Cotransport of clay colloids and viruses in water saturated columns packed with glass beads

Constantinos V. Chrysikopoulos and Vasiliki I. Syngouna

Department of Civil Engineering, Environmental Engineering Laboratory, University of Patras, Patras 26500, Greece.

Emails: gios@upatras.gr, vsyngouna@upatras.gr

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ABSTRACT

The combined and synergistic effects of clay colloids and pore water velocity on virus transport and retention in porous media were examined at three pore water velocities (0.38, 0.74, and 1.21 cm/min).The results indicated that the mass recovery of viruses and clay colloids decreased as the pore water velocity decreased; whereas, for the cotransport experiments no clear trend was observed. Mass recovery values for both viruses, calculated based on total virus concentration in the effluent, were reduced compared to those in the absence of clays. The transport of both suspended and attached onto suspended clay-particles viruses was retarded, compared to the tracer, only at the highest pore water velocity. Moreover both clay colloids were shown to hinder virus transport at the highest pore water velocity. At the lower velocities MS2 transport was hindered and ΦX174 transport was facilitated with the exception of U=0.74 cm/min in the presence of KGa-1b. Both MS2 and ΦX174 were attached in greater amounts onto KGa-1b than STx-1b. Also, MS2 exhibited greater affinity than ΦX174 for both clays.

MATERIALS

Bacteriophages

MS2: an F-specific single-stranded RNA phage with effective particle diameter ranging from 24 to 26 nm

ΦX174: a somatic single-stranded DNA phage with effective particle diameter ranging from 25 to 27 nm

Clays

Kaolinite (KGa-1b): a well-crystallized kaolin from Washington County, Georgia

Montmorillonite (STx-1b): a Ca-rich montmorillonite, white, from Gonzales County, Texas

The <2 μm clay colloidal fraction was separated by sedimentation and then was purified (Rong et al., 2008). The optical density of the clay colloids was analyzed at a wavelength of 280 nm by a UV-vis spectrophotometer. Using calibration curves, each measured KGa-1b absorbance was converted to KGa-1b concentration and each measured STx-1b absorbance was converted to STx-1b concentration.

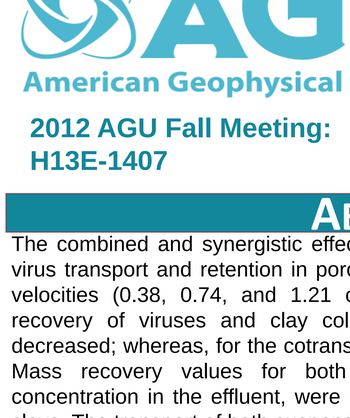

Figure 1. X-ray diffraction patterns of (a) KGa-1b, and (b) STx-1b.

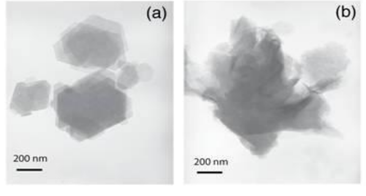

Figure 2. Transmission electron micrographs of (a) KGa-1b, and (b) STx-1b.

METHODS

Column Experiments

- columns (2.5 cm diameter and 30 cm length)
- glass beads 2mm in diameter
- q= 2.5, 1.5 and 0.8 mL/min
- U=q/θ= 1.21, 0.74, and 0.38 cm/min
- 3 pore volumes of feed suspension in ddH_2O
- 5 pore volumes of ddH_2O solution

Cotransport Experiments

C_c : Suspended clay particles

$C_{Total\text{-}v}$: Total viruses $\quad C_{Total\text{-}v} = C_v + C_{vc}$

C_v: Suspended viruses

C_{vc}: Viruses attached onto suspended clays

C_{c^*} : Clays attached onto glass beads

C_{v^*} : Viruses attached onto glass beads

C_{vc^*}: Viruses attached onto attached clays

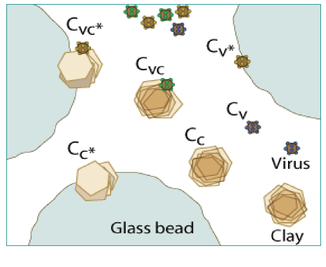

Figure 3. Schematic illustration of the six concentration components involved in cotransport experiments (Syngouna and Chrysikopoulos, 2012).

