Another look at the colloid particle size-dependent dispersivity

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Abstract

Laboratory and field studies have demonstrated that dispersion coefficients evaluated by fitting advection-dispersion transport models to nonreactive tracer breakthrough curves do not adequately describe colloid transport under the same flow field conditions. Here an extensive laboratory study was undertaken to assess whether the dispersivity, which traditionally has been considered to be a property of the porous medium, is dependent on colloid particle size and interstitial velocity. A total of 48 colloid transport experiments were performed in columns packed with glass beads under chemically unfavorable colloid attachment conditions. Nine different colloid diameters, and various flow velocities were examined. The breakthrough curves weresuccessfully simulated with a mathematical model describing colloid transport in homogeneous, water saturated porous media. The experimental data set collected in this study demonstrated that the dispersivity is positively correlated with colloid particle size, and increases with increasing velocity. The dispersivity values determined in this laboratory study were compared with 380 dispersivity values from earlier laboratory- and field-scale solute, colloid and biocolloid transport studies published in the literature.

Experimental Approach

A total of 48 flowthrough experiments were conducted in glass columns with diameter 2.5 cm and length L=15 or 30 cm, packed with spherical glass beads with diameter d_c=2 mm. Each column was packed with beads under standing distilled deionized water (ddH_2O) to minimize air entrapment. The columns were placed horizontally to minimize gravity effects (*Chrysikopoulos and Syngouna*, 2014). Fluorescent polystyrene microspheres with diameters d_p=28, 300, 600, 1000, 1750, 2100, 3000, 5000, and 5500 nm were used as model colloid particles. Microsphere concentrations were measured by a fluorescence spectro-photometer. Straining and wedging are not considered important mechanisms of mass loss in the packed columns examined in this study, because the colloid to collector diameter ratios (d_p/d_c) were well below the suggested threshold of 0.004 (*Johnson et al.*, 2010) or 0.003 (*Bradford and Bettahar*, 2006) for all cases examined. In the experiments conducted only the two unknown model parameters U and D_L were estimated by fitting the analytical solution. All fittings were conducted with the in-house developed nonlinear least squares regression software "ColloidFit," which incorporates the state of the art model-independent parameter estimation package "Pest" (*Doherty et al.*, 1994). Furthermore given the flow rate of the pump along with the aquifer porosity, the target velocities were calculated and compared against the fitted velocities, indicating that no systematic error existed.

