The Influence of Soil Composition on Bioremediation Of PAH-Contaminated Soils

Andrew C. Middleton • David V. Nakles • David G. Linz

As a result of former industrial activities, many properties across the United States contain various chemicals in their soils at concentrations above background levels. Polynuclear aromatic hydrocarbons (PAHs) are often encountered at sites of gas manufacture, wood treating, tar refining, coke making, and petroleum refining. When the presence of PAHs in site soil is deemed to create a situation of unacceptable risk to public health or the environment, treatment or disposal is required to reduce concentrations to acceptable levels.

The ideal remedial process for PAHs in soils would destroy them to an environmentally sound level at relatively low cost without producing adverse by-products. In many cases bioremediation can accomplish these goals. The degree to which bioremediation can destroy PAHs in a particular soil, however, is highly dependent on the characteristics of that soil, including the nature of the hydrocarbon that is the source of the PAHs.

It is the objective of this article to describe efforts leading to this conclusion and to summarize how soil characteristics influence bioremediation of PAHs.

Bioremediation is the use of bacteria in engineered systems to destroy biodegradable contaminants in soils, waters, and sludges. The engineered system creates conditions to optimize the growth of bacteria on the chemical that is targeted for destruction. Bacteria use the chemical for food, oxidizing part for energy and synthesizing the remainder into new bacterial cells.

Many studies and full-scale remediations have found PAHs to be biodegradable (Mihelic and Luthy, 1988; Loehr and Malina, 1986; Sims and Overcash, 1983; Nakles and Smith, 1989; Smith and Weightman, 1988). Others have described the metabolic pathways for PAH degradation (Gibson and Subramanian, 1984). Unquestionably, bioremediation is a technology that should be initially considered for destruction of PAHs in contaminated soils. It cannot be assumed, however, that bioremediation will achieve a reduction in the soil PAH concentration to cleanup criteria in all situations.

TREATABILITY TESTS ON UNSATURATED SOILS

Four cases will serve to illustrate the conclusion. As part of a research
Initially, a series of soils were bioremediated in laboratory-scale pan reactors. Pan reactors simulate bioremediation of soils in an unsaturated state. Contaminated soils are placed into a pan of approximate dimensions 8 x 12 x 4 inches, and nitrogen, phosphorus, and water are added to optimize the growth of the indigenous soil bacteria. The reactor is operated for a relatively long period of time, in some cases in excess of 20 weeks. During operation, soil moisture is maintained by the addition of water to provide a moist but drained soil. Nitrogen and phosphorus are added, as necessary, for bacterial growth. The pH is adjusted with addition of lime to maintain it in the range of 6-8. The soils are mixed weekly for aeration and homogenization.

The soils are monitored for PAH concentration as a function of time. The reduction in PAH concentrations over time forms the basis for conclusions about the response of the PAH-contaminated soil to bioremediation.

This treatability test simulates the full-scale bioremediation technologies that operate in an unsaturated state. These include ex situ land treatment, in situ land farming, and, to some degree, composting.

To return to the four cases, PAH-contaminated soils from four different sites were subjected to pan reactor treatability tests. Initial PAH concentrations were 160, 190, 20,000, and 29,000 mg/kg for the four soils, identified as Soils B, D, F, and J respectively. The sites were former manufactured-gas plants where coal and oil had been converted to gas for some period during the era of gas manufacture (1816-1960s). Tar ore lampblack, by-products of gas manufacture, contain high concentration of PAHs and were the likely source of PAHs in these soils.

The individual soils responded very differently to bioremediation. Soil B responded very well. Figure 1 shows the decrease in total PAH concentration with time for Soil B. PAHs decreased from the initial concentration of 160 mg/kg to less than 20 mg/kg within fourteen weeks, a reduction greater than 85 percent.

Soil F also responded well, but achieved a lower reduction of PAHs (75 percent) within 22 weeks. Figure 2 shows the PAH concentration with time for Soil F. The concentration decreased from 20,000 mg/kg to 5,000 mg/kg within twenty-two weeks. The final concentration began to reach an asymptote or plateau concentration substantially above zero.

Soil J responded to bioremediation, but not as well as Soil F. Figure 3 shows the PAH concentration with time for Soil J. The concentration decreased from 30,000 mg/kg to 17,000 mg/kg within sixteen weeks, a reduction of 43 percent. As with Soil F, the final concentration approached a plateau well above zero.

