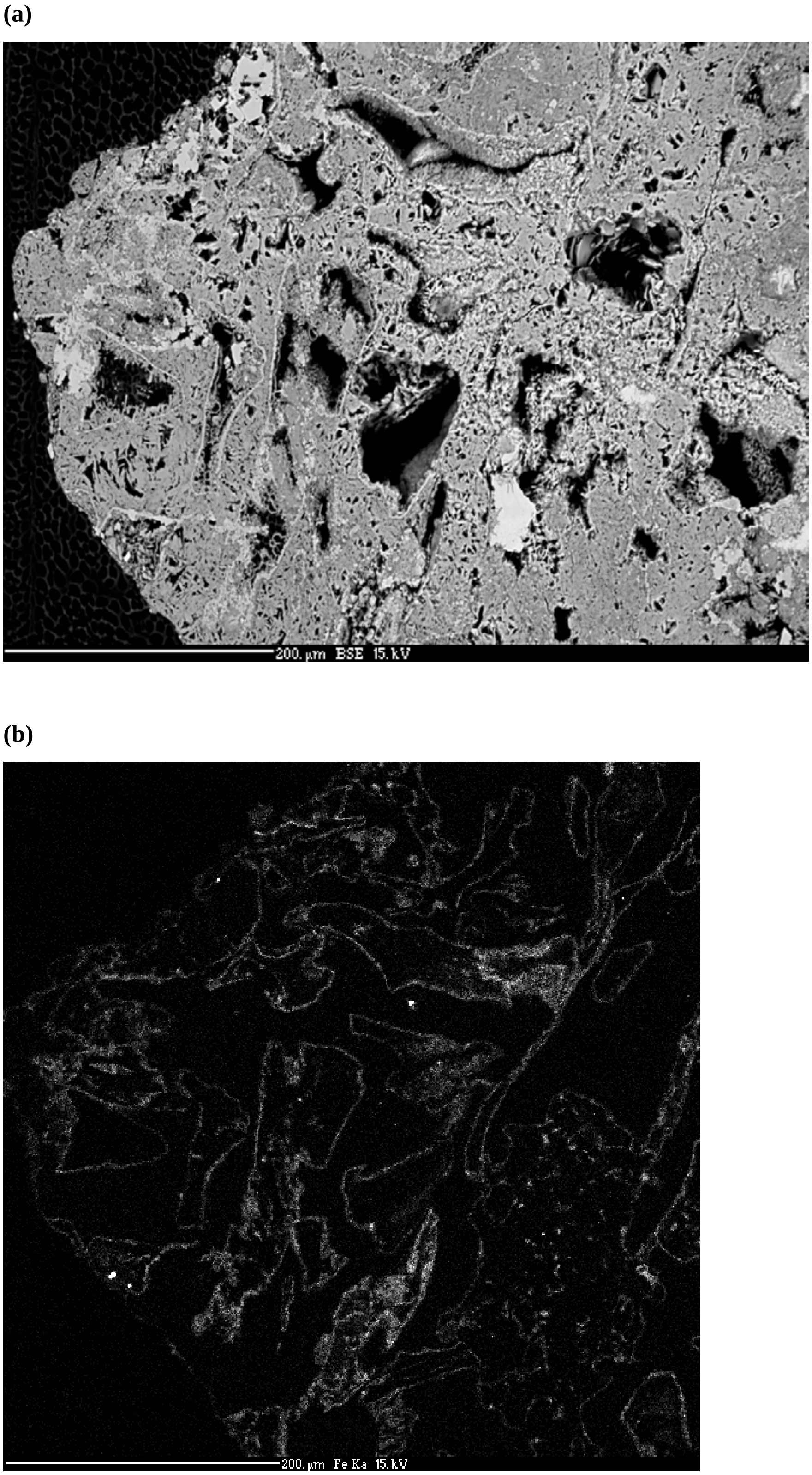

Figure E- 7. (a) Backscattered electron image and (b) iron distribution map of a used SMZ grain from column LST1