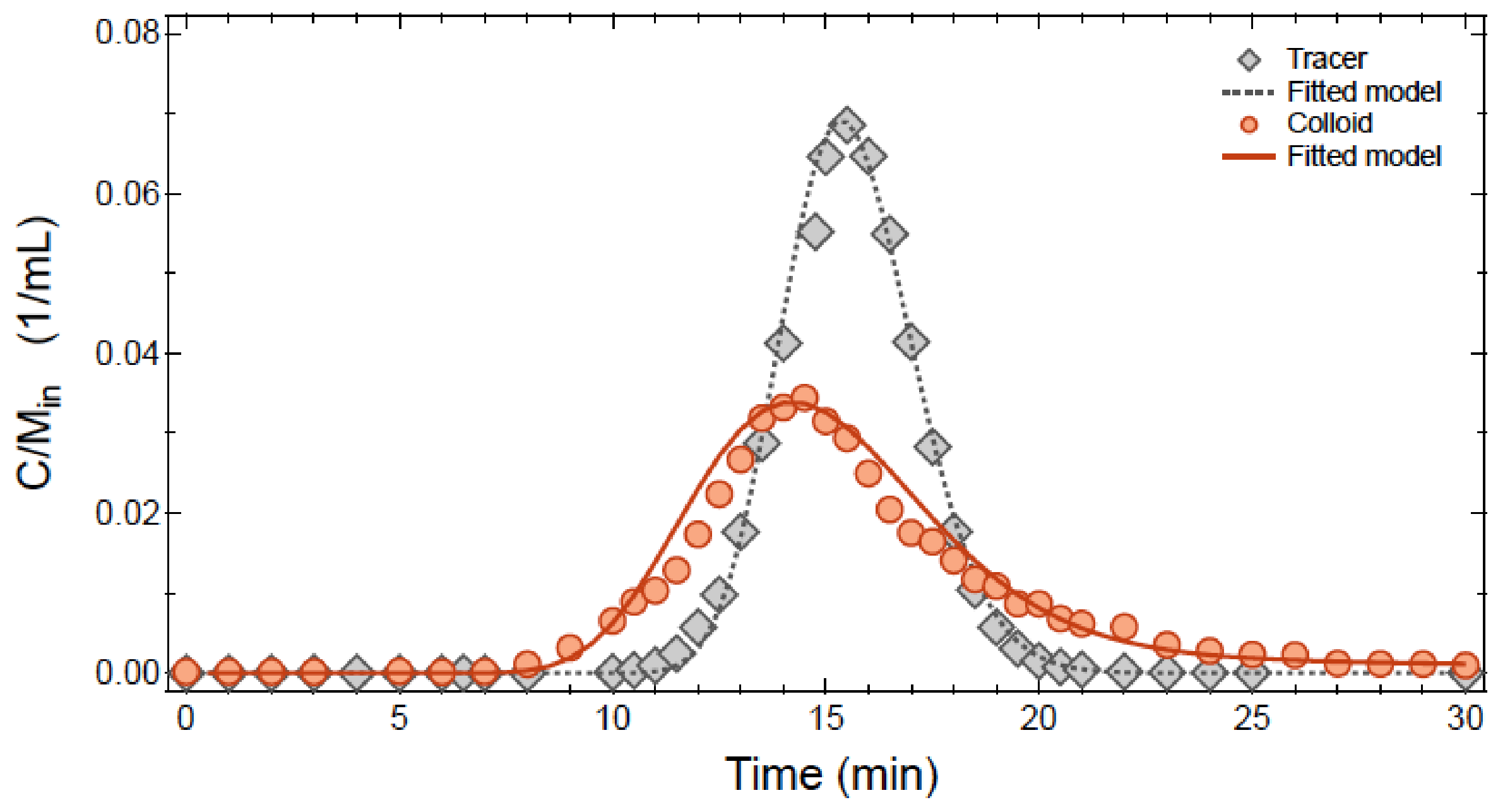

Figure 1. Breakthrough concentration data normalized with respect to M_{in}, for the tracer (diamonds) and the colloids with d_p=5000 nm (circles) as a function of time. The experiments were conducted in a 30–cm column. The curves represent fitted model simulations for the tracer (dotted curve) and the colloids (solid curve). Here α_L=0.14 cm for the tracer, and α_L=0.54 cm for the colloids

Mathematical Model

The transport of colloids (including biocolloids) in one-dimensional, homogeneous, water-saturated porous media with first-order attachment (or filtration) and inactivation is governed by (*Sim and Chrysikopoulos*, 1995):

$$\frac{\partial C(t,x)}{\partial t}+\frac{\rho_b}{\theta}\frac{\partial C^*(t,x)}{\partial t}=D_L\frac{\partial^2 C(t,x)}{\partial x^2}-U\frac{\partial C(t,x)}{\partial x}$$
$$-\lambda C(t,x)-\lambda^*\frac{\rho_b}{\theta}C^*(t,x)$$

The rate of colloid attachment onto the solid matrix is described by the following first-order equation (*Sim and Chrysikopoulos*, 1998):

$$\frac{\rho_b}{\theta}\frac{\partial C^*(t,x)}{\partial t}=k_c C(t,x)-k_r\frac{\rho_b}{\theta}C^*(t,x)-\lambda^*\frac{\rho_b}{\theta}C^*(t,x)$$

For a semi-infinite one-dimensional porous medium in the presence of a colloid source in the form of an "instantaneous" pulse, the appropriate initial and boundary conditions are:

$$\frac{\partial C(t,\infty)}{\partial x}=0,\qquad C(0,x)=0,\qquad -D_L\frac{\partial C(t,0)}{\partial x}+UC(t,0)=M_\delta\delta(t)$$

