# Flow of Dilute, Stable Liquid and Solid Dispersions in Underground Porous Media

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## INTRODUCTION

Transport of fines is important in many underground processes such as enhanced oil recovery. With water-sensitive reservoirs, abrupt decreases in salinity can lead to solid particle entrainment with subsequent plugging and loss of fluid injection rates (Mungan, 1965; Muecke, 1979; Gruesbeck and Collins, 1982; Khilar and Fogler, 1983). Likewise, oil-in-water emulsions may form inadvertently in steam flooding (Doscher, 1967) or chemical flooding (Willhite et al., 1980), or they may be injected to improve sweep efficiency (Jennings et al., 1974; Schmidt et al., 1984). These applications call for an improved understanding of the flow of both liquid and solid aqueous dispersions in porous media where the pore and particle sizes may be comparable.

This work investigates the flow behavior of stabilized dispersions of liquid and solid particles in porous media under conditions where the two types of suspension have, as closely as possible, identical physical and chemical characteristics. That is, liquid droplets and solid particles of the same particle size and shape, same bulk density, and about the same surface charge density are suspended in aqueous solution at identical volume concentrations and injected into a porous medium of known pore size distribution. We find that both the solid and liquid suspensions follow deep-bed filtration principles (Herzig et al., 1970), but they flow in distinctly different fashions.

## EXPERIMENTAL

Suspensions of 0.5 vol. % ($c_i$ = 0.005) are injected continuously into a quartz sandpack of initial permeability $K_o$ = 1.15 $\mu m^2$ at a constant superficial velocity of $u$ = 0.07 mm/s. The mean grain size from sieve analysis and mean pore throat size from centrifugal water drainage experiments (Soo, 1983) of the sandpack are 107 $\mu$m and 29.5 $\mu$m, respectively; sandpack initial porosity, $\epsilon_o$, is 0.34. Both transient pressure drop and effluent particle concentration and size distribution are monitored.

The oil drops consist of a neutrally buoyant mixture of mineral oil (Chevron 410H) and carbon tetrachloride, giving a mixture density of 1.00 ± 0.02 g/cm$^3$ and a viscosity of 1.5 mPa·s. Emulsions are produced in a Waring blender and stabilized by sodium oleate in pH 10 aqueous solution. In the experiments reported here the volume mean droplet size is 2.2 $\mu$m with a standard deviation of less than 10% (Soo, 1983; Soo and Radke, 1984a).

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The solid particles are spherical polystyrene latexes (Dow #1A12) with a density of about 1.04 g/cm$^3$. Again, the volume mean particle size is 2.2 $\mu$m with a standard deviation of less than 5%.

In the pH 10 aqueous solution both the oil drops and latex particles have zeta potentials near −75 mV, as ascertained from microelectrophoresis. Accordingly, the suspensions are electrically stabilized (Kruyt, 1952) and little if any coalescence or agglomeration is noted within the experimental time frame of the flow experiments (i.e., up to 8 h). Likewise, microelectrophoresis of selected smaller quartz sand grains reveals zeta potentials of −70 mV in the alkaline aqueous phase. Thus, significant electrical repulsion also exists between the particles and the sand grains.

Extensive details on the experimental equipment and procedures are available in the work of Soo (1983) and Soo and Radke (1984a).

## RESULTS

Figure 1 contrasts the transient flow behavior of the latex particles and the oil droplets in the 1.15 $\mu m^2$ sandpack. Solid symbols and lines refer to the permeability reduction, $K/K_o$, (i.e., the inverse of the relative pressure increase), while open symbols and dashed lines refer to the relative effluent particle volume concentration, $c_L/c_i$. Lines for the latex suspension are best eye