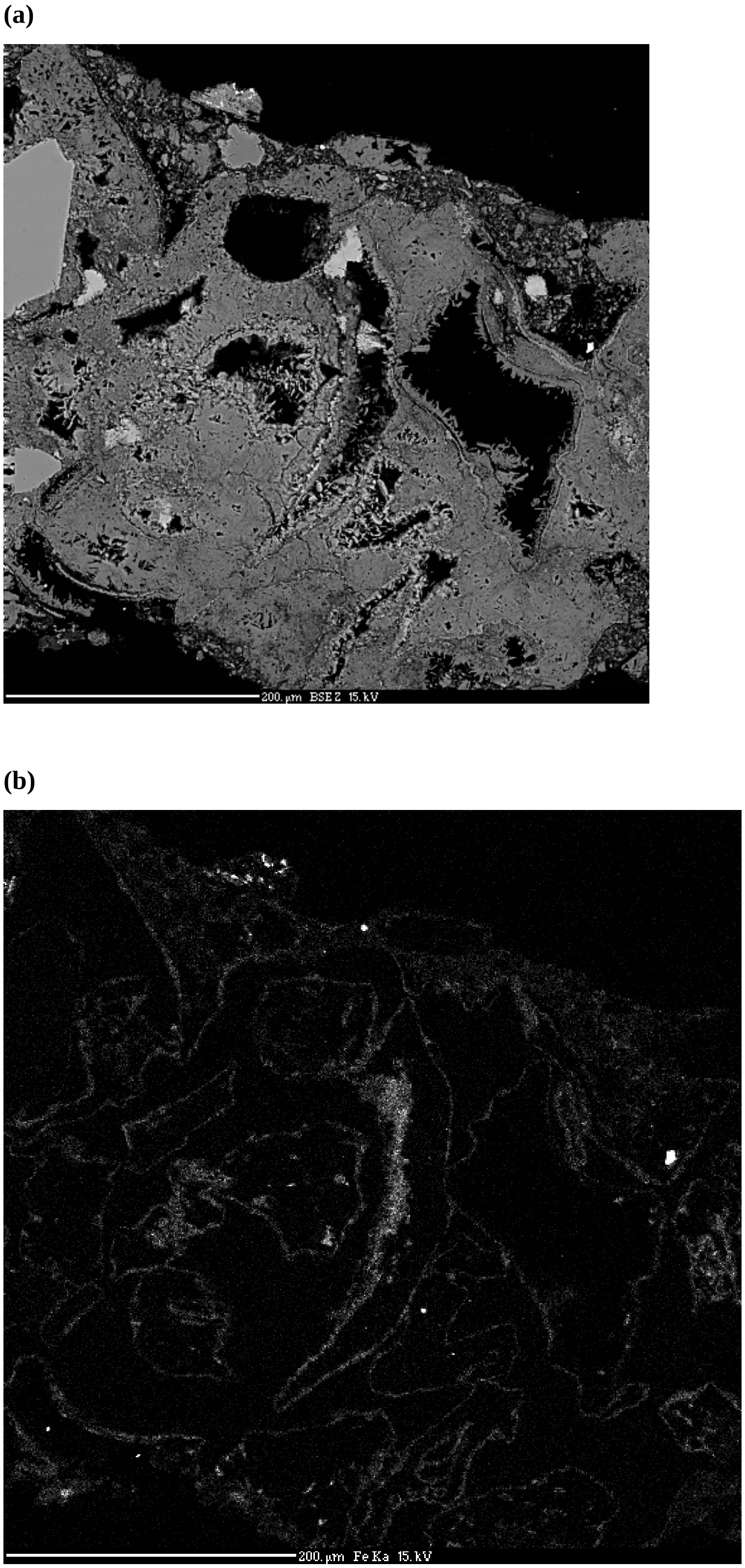

Figure E- 8. (a) Backscattered electron image and (b) iron distribution map of a used SMZ grain from column LST2