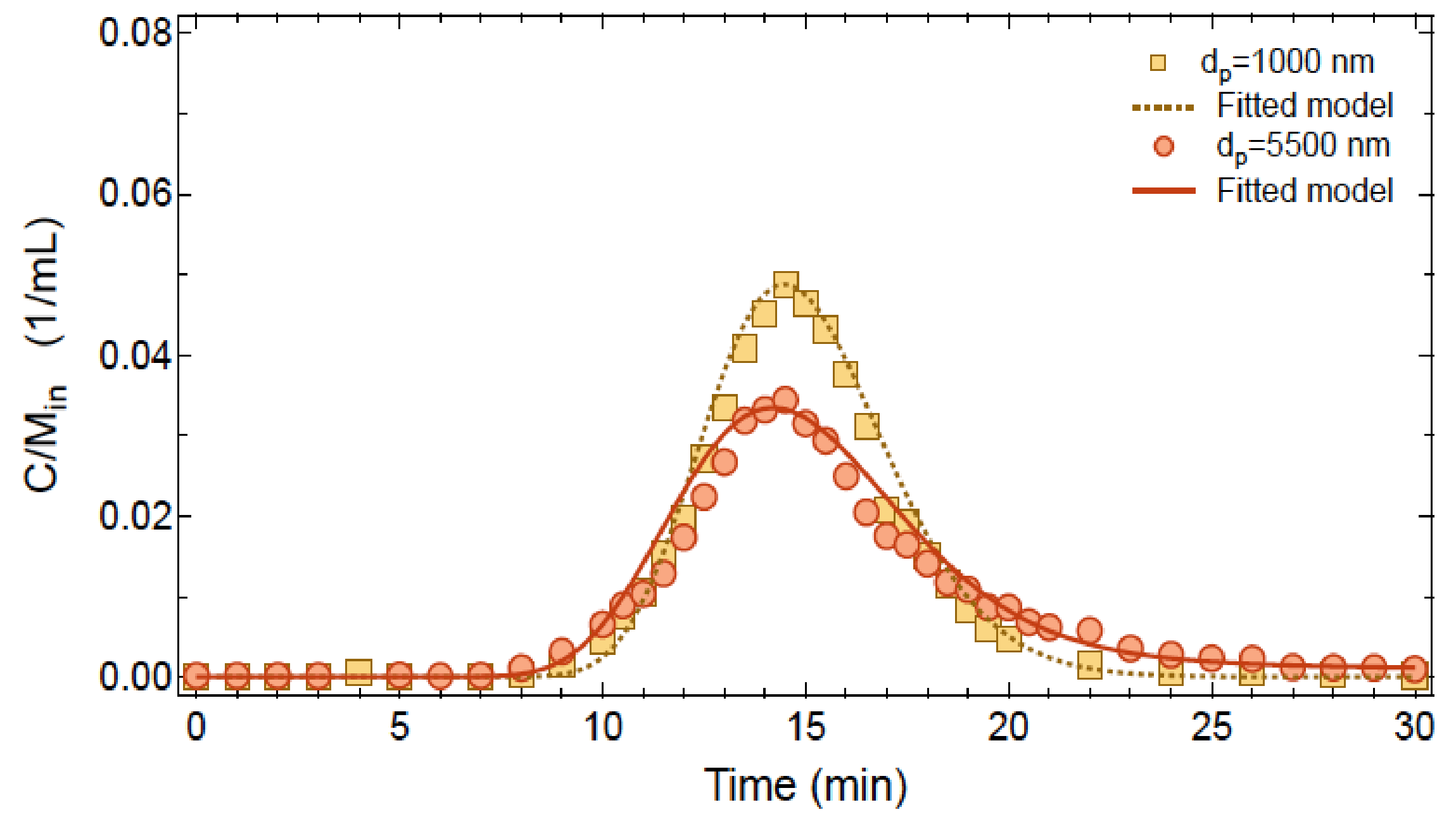

Figure 2. Breakthrough concentration data normalized with respect to M_{in}, for the colloids with d_p=1000 nm (squares) and the colloids with d_p=5500 nm (circles) as a function of time. The experiments were conducted in a 30–cm column. The curves represent fitted model simulations for the colloids with d_p=1000 nm (dotted curve), and d_p=5500 nm (solid curve). Here, α_L=0.36 cm for the colloids with d_p=1000 nm, and α_L=0.57 cm for the colloids with d_p=5500 nm.