THEORY

1. Colloid filtration theory

The dimensionless collision efficiency, α (Rajagopalan and Tien 1976):

$$\alpha = -\frac{2d_c \ln(RB)}{3(1-\theta)\eta_0 L} \qquad RB = \frac{M_{r(i)}}{M_{r(t)}} \qquad M_r(L) = \frac{\int_0^\infty C_i(L,t)dt}{\int_0^{t_p} C_i(0,t)dt}$$

The single collector contact efficiency, η_0 (Tufenkji and Elimelech, 2004):

$$\eta_0 = 2.4A_s^{1/3}N_R^{-0.081}N_{Pe}^{-0.715}N_{vdW}^{0.052} + 0.55A_sN_R^{1.675}N_A^{0.125} + 0.22N_R^{-0.24}N_G^{1.11}N_{vdW}^{0.053}$$

2. Moment Analysis

$$M_n(x) = \frac{\int_0^\infty t^n C_i(x,t)dt}{\int_0^\infty C_i(x,t)dt}$$

3. Virus-glass and clay-glass beads interactions

a. Classical DLVO theory (Loveland et al.,1996)

$$\Phi_{DLVO}(h) = \Phi_{vdW}(h) + \Phi_{dl}(h) + \Phi_{Born}(h)$$

b. Extended DLVO theory (Bergendahl and Grasso,1999)

$$\Phi_{XDLVO}(h) = \Phi_{DLVO}(h) + \Phi_{AB}(h)$$

RESULTS

Transport Experiments

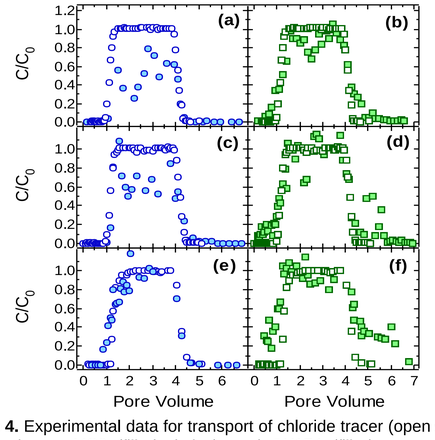

Figure 4. Experimental data for transport of chloride tracer (open symbols), bacteriophages MS2 (filled circles), and ΦX174 (filled squares) with U equal to: (a,b) 0.38, (c,d) 0.74, and (e,f) 1.21 cm/min.

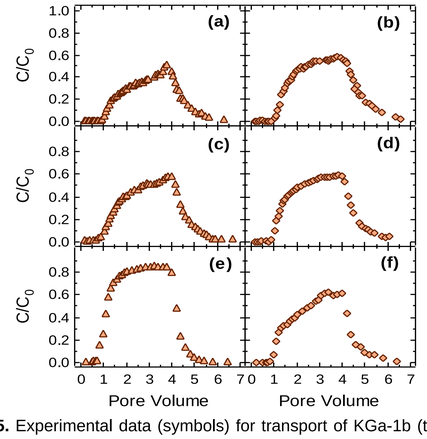

Figure 5. Experimental data (symbols) for transport of KGa-1b (triangles), and STx-1b colloids (diamonds) with U equal to: (a,b) 0.38, (c,d) 0.74, and (e,f) 1.21 cm/min.

Cotransport Experiments

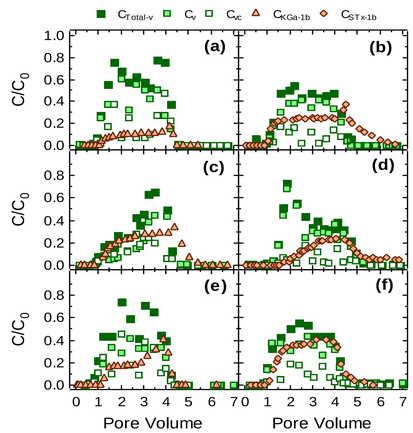

Figure 6. Experimental data for cotransport of ΦX174 with KGa-1b (a,c,e), and STx-1b (b,d,f) with U equal to: (a,b) 0.38, (c,d) 0.74, and (e,f) 1.21 cm/min.