Soil D, however, did not respond in any obvious manner to
The Influence of Soil Composition on Bioremediation of PAH-Contaminated Soils

Figure 1. Soil B.

![Graph showing bioremediation of PAH concentration with time for Soil B.](image)

bioremediation. Figure 4 shows the PAH concentration with time for Soil D. The initial concentration of 190 mg/kg was similar to that of Soil B, but subsequent concentrations over the twenty-five weeks of testing oscillated with no apparent functional relationship.

The Effects of Soil Characteristics on Bioremediation

These results clearly illustrate the varying responses of PAH-contaminated soils to bioremediation. Some soils responded with varying degrees of PAH reductions to less than 20 mg/kg in the best case, but only to around 17,000 mg/kg in the least responsive case. One soil did not respond at all with no apparent reduction in PAH concentrations. The obvious question was why.

Soil characteristics provided some insight into the phenomena that were causing these variations. Table 1 lists fines content and organic carbon fraction for the four soils. Fines content, as used here, is the percent by weight of soil that passes a 0.075-mm sieve and primarily represents the amount of silt and clay present in the soil. The organic carbon fraction is the percent by weight of organic carbon present in the soil. It is a measure of the natural organic carbon as well as that from the hydrocarbons present.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Initial PAH Concentration mg/kg</th>
<th>Fines Content Percent</th>
<th>Organic Carbon Fraction Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>160</td>
<td>2</td>
<td>64</td>
</tr>
<tr>
<td>D</td>
<td>190</td>
<td>26</td>
<td>63</td>
</tr>
<tr>
<td>F</td>
<td>20,000</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>J</td>
<td>20,000</td>
<td>27*</td>
<td>28</td>
</tr>
</tbody>
</table>

*Includes humic and fulvic acids
Soil B had both the lowest fines content and organic carbon fraction. Soil J had the highest fines content and organic carbon fraction. However, it contained a substantial amount of lampblack, which accounted for a portion of both. Soil D had the highest amount of fines due solely to silts and clays. The organic carbon fraction was next to the lowest. Finally, Soil F had the second to lowest fines content and next to highest organic carbon fraction. Tar, which was visibly present in this soil, accounted for a portion of the organic carbon fraction.

These four soils covered a wide range of values of fines content and organic carbon fraction. Similarly, they responded to bioremediation in an unsaturated state in a widely varying manner. The apparent potential for a relationship between bioremediation response and these characteristics motivated development of a conceptual model of soil bioremediation.

THE CONCEPTUAL MODEL

Site soils are mixtures of cohesive and noncohesive inorganic soil, natural organics, and often separate phase hydrocarbons. The noncohesive soils include sands and gravels; the cohesive soils include silts and clays. The cohesive soils are made up of aggregates of the individual silt and clay particles. Natural organics include the humus and other remnants of decayed vegetation. The separate phase hydrocarbons are pockets of oils, tars, and other nonaqueous phase liquids (NAPLs). Figure 5 is a schematic diagram of a conceptual model of a site soil showing the mixture of NAPLs, sand particles, and fines aggregates. In a saturated state, the void space is filled with water; in an unsaturated state, it is filled with air.
Greater magnification of this model provides details that permit the development of a conceptual model. **Figure 6** shows a magnification of three key components: NAPLs, sand grains, and final aggregates. Where active biodegradation is occurring, a biofilm exists around each of these as shown in Figure 6. A biofilm is simply a layer of bacterial cells and other soil microorganisms adhered to a surface. Biodegradable organics diffuse through water or soil moisture into the biofilm where they are degraded by the microorganisms (Rittman et al., 1990). Microorganisms cannot penetrate to the interior of a pocket of NAPL or a sand grain because of the liquid or crystalline nature of the material. Nor can they penetrate into the micropore structure of a fines aggregate because the micropore diameters are too small. Hence, active biodegradation must occur in the biofilms surrounding the surfaces of these materials.