Results

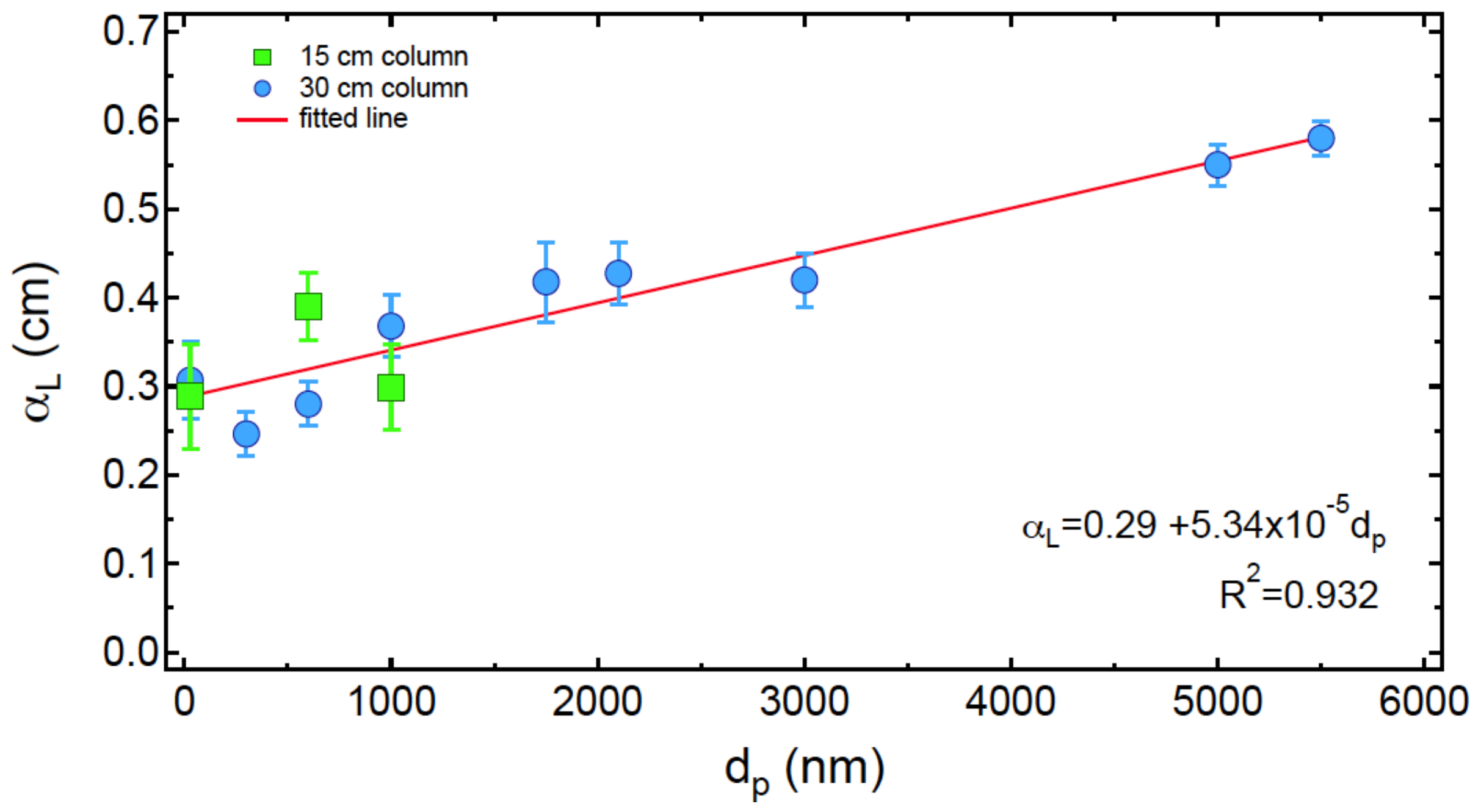

Figure 3. Averaged longitudinal dispersivity as a function of colloid particle diameter. The solid line is a standard linear regression line.

