Effect of gravity on virus and clay colloid cotransport through vertical water-saturated columns

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ABSTRACT

The cotransport of clay colloids and viruses in vertically oriented laboratory columns packed with glass beads was investigated. Bacteriophages MS2 and ΦX174 were used as model viruses, and kaolinite (KGa-1b) and montmorillonite (STx-1b) as model clay colloids. A steady flow rate of Q=1.5 mL/min was applied in both vertical upward (VU) and vertically downward (VD) flow directions. For most of the cases examined in this study, estimated mass recovery values were higher for VD than VU flows, suggesting that the flow direction significantly influenced particle deposition. KGa-1b hindered the transport of ΦX174 under VD flow conditions, while STx-1b facilitated the transport of ΦX174 under both VU and VD flow conditions. Moreover, KGa-1b and STx-1b facilitated the transport of MS2 in most of the cases examined except of the case where KGa-1b was present under VD flow.

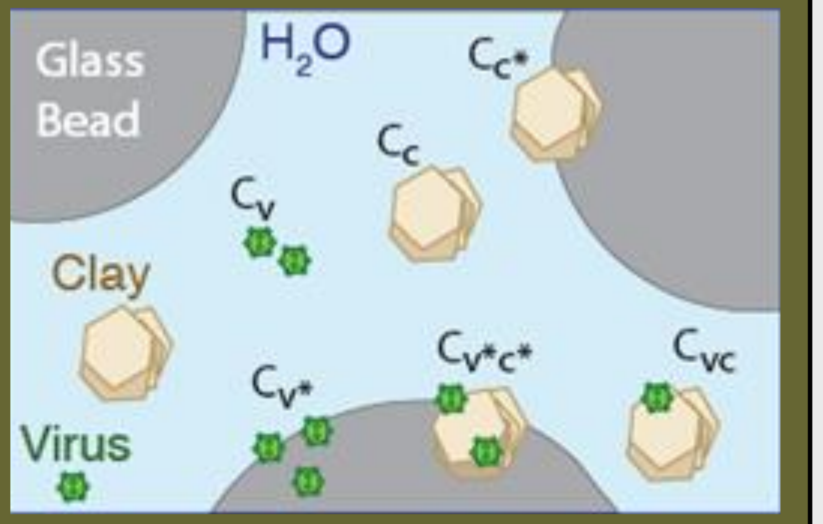

Figure 1. Schematic illustration of the various concentrations employed in the cotransport experimental study.

NOTATION

- C_c : suspended clay particles
- $C_{Total-v}$: total virus concentration
- C_v: suspended viruses
- C_{vc}: viruses attached onto C_c
- C_{c^*} : clays attached onto glass beads
- C_{v^*} : viruses attached onto glass beads
- $C_{v^*c^*}$: viruses attached onto C_{c^*}
- C_{v0} : influent (initial) virus concentration
- C_{c0} : influent (initial) clay concentration

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MATERIALS AND METHODS

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

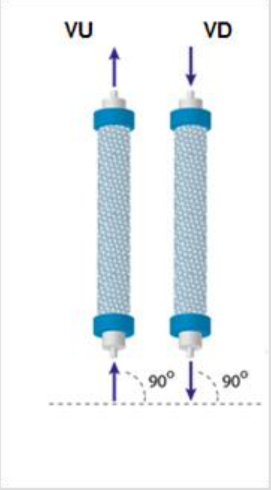
Clays

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)

Experimental Set Up

- Glass column
  - Length 30 cm
  - Internal diameter 2.5 cm
- Glass beads
- Flow rate of Q=1.5 mL/min
- pH=7.0±0.2
- vertical upward (VU) and downward (VD) flow directions



ANALYSIS OF EXPERIMENTAL DATA

⊙ Collision efficiency, α [-]
(Rajagopalan and Tien, 1976)

$$\alpha = -\frac{2d_c \ln(RB)}{3(1-\theta)\eta_0 L} \qquad RB = \frac{M_{r(i)}}{M_{r(t)}}$$

