Bioclogging Effects Relevant to In-Situ Bioremediation of Organic Contaminants

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Motivation
- Types of contaminants found at Air Force Sites
  - Fuel spills (LNAPLs)
  - Aircraft De-Icing Fluids (ADF)
- Could bioclogging be significant under field conditions?
- Should bioclogging effects be incorporated into natural attenuation/remediation models?
  - Bioscreen, Bioplume, etc.

Comparison of Contaminants
- **Fuel Spills**
  - PAHs, alkanes, …
  - Readily biodegraded under range of redox
  - LNAPL
    - Continuous substrate source
    - Low/slow carbon availability
    - <100s mg/L
- **Deicing Chemicals**
  - ADF, PG, surfactants, AdPack
  - Readily biodegraded under range of redox
  - Intermittent input
  - High concentrations
  - <300,000 mg/L

Field Characteristics of Potential Importance
- Porous media type/size distribution
- Groundwater flowrates
- Groundwater chemistry
  - Electron acceptors [O₂, NO₃, Fe(III), SO₄ ]
  - Nutrient concentrations [N, P]
  - pH, temperature, etc.
  - These affect biokinetics, cell yield, EPS production…

Overview of Results
- 1D fuel spill
- 1D de-icing fluid
- Mini 2-D diesel fuel spill
- 2D tanks with fuel or PG assoc.

General Methods
- Well-characterized homogeneous sands
- Uncharacterized mixed bacterial cultures
- Hydraulic conductivity (K) by head loss and Q
- Dispersivity (α) by bromide tracer test, best-fit to breakthrough curve
- “Bulk” measurement of total biofilm (dry mass carbon) in effluent water & final sand
- Contaminant/substrate depletion
- Biokinetics [Y, b, deg. rate coefficients] in batch tests or calculated from column data
**Methods: 1D columns**

- **Flow measurement**
- **SAND**
- **Groundwater**
- **Gravel**
- **Gravel**
- **Pump**
- **Contaminant + nutrients**
- **8-10 cm**
- **5-7 cm dia**
- **Head from pump or constant head tank**

**Example K results**

- **K, cm/sec**
- **Days Growth**
- **#50 sand**
- **2.5 mg Nap/d**
- **40C:1N**

**Effects on K**

- **Grain size:**
  - Larger grains had more biomass
  - 1.5, 1.2, 0.9 mg dry wt/g sand
- **Kmin vs v**
  - Decreasing Q from 0.21 → 0.03 cm/min decreased min. K by ~2 orders of magnitude
  - Logical with increased shear; 0.31 cm/min between 0.03&0.08 mL/min?

**Effects on K**

- **Nitrogen limitation**
  - Similar minimum K for 5:1 and 40:1 C:N, significantly lower than 100:1
  - Fastest K decrease for 40:1, possibly due to affects on EPS production
1D Delcers: Effects on K

- **Loading**
  - Inlet 400-300,000 mg/L PG or ADF
  - Continuous vs intermittent (recirculated)
- **Nutrient availability**
  - N limited at high C loading since const. N
  - Vary with NO₃ and/or ammonia addition
- **Flowrate:** v 0.03-0.31 cm/min
- **Endogenous decay:** remove PG from feed

![Final K at Variable Loading](image)

PG biodegraded, mg/d
PG load 43 to 32,140 mg/d @ 99-3% biodegraded
C:N ratio 6:1 up to ~5000:1 at highest PG load

Delcers: Endogenous Effects

![Dynamic Dispersivity](image)

- c increased as biogrowth decreased K

1-D Delcers: Dispersivity

![1-D ADF: K, α, X correlations](image)

Mini 2D: Diesel fuel

- **Goal:** in field systems both vertical and transverse dispersion are important, so quantify in a lab system with biomass
Methods: Biobox

Mini 2D: Diesel fuel

\[
\begin{array}{cccccc}
\text{d}_{50} & \text{K}_{\text{bio}} & \alpha_{\text{x,bio}} & \alpha_{\text{z,bio}} & \text{mg VS} & \Delta \text{TOC} \\
\text{cm} & & & & \text{g sand} & \text{mg/L} \\
0.32 & 0.87 & 8.7 & >1 & 0.35 & 0.59 \\
0.19 & 0.90 & 2.6 & >1 & 0.29 & 0.56 \\
\end{array}
\]

Methods: 2-D Tank

2D tank with Biozone

- Naphthalene or PG-grown biozones for different lengths of time [in theory pertaining to different X, bulk K and Disp]
- Bromide tracer tests conducted to determine breakthrough effects of clean and biomass-containing zones

Example 3 wk Nap biozone data

Biozones Grown on Naphthalene
Biozones Grown on Naphthalene

2D tanks summary
- Minimal influence on $K$
  - $K_{biozone}/K_{clean} = 0.08-0.8$
  - $K_{tank+bio}/K_{clean} = 0.2-1.1$
- Significant shear of biomass out of the biozone and measured downgradient
- Dye tracers contain C leading to biogrowth through tank over time

Implied effects on field scale
- Due to flow routing, overall effects on $K$ may be minimal
  - Near well clogging may be significant
  - Biogrowth in well pack likely
- Due to microbial heterogeneity, may increase plume dispersion

Conclusions
- Biogrowth may have significant effects under many different conditions
  - Nutrient limitation minimizes bioclogging
- Further testing on 2D scale may be most helpful to predict field effects
- Vadose zone important for attenuation of ADF & LNAPLs, but bioclogging effects less clear