**Biodegradation of NAPLs**

In the case of the pocket of tar-NAPL, the biofilm is a mixture of PAHs. As the PAHs at the surface are degraded, mobile PAHs from within the NAPL diffuse to the surface to the biofilm. The first circle in Figure 6 depicts this schematically. In this process the nature of the NAPL changes to a mixture of mobile PAHs. Depending on the composition of the NAPL with respect to the relative presence of mobile and immobile PAHs, it may be substantially biodegraded or converted to an insoluble, inert NAPL like a roofing or road tar. If it is converted to an insoluble, inert NAPL, the soil may have a substantial concentration of PAHs remaining after bioremediation (i.e., a relatively high plateau concentration as discussed earlier). Hence, the quantity and composition of a NAPL in soil is clearly a factor influencing the response to bioremediation.
Biodegradation of Sand Grains

In the case of a sand grain, PAHs are adsorbed to the surface of the particle. They desorb and diffuse into the biofilm in the bioremediation process. The second circle in Figure 6 depicts this schematically. This situation contrasts significantly from that of the NAPL. The biofilm and adsorbed PAHs are in close proximity, and the relatively thin layer of adsorbed PAHs do not significantly change in composition during

Figure 4. Soil D.

Figure 5. Conceptual Model.
When subjected to bioremediation, PAHs on the exterior surface of the aggregate have a much shorter pathway to the surrounding biofilm than those within the fines.

bioremediation as does that of tar NAPL. They desorb, diffuse a short distance into the biofilm, and are degraded. Bioremediation of PAHs in sand probably represents the most straightforward and rapid process of these three situations.

**Biodegradation of Fines Aggregates**

The situation for the fines aggregate is the most complex of the three. The third circle in Figure 6 depicts this schematically. The fines aggregate is made up of individual particles (i.e., silts and clays) adhering in a cohesive mass. The surface area of the particles within the aggregate is orders of magnitude higher than that of an equivalent volume of sand. The micropores within the fines are typically water saturated and too small for bacterial cells to enter.

PAHs will adhere to the interior and exterior surfaces of the individual particles making up the aggregate. When subjected to bioremediation, PAHs on the exterior surface of the aggregate have a much shorter pathway to the surrounding biofilm than those within the fines. The ones within must desorb from the microsurface and diffuse through the micropore structure to the outer surface where the biofilm is located. This pathway is further complicated by the continuous opportunity for surface adsorption and desorption along the micropore (Brusseau and Rao, 1989). The presence of fines in the soil represents a situation where bioremediation will be limited by the transport of PAHs through the micropore structure to the surface.

**The Prediction for Bioremediation of Unsaturated Soils**

In summary, this conceptual model predicts that bioremediation of soils in an unsaturated state will depend on two additional factors as well as classical biodegradation factors such as pH and temperature. The additional factors are

- The quantity and composition of NAPL present in the soil, and
ANDREW C. MIDDLETON • DAVID V. NAKLES • DAVID G. LINZ

• The quantity and composition of fines (i.e., silts and clays) in the soil.

The conceptual model also predicts that in certain situations bioremediation of soil in a saturated, well-mixed state should improve the response. In situations where there is a substantial amount of fines present in the soil, part of the limitation to bioremediation is the relatively slow transport rate of contaminants from the interior of the fines aggregate to the outer surface biofilm. If the fines aggregate were dispersed in a well-mixed water slurry, the interior surfaces would be exposed to the bulk water and should be much more available for bioremediation. If the water were also aerated and supplemented with nutrients, then conditions should be optimal for bioremediation of the PAHs in the soil.

Similarly, where pockets of NAPL are present in the soil, dispersal in a well-mixed water slurry should produce a better situation for bioremediation than in an unsaturated state because of the mixing and exposure of more surface area to the water that supports the biofilm.

Hence, better and faster treatment of PAH-contaminated soils should occur in a water-slurry bioremediation system. Quantitation of experimental results provides a means to better compare and contrast the various responses to bioremediation. The variation of PAH concentration as a function of time for these pan treatability studies can be described mathematically with a modified first-order equation:

\[ C = C_r + (C_o - C_r)e^{-kt} \]  

(1)

in which,

- \( C \) = PAH concentration, M/L;
- \( C_o \) = initial PAH concentration, M/L;
- \( C_r \) = PAH concentration resistant to biodegradation or not bioavailable, M/L;
- \( k \) = first-order decay coefficient, T\(^{-1}\); and,
- \( t \) = time, T.

In this equation the term \( C_r \) represents the plateau concentration at which the decrease in PAH concentration levels out.

It is recognized that mathematically describing the total PAH concentration rather than the concentration of individual PAH compounds is a simplifying assumption. The intent here, however, is to determine whether the conceptual model is supported by the experimental data, and this simplification will facilitate this analysis. Future work will refine the analysis by examining individual compounds.

