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A review of visualization techniques of biocolloid transport processes at the pore scale under saturated and unsaturated conditions

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Abstract

Field and column studies of biocolloid transport in porous media have yielded a large body of information, used to design treatment systems, protect water supplies and assess the risk of pathogen contamination. However, the inherent "black-box" approach of these larger scales has resulted in generalizations that sometimes prove inaccurate. Over the past 10–15 years, pore scale visualization techniques have improved substantially, allowing the study of biocolloid transport in saturated and unsaturated porous media at a level that provides a very clear understanding of the processes that govern biocolloid movement. For example, it is now understood that the reduction in pathways for biocolloids as a function of their size leads to earlier breakthrough. Interception of biocolloids by the porous media used to be considered independent of fluid flow velocity, but recent work indicates that there is a relationship between them. The existence of almost stagnant pore water regions within a porous medium can lead to storage of biocolloids, but this process is strongly colloid-size dependent, since larger biocolloids are focused along the central streamlines in the flowing fluid. Interfaces, such as the air–water interface, the soil–water interface and the soil–water–air interface, play a major role in attachment and detachment, with significant implications for risk assessment and system design. Important research questions related to the pore-scale factors that control attachment and detachment are key to furthering our understanding of the transport of biocolloids in porous media.

Keywords: Colloid; Sorption; Desorption; Filtration; Straining; Groundwater

1. Introduction

The transport of biocolloids (e.g., viruses, bacteria, spores and other microorganisms) through saturated and unsaturated porous media is of significant interest, from the perspective of protection of groundwater supplies from contamination (e.g., [87,53,128,85,104,99]), assessment of risk from pathogens in groundwater (e.g., [9,40,49,51,54, 111,143,1,28,124,14,88,108,95,130]), natural and enhanced bioremediation (e.g., [106,96,141,3,38,33,37,2,68]) and for the design of better water treatment systems to remove biocolloids from drinking water supplies (e.g., [42,81,114]). Microorganisms can also travel attached to abiotic particles (e.g., [83,24,55,61]). In addition, certain microorganisms can also facilitate the transport of metals and other chemicals (e.g., [72,35,132,145]). Thus, it is important to understand the transport of colloids in general, and that of biocolloids in specific.

Biocolloids are affected by many of the physical and chemical processes that influence solute transport, i.e., advection, diffusion, dispersion and adsorption (Fig. 1). Advection is the motion of the biocolloids along the trajectories of the fluid streamlines. This mechanism can create dispersion of the biocolloids because of the heterogeneity of the fluid velocity field and the tortuosity of the paths through the porous media. Dispersion can be more important for colloids than for solutes, since it can lead to earlier breakthrough of the colloids, as presented below. In addition, random interactions among molecules and/or particles result in Brownian movements [117] that diffuse the

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Nomenclature

A	Hamaker constant (J)
a_p	particle radius (m)
A_s	soil porosity function (–)
AWI	air–water interface (–)
D_∞	colloid bulk diffusion coefficient (m^2/s)
d_g	effective grain diameter (m)
d_p	particle effective diameter (m)
g	gravitational acceleration (m/s^2)
k_B	Boltzmann's constant (J/K)
N_A	Hamaker number (–)
N_G	gravity number (–)
N_{Pe}	Peclet number (–)
N_R	Reynolds number (–)
N_{vdW}	van der Waals number (–)
SWA	soil–water–air interface (–)
SWI	soil–water interface (–)
T	temperature (K)
T/C	pore throat to colloid diameter (m/m)
U	pore water velocity (m/s)
η	collision efficiency (–)
θ_m	soil matrix porosity (–)
μ_w	viscosity of aqueous solution (kg/m s)
ρ_p	particle density (kg/m^3)
ρ_w	density of aqueous solution (kg/m^3)

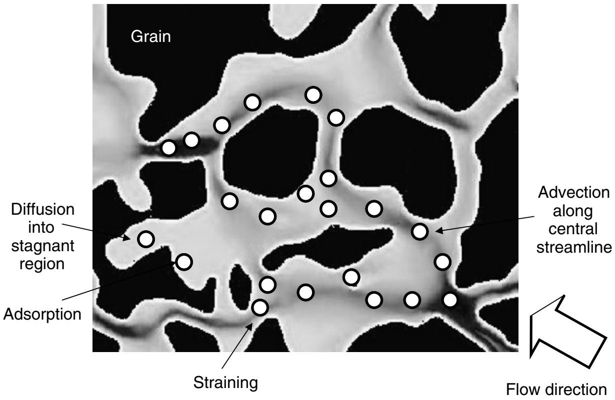

Fig. 1. Schematic of pore scale processes under saturated flow.

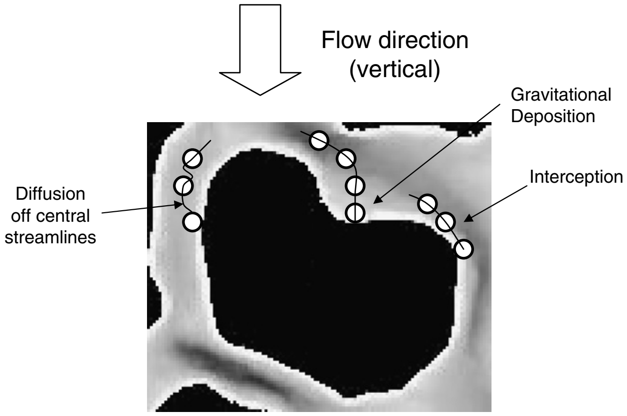

Fig. 2. Schematic of processes that lead to attachment.

biocolloids. The biocolloids can attach to the soil–water interface (SWI), the air–water interface (AWI), or the triple contact of soil–water–air (SWA). Attachment/adsorption to these interfaces can be reversible or essentially irreversible under certain conditions, and is perhaps the most complex process, given the large number of colloid and grain surface characteristics that determine the probability of attachment, and the influence of the dissolved chemical species in the aqueous solution on attachment and detachment. In addition to those four processes, colloids are subject to removal by physical mechanisms, such as straining, interception, diffusion to the wall and gravitational deposition. These physical processes are precursors to attachment (Fig. 2).

At the level of the individual biocolloid, there are processes that can result in the formation of clusters of biocolloids, either attached to an interface or mobile within the aqueous phase. Clusters can also be initiated via biological processes, to form biofilms (e.g., [23,76,129,21,94,126,7]). Individual or clustered biocolloids can break off from the film, releasing them into the flowing aqueous medium (e.g., [18,140,127]).

Biological processes such as growth, death, predation, parasitism and other processes can result in the increase or removal of mobile or attached microorganisms (e.g., [30,36,48,91]). Many of these biological processes are also influenced by physical and chemicals conditions, and the changes in these conditions. Although these processes are extremely important, they are outside the scope of this manuscript, which will focus on the transport of biocolloids through porous media.

Conventional methods to investigate biocolloid transport through saturated and unsaturated porous media often include column and field studies (e.g., [58,67,86,30,42,53,114,130]). These experiments are generally limited to the evaluation of effluent breakthrough curves and destructive sampling at the end of the experimentation that represent some average behavior of biocolloids. Some studies focus on the collection of biogeochemical parameters that can monitor the biological process. Unfortunately, direct observations of the internal processes occurring are not possible, and mechanisms that control biocolloid transport are therefore poorly understood. A useful method to investigate pore scale processes implicates the use of micromodels.

In recent years, micromodels have been increasingly employed to study the fate and transport of colloids and