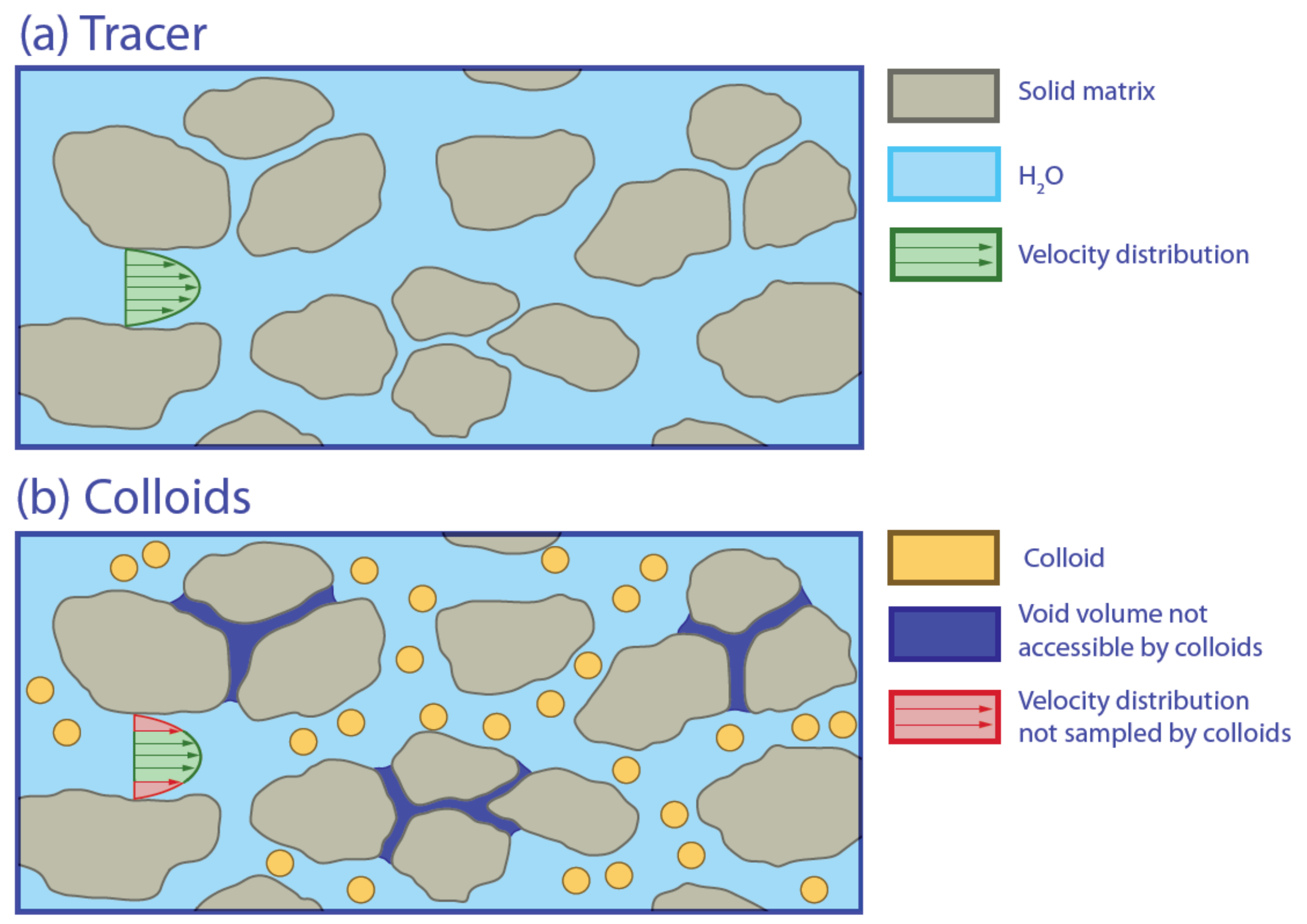

Figure 4. Schematic illustration of (a) tracer (conservative solute) and (b) colloid transport in water saturated porous media. The tracer can sample the entire velocity spectrum within the parabolic profile (green region). Colloids do not sample the truncated portion of the parabolic velocity profile (red region). Also, colloids do not enter pore spaces with opening smaller than d_p, which essentially leads to reduction of the volume of void-space accessible by colloids (reduction of the colloid effective porosity). Under the experimental conditions of this study, the interstitial fluid has continuous access to the entire volume of void-space.