Values of \( C_o \) and \( k \) can be estimated by fitting this model to the experimental data using a least-squares technique. When this is done, the values for Soil B in response to unsaturated bioremediation in a pan were 0.054 day\(^{-1}\) and 11 mg/kg for \( k \) and \( C_o \), respectively. Those for Soil F were 0.024 day\(^{-1}\) and 4,500 mg/kg, and for Soil J, 0.041 day\(^{-1}\) and 16,800 mg/kg.
No values for Soil D were estimated because the data did not show a clear decrease in concentration with time. The curves plotted through the data points in Figures 1-3 were determined using Equation 1 and the above values.

**SLURRY REACTOR EXPERIMENTS**

To test the prediction of better and faster treatment in a saturated state, the four soils were also bioremediated in laboratory-scale slurry reactors. The apparatus and procedures were developed as part of protocol for accelerated biotreatability testing for Gas Research Institute and have been described in detail elsewhere (Cushey and Morgan, 1990). Briefly, a soil-water slurry (20 percent soil) was added to a twelve-liter stainless-steel vessel equipped with a high-speed mixer, aeration devices, and means to sample volatiles in the off-gas exiting the reactor. Nitrogen and phosphorus nutrients were added to the water to provide the supplemental macro-nutrients for bacterial growth. The reactor was operated as a batch reactor for typically four to eight weeks. During this time soil samples were collected for PAH analysis. Additionally, if nutrients or pH control were required, appropriate chemical additions were made.

**Application of the Results to the Conceptual Model**

Results of the response of the four soils (B, D, F, and J) to bioremediation in a saturated state provide a basis for evaluating the conceptual model. Figure 7 shows the PAH concentration with time for Soil B in both the pan and slurry reactors. The concentration in the slurry reactor decreased more rapidly than in the pan, but approached a similar plateau concentration. Values of $C_L$ and $k$ in Equation 1 were also estimated for the slurry reactor.
Figure 8. Soil F.

Figure 8 shows the PAH concentration with time for Soil F in both the pan and slurry reactors. The relative response of the two reactors was similar to that for Soil B. The slurry reactor concentrations decreased more rapidly than in the pan, but approached a similar plateau concentration well above zero. Values of $k$ and $C_B$ for the slurry reactor were estimated...
THE INFLUENCE OF SOIL COMPOSITION ON BIOREMEDIATION OF PAH-CONTAMINATED SOILS

Figure 10. Soil D.

Figure 9 shows the PAH concentration with time for Soil J in both the pan and slurry reactors. Again the relative response was similar to that of both Soil B and Soil F. Values of k and C, for the slurry reactor were estimated to be 0.24 day\(^{-1}\) and 15,700 mg/kg, respectively.

Figure 10 shows the PAH concentration with time for Soil D in both the pan and slurry reactors. The difference between the responses of the two was dramatic. There was essentially no response of Soil D to bioremediation in an unsaturated state. In the slurry reactor, however, the PAH concentration rapidly dropped to a relatively low plateau concentration. Values of k and C, for the slurry reactor were estimated to be 0.57 day\(^{-1}\) and 31 mg/kg, respectively.

These results motivate the discussion as to whether they are consistent with the conceptual model.

THE RELIABILITY OF THE CONCEPTUAL MODEL

The response to bioremediation in both a saturated and unsaturated state of four soils of different characteristics and tar NAPL produced a broad range of results. Table 2 summarizes the soil characteristics and estimated modified first-order coefficients for the four soils. Examination of this table yields several trends supporting the conceptual model.