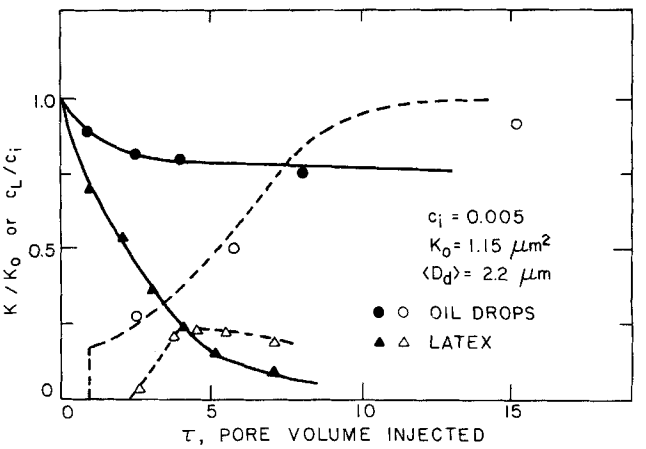


**Figure 1. Experimental permeability-reduction (filled symbols) and breakthrough-concentration (open symbols) histories for an oil-in-water emulsion ○, and a latex suspension △, of nearly identical physical and chemical properties.**

fit, but those for the emulsion are drawn according to theory (Soo and Radke, 1984b; Soo et al., 1984). The abscissa gives the pore volumes of suspension injected or $\tau \equiv ut/\epsilon_o L$, where $t$ denotes time and $L$ is the length of the porous medium.

Three major distinctions arise between the oil-in-water emulsion and the solid latex suspension. First, the amount of flow restriction, as gauged by the permeability reduction, is much larger for the solid particles. Before breakthrough of any particles, both suspensions have the same amount of particles retained in the medium. Therefore, the deposition structure of the latex particles must differ from that of the oil droplets. Further, the solid-particle deposition structure is more effective in impeding flow. Second, in the initial injection stage, with $\tau \lesssim 3$, elution of the solid and liquid particles parallel each other, but after about three pore volumes of injection the outlet concentration of the solid particles begins to decrease. This suggests a change in the latex retention mechanism towards highly efficient capture. Third, both the pressure drop and effluent concentration data for the emulsion reveal that a steady state is attained (further confirmation of this steady flow regime is demonstrated by Soo and Radke, 1984a). Conversely, the solid suspension is unable to reach a steady state.

## DISCUSSION

For the particle sizes and densities employed in this study, straining and interception are the operative capture modes (Herzig et al., 1970). Straining capture refers to occlusion in pores of diameters less than the particle diameter, while interception capture refers to trapping of particles in recirculation eddies or crevices, or attaching to pore walls due to van der Waals and hydrodynamic forces (Soo and Radke, 1984b). The kinetics of the straining and interception processes define the overall capture rate, $\partial\sigma/\partial t$, as a function of the local volume concentration, $c(t,x)$, and the local volume of retained particles, $\sigma(t,x)$:

$$\partial\sigma/\partial t = f(c,\sigma;\alpha) \tag{1}$$

where $x$ is the axial distance along the medium, $t$ is time, and $\alpha$ is a vector of parameters such as, for example, flow velocity, particle and medium surface charge density, ionic strength, and deposit structure (Tien and Payatakes, 1979). Aside from the very early stage of filtration onto clean sand grains, which does not appear important in Figure 1, capture kinetics depend on the amount of previously retained particles, $\sigma$. If $\partial\sigma/\partial t$ decreases with increasing $\sigma$, then steady flow is possible. If not, a steady state is unlikely. Even though the two dispersions in Figure 1 have almost identical physicochemical properties, the retention dependence of their capture rates is completely different. This must be due to disparate spatial distribution and morphology of the retained particles within the pores of the medium.

The explanation for the transient and steady flow behavior of the emulsion in Figure 1 is as follows (Soo and Radke, 1984a,b; Soo et al., 1984). Droplets are strained out in the smaller pores of the packed bed, which are about the same size as the particles. Flow then diverts to the larger pores where interception capture prevails. Eventually, interception capture ceases when a maximum number of capture sites are filled. A maximum interception amount arises primarily because the flowing, stabilized liquid droplets are not captured on top of droplets already adhering to the sand grains. If the large pore channels form interconnected paths through the medium, then steady state is established with all emulsion flow occurring in those channels. Extensive experimental flow data, like those in Figure 1, along with visual micromodel studies and theoretical analysis confirm this proposed mechanism (Soo and Radke 1984a,b; Soo et al., 1984).

Of course, steady state is possible only if the droplet-to-pore size ratio is below some critical value. For the types of emulsions and porous media studied here, this critical ratio of mean drop size to mean pore throat size is found to be about 0.3 (Soo and Radke, 1984a).