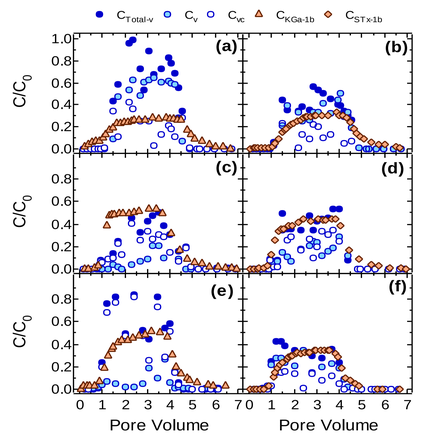

Figure 7. Experimental data for cotransport of MS2 with KGa-1b (a,c,e), and STx-1b (b,d,f) with U equal to: (a,b) 0.38, (c,d) 0.74, and (e,f) 1.21 cm/min.

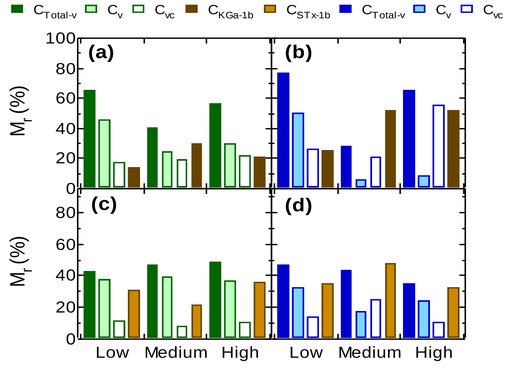

Figure 8. Calculated M_r values based on $C_{Total\text{-}v}$, C_v, C_{vc}, and C_c for cotransport of: (a) ΦX174 with KGa-1b, (b) MS2 with KGa-1b, (c) ΦX174 with STx-1b, and (d) MS2 with STx-1b at low (U=0.38 cm/min), medium (U=0.74 cm/min) and high (U=1.21cm/min) interstitial velocities.

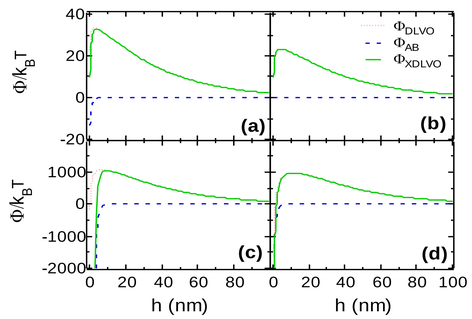

Figure 9. Predicted sphere-plate Φ_{DLVO}, Φ_{AB}, and Φ_{XDLVO} interaction energy profiles for: (a) MS2 and glass beads, (b) ΦX174 and glass beads, (c) KGa-1b and glass beads, and (d) STx-1b and glass beads, as a function of separation distance (here pH=7, $I_s=10^{-4}$ M).

CONCLUSIONS

Transport Experiments

- The peak-concentrations and mass recoveries for both viruses increased with increasing U.
- With no exception, all estimated M_r values for MS2 were lower than those of ΦX174.
- For the case of the lowest U, slight enhancement was observed ($M_{1(i)}/M_{1(t)}>1$) for both viruses.
- Higher mass recoveries observed for STx-1b than KGa-1b for the lowest U.
- The $\alpha_{Total\text{-}v}$ values of MS2 in the transport experiments were higher than those of ΦX174.

Cotransport Experiments

- The transport of $C_{Total\text{-}v}$ and C_{vc} for ΦX174 was retarded only at the highest U compared to the tracer.
- The same trend was observed at the highest U for C_v and C_{vc} of MS2, except KGa-1b presence.
- In most cases, in the presence of KGa-1b, C_{vc} of ΦX174 was enhanced more than $C_{Total\text{-}v}$ of ΦX174.
- For all cases examined, C_v of MS2 was enhanced more than $C_{Total\text{-}v}$ of MS2, and $C_{Total\text{-}v}$ of MS2 was enhanced more than C_{vc} of MS2 for both clays employed (KGa-1b, STx-1b).
- In the presence of KGa-1b, the M_r values based on C_{vc} of MS2 were quite high (21.4 to 55.4%).
- In the presence of STx-1b, the M_r values based on $C_{Total\text{-}v}$ of MS2 were lower.
- The M_r values based on C_{vc} of ΦX174 were considerably lower than those of MS2.
- The $\alpha_{Total\text{-}v}$ values were higher for both viruses in all cases examined, which indicated that more attachment sites were available on the solid matrix (glass beads and C_{c^*}).
- In the presence of STx-1b, $\alpha_{Total\text{-}v}$ values decreased with decreasing U, while in the presence of KGa-1b no clear trend was observed.

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