⊙ Mass recovery of $C_{Total-v}$, C_v, M_r [-]
(James and Chrysikopoulos, 2011)

$$M_r(L) = \frac{\int_0^\infty C_i(L,t)dt}{\int_0^{t_p} C_i(0,t)dt}$$

⊙ Produced mass of C_{vc}, M_p [-]
(Syngouna and Chrysikopoulos, 2015)

$$C_{vc} = C_{Total-v} - C_v$$

⊙ First normalized temporal moment
(James and Chrysikopoulos, 2011)

$$M_1(x) = \frac{\int_0^\infty tC_i(x,t)dt}{\int_0^\infty C_i(x,t)dt}$$

⊙ Degree of colloid velocity enhancement relative to the conservative tracer

$$M_{1(C_{Total-v})}/M_{1(t)} \qquad M_{1(C_v)}/M_{1(t)}$$
$$M_{1(C_{vc})}/M_{1(t)} \qquad M_{1(C_c)}/M_{1(t)}$$

RESULTS

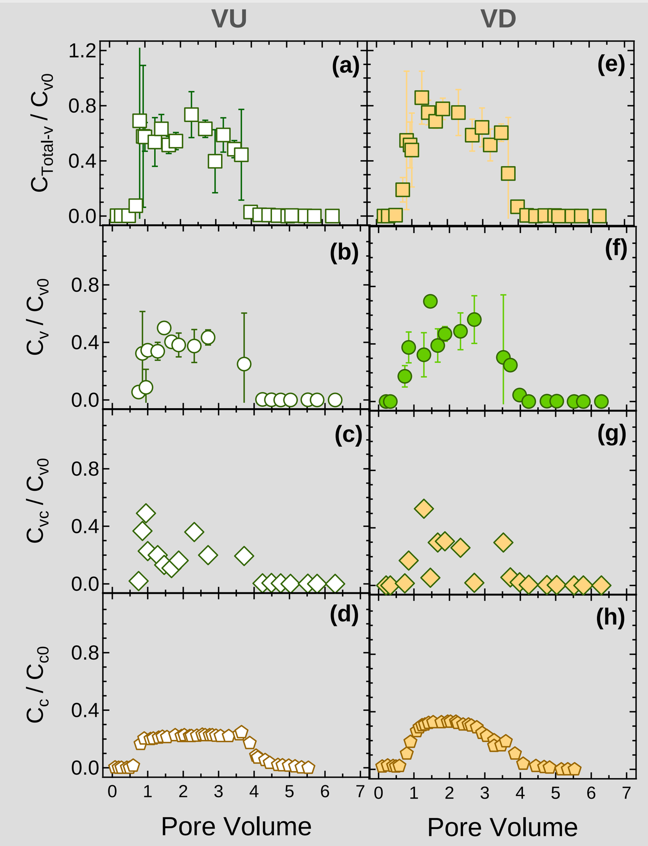


Figure 2. Experimental data of $C_{Total-v}$ (squares), C_v (circles), C_{vc} (diamonds), and C_c (pentagons) for the ΦX174 and KGa-1b cotransport experiments with: (a–d) vertical up (open symbols), and (e–h) vertical down (filled symbols) flow directions.