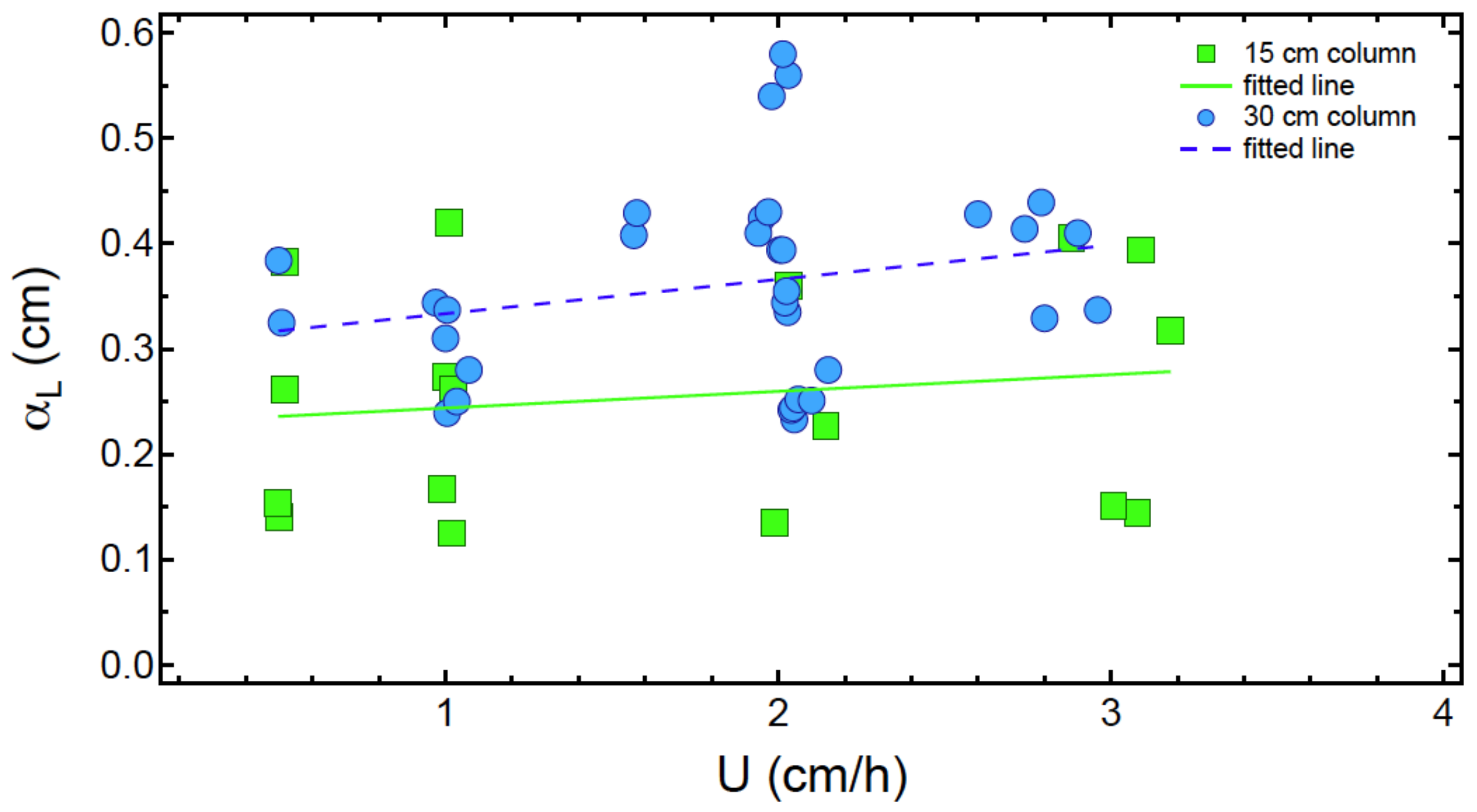

Figure 5. Longitudinal dispersivity as a function of interstitial velocity. The solid line is a standard linear regression line for the experiments conducted in the 15–cm column, and the dashed line for the experiments conducted in the 30–cm column.