Rates of Bioremediation: Saturated versus Unsaturated States

The first-order decay rates (k) for saturated bioremediation (i.e., slurry reactors) are consistently higher by an approximate order-of-magnitude than the rates for unsaturated (i.e., pan reactors). One of the basic premises of the conceptual model is that soil bioremediation is a water-based...
Table 2. Summary of Soil Characteristics and Modified First-Order Coefficients.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Initial PAH Concentration (C₀), mg/L</th>
<th>PAH Content, (Percent)</th>
<th>Organic Carbon Fraction, (Percent)</th>
<th>First-Order Decay Rate (k), DAY⁻¹</th>
<th>PAH Concentration Resistant to Degradation (Cg), mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>100</td>
<td>5</td>
<td>6.4</td>
<td>0.054</td>
<td>0.24</td>
</tr>
<tr>
<td>B</td>
<td>150</td>
<td>5</td>
<td>6.5</td>
<td>0.054</td>
<td>0.27</td>
</tr>
<tr>
<td>C</td>
<td>20,000</td>
<td>7</td>
<td>6.5</td>
<td>0.054</td>
<td>0.19</td>
</tr>
<tr>
<td>D</td>
<td>30,000</td>
<td>7</td>
<td>6.5</td>
<td>0.054</td>
<td>0.19</td>
</tr>
</tbody>
</table>

process. Water provides the medium of transport for the PAHs, the NAPLs, and the soil to the biofilm. The ratio of water to soil in a slurry reactor is thirty to fifty times greater than in a pan reactor. This water is aerated and supplemented with nutrients to optimize bacterial growth. Hence, with the excess water and mixing present and the water being an optimal bacterial growth medium, it is logical to expect degradation rates to be faster than in an unsaturated state.

The Potential Contribution of the Slurry Reactor

This finding has two implications. First, the slurry reactor can be used as an accelerated treatability test. If degradation is going to occur, it will do so in a two-to-six-week period rather than a two-to-six-month period as is often required in pan reactor tests. This accelerated test is a key benefit of the protocol developed by GRI to shorten the time necessary to evaluate the potential response of soils to bioremediation (Linz et al., 1990).

Slurry reactor testing can also help with technology screening. The slurry reactor represents an optimal situation for bioremediation of soils; if results from it do not achieve desired cleanup levels, then other forms of bioremediation are unlikely to do so either. In this situation bioremediation may be screened out as an applicable remedial technology. If the results do achieve desired cleanup levels, then bioremediation should be retained as a potential remedial technology. As will be discussed below, additional treatability may be required to confirm that unsaturated bioremediation would achieve similar levels.

Second, the results support the concept of slurry reactor bioremediation as a potentially viable full-scale treatment technology for soils as it has been used for organic sludges. Clearly, treatment times could be shortened in a slurry reactor. However, substantial evaluation of the mechanical requirements for slurry handling, mixing, and dewatering would be necessary to determine the economic competitiveness of it compared to other remedial technologies for soils.
Bioavailability of PAHs

The estimated values of the PAH concentration resistant to bioremediation \( (C_r) \) also supports the validity of the conceptual model. \( C_r \) represents the PAH concentration that is not bioavailable because of mass transport limitations or insolubility.

In unsaturated bioremediation, PAHs deep within micropores of fines aggregates may not be subject to transport to the outer surface in any relatively short period of time desired for treatment. Soils higher in fines content will not respond very well to unsaturated bioremediation. In saturated bioremediation, however, where the surfaces of the fines are exposed by dispersion, bioremediation may readily proceed. Soil D illustrated this situation. There was no clear trend of bioremediation in the unsaturated test. Concentrations oscillated in the vicinity of the initial concentration of 190 mg/kg. When dispersed in a slurry, however, bioremediation was rapid and produced a relatively low plateau concentration \( (C_p) \) of 31 mg/kg.

Similar Plateau Concentrations

The plateau concentrations \( (C_p) \) for the other three soils were similar between the saturated and unsaturated treatment. For Soil B, values of \( C_r \) were 11 and 7 mg/kg for unsaturated and saturated treatment, respectively; for Soil F, 4,500 and 5,200 mg/kg; and, for Soil J, 16,800 and 15,700 mg/kg. Soils B and F had the lowest fines contents of 3 percent and 7 percent, respectively. Soil J had a fines content of 27 percent, but some of this was due to lampblack, which made it difficult, if not virtually impossible, to estimate the fines caused only by silts and clays. The similarity of \( C_r \) for these soils between the saturated and unsaturated states suggests that mass transport from the interiors of fines aggregates did not significantly influence bioremediation in the unsaturated state. Based on the results for Soils B, D, and F, the fines content threshold above which unsaturated bioremediation can be significantly influenced lies between 7 percent and 27 percent. Until this threshold level is more precisely defined, the round number of 10 percent should be reasonable as an initial definition.