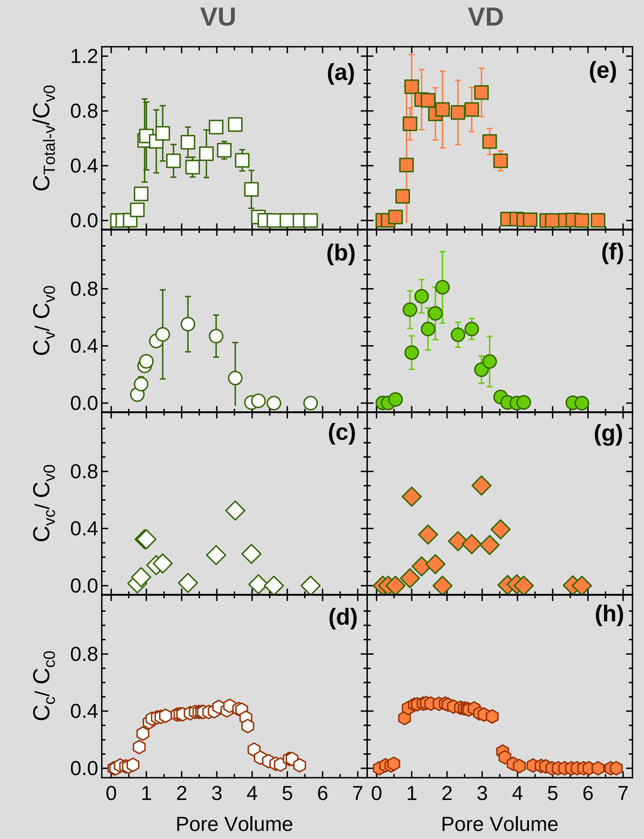


Figure 3. Experimental data of $C_{Total-v}$ (squares), C_v (circles), C_{vc} (diamonds), and C_c (pentagons) for the ΦX174 and STx-1b cotransport experiments with: (a–d) vertical up (open symbols), and (e–h) vertical down (filled symbols) flow directions.

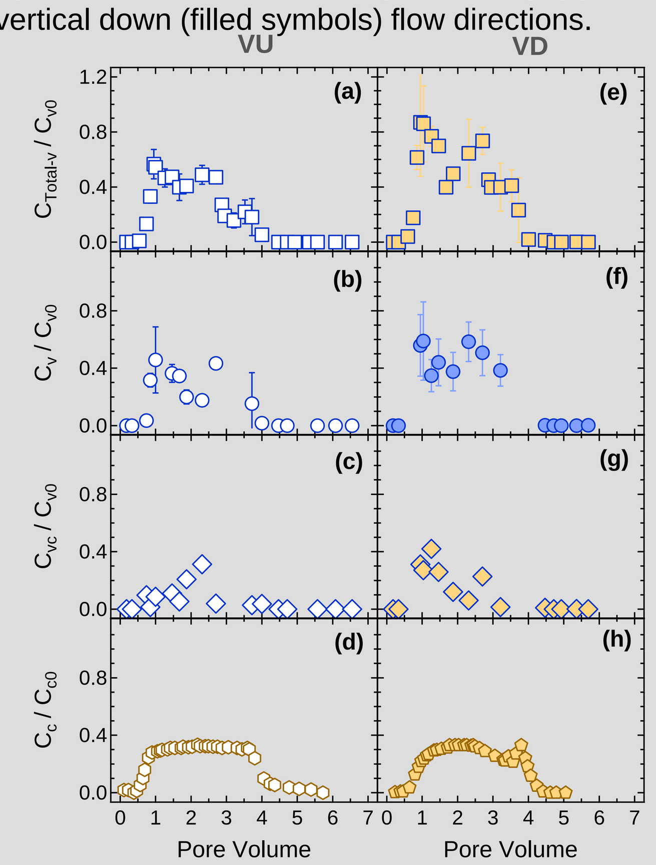


Figure 4. Experimental data of $C_{Total-v}$ (squares), C_v (circles), C_{vc} (diamonds), and C_c (pentagons) for the MS2 and KGa-1b cotransport experiments with: (a–d) vertical up (open symbols), and (e–h) vertical down (filled symbols) flow directions.