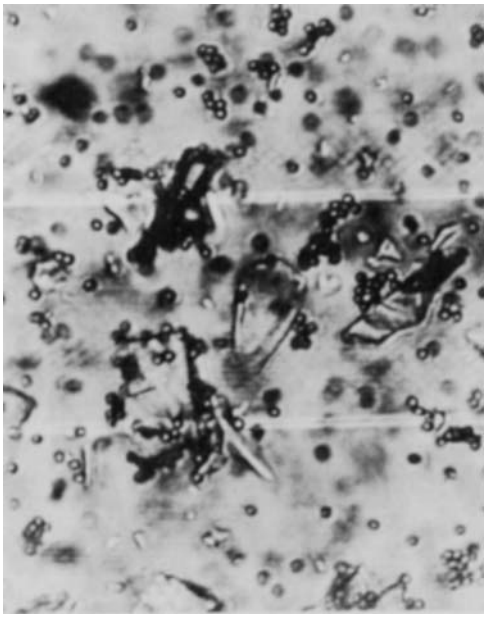

**Figure 2. Photomicrograph of 2.2 $\mu$m spherical latex particles and angular quartz sand grains sampled from the sandpack. Horizontal lines are those scribed on the hemacytometer cell. Particle clustering is believed to be the remnants of dendrites.**

Based on the photomicroscopic observations of Sakthivadivel (1966) for solid particles in granular media and of Billings (1966) for aerosols in fibrous media, we hypothesized that dendrite formation was the origin of the latex particle flow behavior reported in Figure 1. Dendritic protuberances should cause considerable flow resistance and highly efficient capture (Payatakes, 1977). When dendrites growing from opposite pore walls collide, complete blockage may occur (complete plugging may not take place at high velocities where small dendrite fragments could be reentrained). These observations explain the larger permeability reduction of the latex suspension in Figure 1, the decreasing concentration of latex particles eluting from the sandpack, and the lack of a steady state.

To ascertain whether dendrites were formed with the solid latex dispersion, we examined the porous medium microscopically after the flow experiment. The sandpack was sampled near the inlet. Disaggregated sand grains with retained particles were mixed with a pH 10 aqueous solution (i.e., with the original suspending fluid) in a test tube by gently inverting the tube several times. The resulting suspension of sand grains and latex particles was then placed in a hemacytometer cell and observed under an optical microscope.

Figure 2 is a photomicrograph of the sampled suspension from the quartz sandpack. The two sets of horizontal lines are scribed markings on the hemacytometer cell. Several angular sand grains are visible in addition to the 2.2 $\mu$m latex particles. The important observation from Figure 2 is the existence of latex particle clusters. Since no particle agglomeration was ever observed from fluid samples taken at the inlet to the sandpack, we interpret the particle clusters in Figure 2 to be broken dendrites that originally adhered to the sand grains. This interpretation is consistent with the latex-suspension flow results depicted in Figure 1.

Similar microscopic examinations were conducted with the oil-in-water emulsion. No liquid droplet clustering was found. Ap-

parently, the deformability and shear sensitivity of the liquid particles abates dendrite formation.

## CONCLUSIONS

A major distinction is found between the flow behavior in underground porous media of dilute, stabilized solid and liquid particle dispersions with nearly identical physicochemical characteristics. Liquid particles can establish steady flow because they are unable to be captured on top of each other. Conversely, solid particles exhibit continual plugging because they build dendritic structures.

Although this conclusion is specific to the chemistry, flow conditions, and pore and particle sizes studied here, it nevertheless has important ramifications for underground processes. Solid suspensions can be expected to exhibit well-bore damage and small penetration distances. In contrast, liquid suspensions, after satisfying the maximum number of capture sites, may exhibit significant penetration distances without catastrophic permeability loss.


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## NOTATION

$c$ = volume concentration of particles in the suspension, volume of particles/flowing volume
$\langle D_d \rangle$ = volume average drop size, m
$K$ = overall permeability, $m^2$
$L$ = packed-bed length, m
$t$ = time, s
$u$ = superficial velocity, m/s
$x$ = axial distance, m

### Greek Letters

$\alpha$ = vector of parameters
$\epsilon_o$ = initial bed porosity, void volume/bed volume
$\sigma$ = local particle retention, particle volume/bed volume
$\tau$ = suspension pore volumes injected, $ut/\epsilon_o L$

### Subscripts

$d$ = droplet
$i$ = inlet
$L$ = exit
$o$ = initial

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