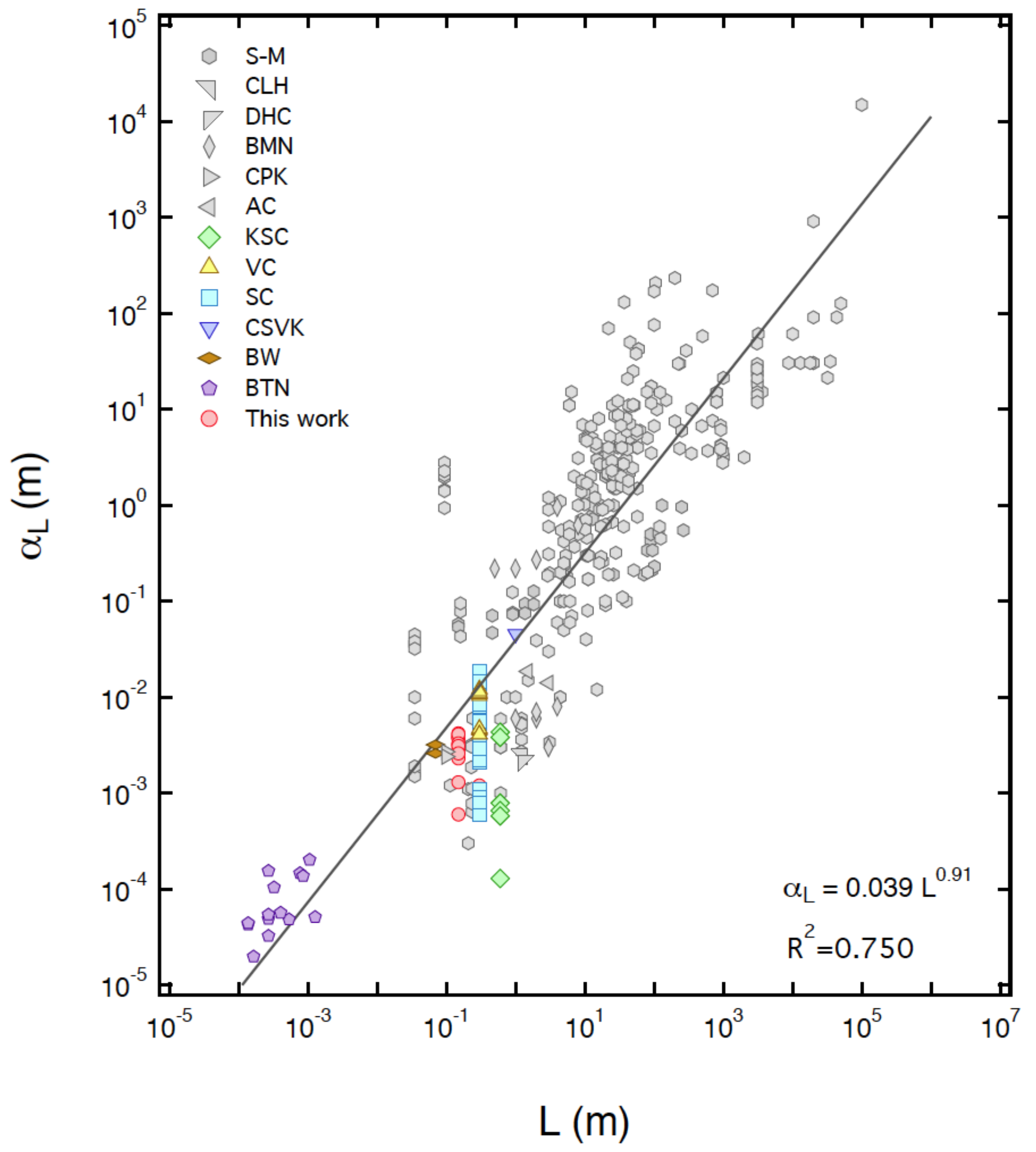

Figure 6. Compilation of 432 longitudinal dispersivities as a function of length scale. Molecular sized solutes are represented by gray symbols, and colloids/biocolloids by various colored symbols. The solid line is a standard linear regression line..