RESULTS

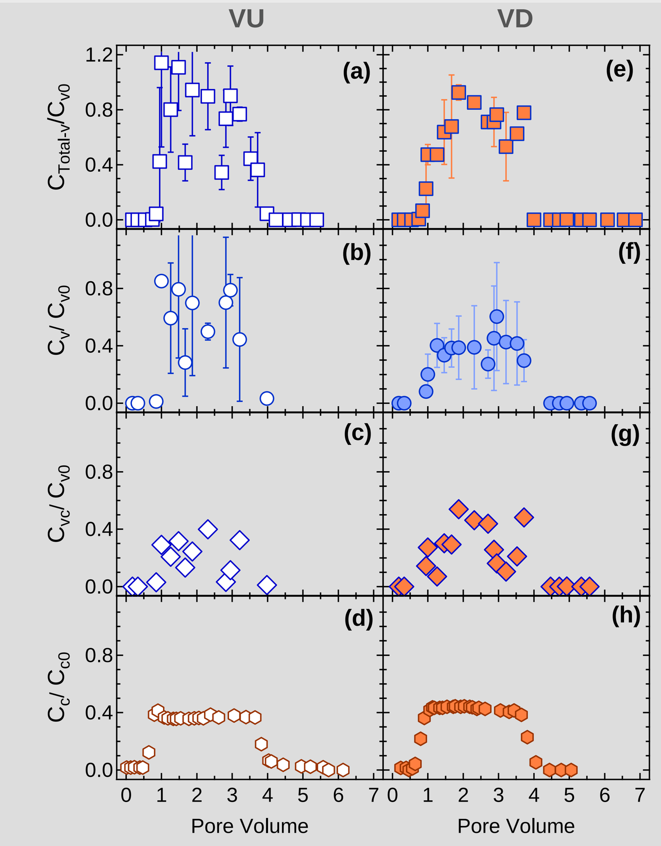


Figure 5. Experimental data of $C_{Total-v}$ (squares), C_v (circles), C_{vc} (diamonds), and C_c (pentagons) for the MS2 and STx-1b cotransport experiments with: (a–d) vertical up (open symbols), and (e–h) vertical down (filled symbols) flow directions.

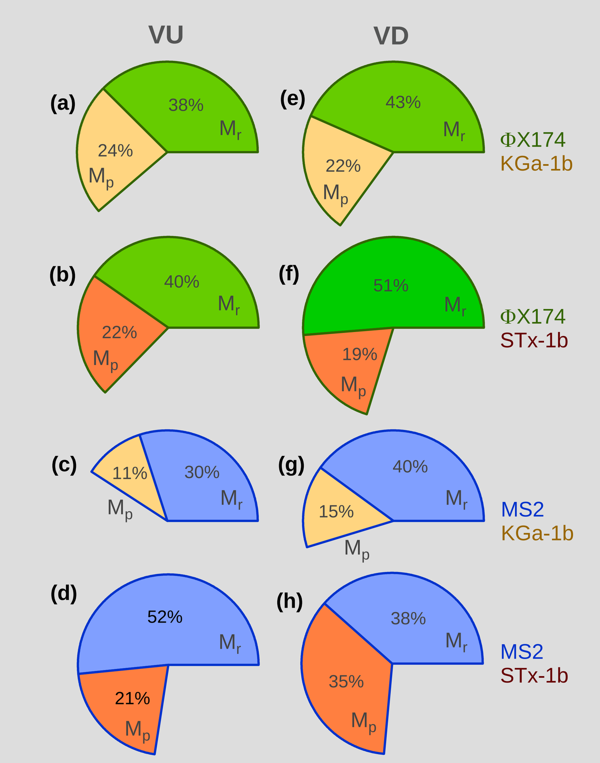


Figure 6. Calculated M_r values based on C_v and M_p values based on C_{vc} for cotransport of: (a,e) ΦX174 with KGa-1b, (b,f) ΦX174 with STx-1b, (c,g) MS2 with KGa-1b, and (d,h) MS2 with STx-1b under (a–d) vertical upward, and (e–h) vertical downward flow directions.

Table 1. Experimental and calculated parameters for cotransport experiments

Cotransport Experiments	ΦX174				MS2			
	KGa-1b		STx-1b		KGa-1b		STx-1b	
Flow Direction#	VU	VD	VU	VD	VU	VD	VU	VD
Initial concentration								
C_{v0} (PFU/mL)	3400	2767	3850	4817	18185	9767	9017	9500
C_{c0} (mg/L)	93	80.75	123.92	122.21	70.69	76.98	114.07	92.56
Mass recovery, M_r (%)								
$C_{Total-v}$	57	64.55	55.65	71.85	40.85	53.75	73.18	67.65
C_v	37.53	43.41	40.31	43	29.99	39.98	51.59	38.45
C_c	25.05	27.2	41.19	47.74	36.8	31.41	39.28	42.88
Mass production, M_p (%)								
C_{vc}	23.69	21.59	22.37	27.22	10.86	14.73	21.01	35.11
Moment ratios, $M_{1(i)}/M_{1(t)}$								
$C_{Total-v}$	0.84	0.82	0.89	0.79	0.77	0.78	0.82	0.89
C_v	0.86	0.83	0.82	0.82	0.79	0.85	0.81	0.92
C_{vc}	0.91	0.79	1.05	1.01	0.80	0.70	0.83	0.93
C_c	0.91	0.87	0.94	0.77	0.9	0.85	0.87	0.85
Collision efficiency								
$\alpha_{Total-v}$	0.1	0.08	0.11	0.06	0.16	0.11	0.06	0.07
α_v	0.18	0.15	0.17	0.15	0.21	0.16	0.12	0.17
α_c	0.91	0.86	0.34	0.36	0.66	0.76	0.36	0.33