Hence, if a soil's fines content is above 10 percent, the certainty of extrapolation of saturated bioremediation test data to unsaturated treatment should clearly be questioned. As the value decreases below 10 percent, certainty of this assumption significantly increases. As mentioned earlier, in cases of uncertainty about such extrapolation, additional treatability testing simulating the unsaturated state should be performed to provide a final basis for decision making.

Although plateau concentrations for saturated and unsaturated bioremediation were similar for the same soil, these varied greatly between the soils for B, F, and J. Soil B had the lowest values of \( C_r \), 7 and 11 mg/kg. Soil F was next at 4,500 and 5,200 mg/kg, with Soil J the highest at 16,800 and 15,700 mg/kg. If mass transport from the interiors of fines aggregates was not a significant influence, why did the total PAH concentration not decrease to similar plateau concentrations? These results
suggest that bioremediation of the tar-NAPL in Soils F and J were significantly influenced by the composition of the NAPL itself. The NAPL constituents were not available for further bioremediation in these soils.

One hypothesis consistent with the conceptual model is that during the course of bioremediation, the mobile constituents are degraded, leaving behind a relatively immobile, insoluble material not subject to further attack by a water-based technology. Another would be that the NAPL initially contained a fraction that was already immobile and insoluble. An example of such a tar-NAPL would be a coal-tar roof, pipeline coating, or driveway sealer. These are produced by distilling off the lighter fractions of coal tar to produce a heavier fraction that is virtually immobile and insoluble. Planned future work is targeted at identifying the composition of the NAPL both before and after bioremediation to determine its similarity to these commercial products consisting of heavier tar fractions.

These results illustrate that a water-based remedial technology, such as bioremediation, can attack the water-mobile portion of a NAPL present in the soil. The water mobility varies in saturated and unsaturated states and with the composition of both the soils and the NAPL. Slurry reactor treatment represents the most aggressive water-based treatment because the soils and pockets of NAPL are highly mixed for weeks in an excess of water where constituents dissolving into the water are removed by biodegradation. When the soils concentration of PAHs levels out at a plateau concentration ($C_f$) in a slurry reactor after weeks of treatment, the limits of a water-based technology have been reached. Transport of constituents from the remaining NAPL to water is virtually insignificant after this plateau has been reached.

This conclusion suggests that bioremediation, especially in a saturated state, may consistently produce a treated soil that is protective of human health and the environment where the contaminant is a hydrocarbon NAPL, like tar. If the water-mobile constituents of the NAPL have been degraded so that remaining constituents are virtually immobile, then the treated soil should not be a source of further groundwater contamination through leaching. Hence, the threat of exposure from ingestion of contaminated groundwater from this treated soil should be alleviated. If the soil itself were ingested, the water-mobile constituents would not be present; hence, a significant reduction in exposure potential would be achieved. However, the availability of other non-water mobile constituents in a biotreated soil when ingested has not been determined definitively. A conservative approach therefore would be to cover biotreated soils so that exposure through ingestion is unlikely. Future research is targeted at determining the bioavailability of PAH-contaminated soils treated by bioremediation.

The Conceptual Model Applied to Other Hydrocarbons

As a final part of the discussion, extrapolation of these results to other hydrocarbon NAPLs (e.g., petroleum products) should be considered. Clearly, the water-based conceptual model plausibly explains experimental
observations with tar-NAPL. There is no apparent reason why these findings are not generally applicable to other hydrocarbons. A petroleum hydrocarbon in soil should respond analogously to a tar hydrocarbon. If mass transport of constituents from the interior of fines aggregates is limiting for tar-contaminated soil, then this should also be the case for petroleum-contaminated soil. If the soil is high in fines, bioremediation of petroleum compounds in an unsaturated state should result in higher plateau concentrations than a more sandy soil or a saturated state. If the petroleum hydrocarbons are composed of immobile, insoluble substances (e.g., asphaltic compounds), then the plateau concentration can be expected to be at a significant level above zero.

CONCLUSIONS
The results of this work allow the following conclusions to be made:

• Bioremediation of PAH-contaminated soils is a viable remedial technology;
• The composition of the soils and NAPL can significantly influence the response of PAH-contaminated soils to bioremediation;
• Bioremediation of soils containing higher fines contents, greater than 10 percent, in an unsaturated state can be limited because of mass transport restrictions from the interiors of the fine aggregates; and
• Bioremediation of soil containing pockets of NAPL can be limited by the immobile, insoluble constituents of the NAPL.

REFERENCES