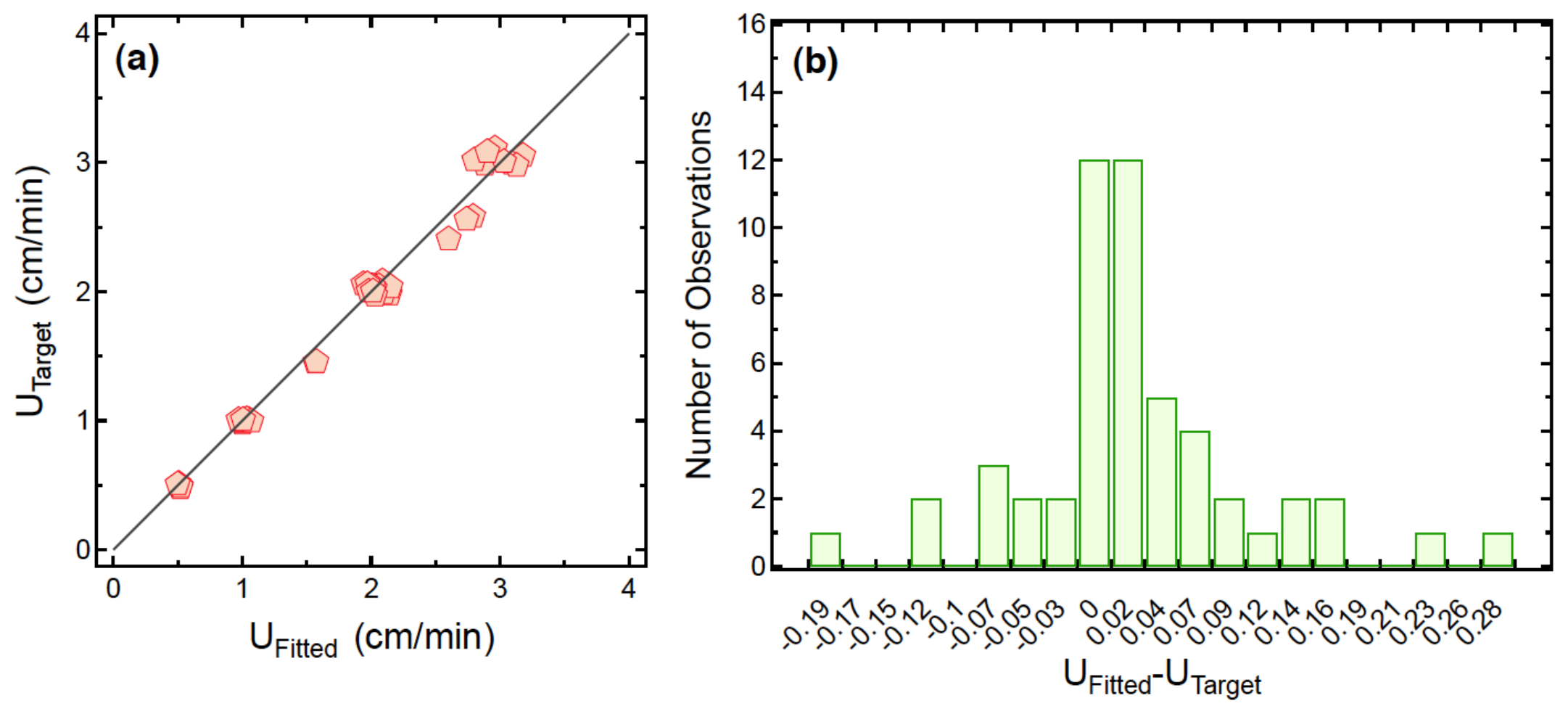

Figure 7. Comparison between the target (based on Q) and fitted interstitial velocities: (a) U_{Target} versus U_{Fitted}, and (b) Histogram of U_{Fitted}-U_{Target}. The solid line represents the ideal one-to-one correlation (R^2=1).

Conclusions

⊙ Colloid dispersivity is not only a function of scale, as conventionally assumed, but also a function of colloid diameter and interstitial velocity.

⊙ It was shown that dispersivity increases linearly with increasing colloid particle size. This phenomenon was attributed to:

1. Size exclusion
2. Exclusion from the lower velocity regions
3. Possible existence of preferential flow paths

⊙ Some of the colloids are getting slowed down having to pass through small pore spaces, where other colloids are managing to stay in fast flow paths

⊙ Fitted dispersion coefficients based on tracer data should not be used to analyze colloid experimental data.

References

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