#VU-vertical up-flow, VD-vertical down-flow

RESULTS

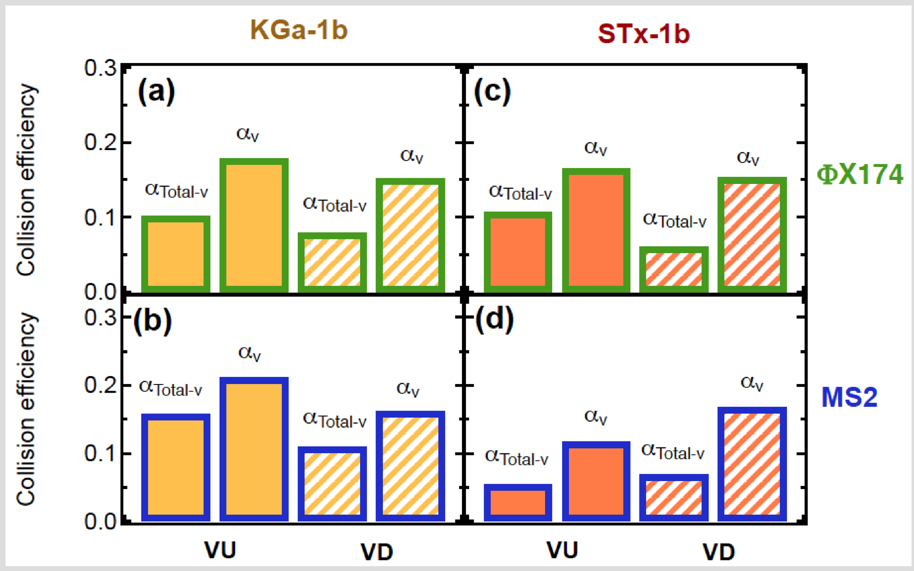


Figure 7. Calculated collision efficiency values, $\alpha_{Total-v}$, based on $C_{Total-v}$, and α_v based on, C_v, for cotransport experiments: (a) ΦX174 with KGa-1b, (b) MS2 with KGa-1b, (c) ΦX174 with STx-1b, and (d) MS2 with STx-1b under vertical upward (solid bars) and vertical downward (partially shaded bars) flow directions.

CONCLUSIONS

- The calculated ratios $M_{1(C_{Total-v})}/M_{1(t)}$ indicated that the transport of both ΦX174 and MS2 ($C_{Total-v}$) was retarded for both VU and VD flow directions, compared to the tracer.
- KGa-1b and STx-1b were retarded for all ΦX174 cotransport cases examined.
- In the presence of KGa-1b, at VD flows, clay colloids hindered the transport of ΦX174.
- In the presence of STx-1b, for both flow directions examined (VU, VD), the presence of clay colloids facilitated the transport of ΦX174.
- In the presence of either of the two clays (KGa-1b, STx-1b) for both flow directions examined (VU, VD), the transport of MS2 was facilitated, except for the case of VD flow direction in the presence of KGa-1b.
- In the presence of KGa-1b, the M_p values based on C_{vc} of MS2 were lower than those in the presence of STx-1b under both flow directions.
- Similar M_p values based on C_{vc} of ΦX174 were observed in the presence of either of the clays under both flow directions examined.
- Similar M_r values based on C_c were observed for both KGa-1b and STx-1b in the presence of viruses under both flow directions examined.
- In the presence of both KGa-1b and STx-1b, $\alpha_{Total-v}$ values were higher in VU than VD flows with the only exception of MS2 and STx-1b cotransport.
- The calculated α_v indicated that the presence of KGa-1b increased the attachment of virus onto glass beads and clay colloids more than STx-1b.

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