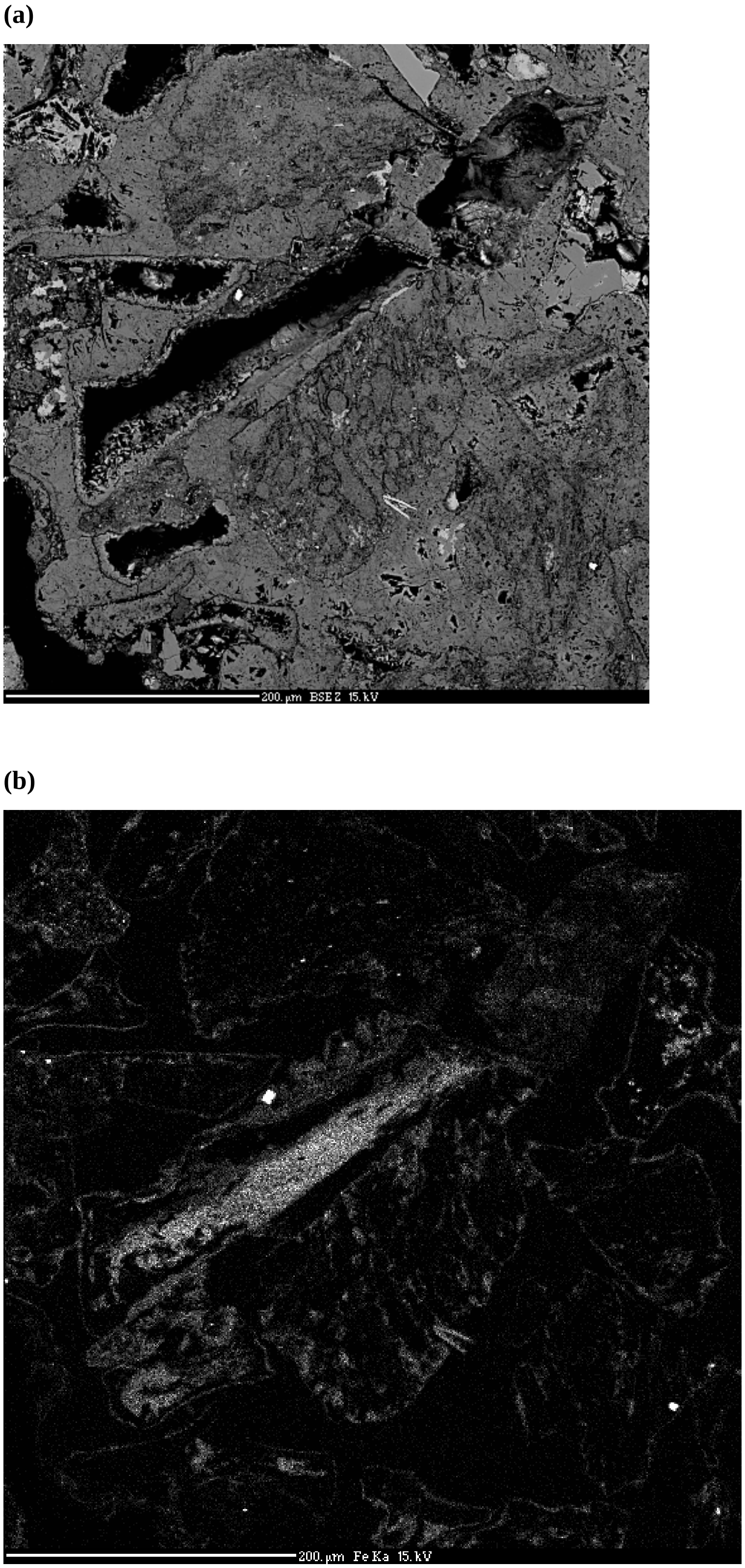

Figure E- 9. (a) Backscattered electron image and (b) iron distribution map of a used SMZ grain from column LST2