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The Influence of Suspended Particle Size Distribution in Deep-Bed Filtration

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Deep-bed filtraton has been used in municipal water treatment since 1890. Many studies have been done on the influence of different independent variables on filter performance. Although from both observations and theory it has been found that the size of suspended particles is one of the most important physical variables influencing deep-bed filtration, size is not often measured because the techniques available are time consuming and expensive (O'Melia and Ali, 1978).

Yao et al. (1970) were the first to study the particle size effects in filtration. Based on their clean-bed filter studies they stated: "There exists a critical size at which the suspended particles have a minimum removal efficiency. This critical suspended particle size is in the order of 1 μm" (Figure 1). O'Melia and Ali (1978), in their detailed study of monodimensional latex suspension, showed that the size effect continues throughout the period of effective filtration, and 1 micron particles always showed the poorest removal. They also developed a mathematical model taking into account the particle size influence on filter removal efficiency.

In reality, the suspension has a wide spectrum of particle sizes. As shown in Figure 2, removal efficiency of different sizes of particles in the suspension would be different. It is also possible that the removal efficiency of particles of a particular size could be altered by the presence of other particles of different sizes. Therefore a detailed study of the influence of particles of different sizes on the removal efficiency of a particle of a particular size would be a useful addition to the earlier works on particle size effect.

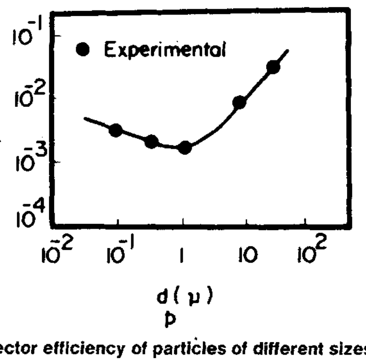

Figure 1. Collector efficiency of particles of different sizes (Yao et al., 1970).

EXPERIMENT

Laboratory-scale filter experiments were performed using artificial suspension of pollen grains of different sizes (Table 1). A known dose of

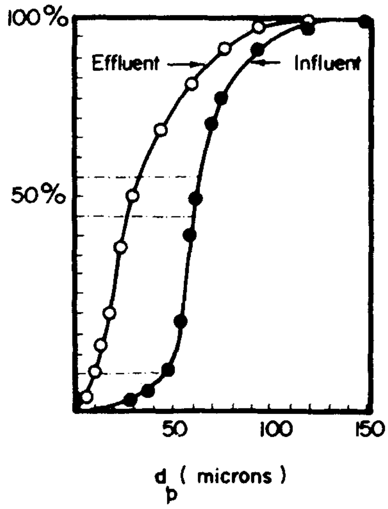

Figure 2. Filter influent and effluent size distribution (suspension used: effluent from municipal wastewater treatment; V_o = 7 m^3/m^2·h; filter media = glass beads of 2.5 mm) (Al Alousi, 1979).

TABLE 1. INFLUENCE OF SUSPENDED PARTICLE SIZE IN FILTRATION

Type of Pollen Grains	Average Size (d_{50}) Measured by Coulter Counter (micron)	Filter Media Size (mm)	Figure No.
Cuppressus Arizonica	26.0	2.5	3
Broussonetia	12.8		
Sorgho	42.0		
Cuppressus Arizonica	26.0	4.0	4
Broussonetia	12.8		
Sorgho	42.0		

flocculant of WAC-2 was added continuously just before the solution reached the filter column, in order to enhance particle removal. The concentration was measured in terms of number of particles of a particular size per unit volume using a Coulter counter (Model ZB).

INFLUENCE OF PARTICLE SIZE IN FILTRATION

The first series of experiments was carried out with monodimensional suspensions (Table 1). The removal efficiency was found to increase with the increase in particle size in the range considered, Figures 3 and 4. This result is in accordance with past research (O'Melia and Ali, 1978). The effects of colloidal particles were not studied in this present research.

ROLE OF COARSER PARTICLES IN THE REMOVAL EFFICIENCY OF FINER PARTICLES WHEN THEY ARE TOGETHER IN THE SUSPENSION

This effect was studied in a simple case of bidimensional particles in the suspension (i.e., two different sizes of particles at known concentrations were mixed in the suspension). Table 2 summarizes the ratio at which particles were mixed. The removal efficiency of finer particles was measured in each case in terms of number concentrations. The results obtained revealed the following:

As the ratio of coarser particles to finer particles increases, the removal efficiency of finer particles also increases. At the start of the filter experiments, the removal efficiency is a direct function of the concentration of particles. But as filtration proceeds, as more

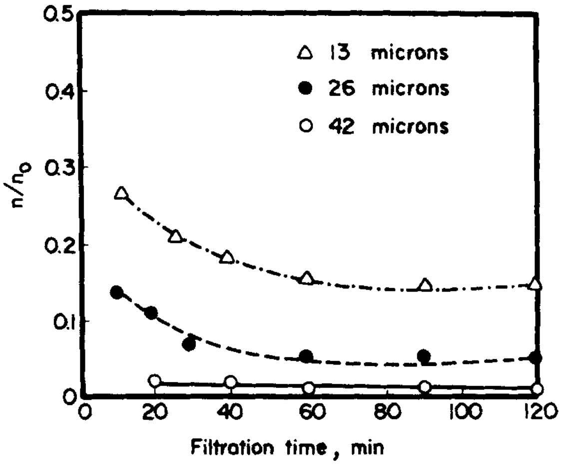

Figure 3. Influence of particle size (V_o = 5 $m^3/m^2{\cdot}h$; d_c = 2.5 mm; influent concentration = 25 mg/L).

TABLE 2. CONCENTRATIONS OF FINER AND COARSER PARTICLES IN THE BIDIMENSIONAL SUSPENSIONS

Filtration Rate $m^3/m^2{\cdot}h$	Concentration of *C. arizonica* mg/l	Concentration of *C. arizonica* No. of Particles/mL	Concentration of *Broussonetia* mg/L	Concentration of *Broussonetia* No. of Particles/mL	Figure No.
	Combination of Suspended Solids Concentration				
5	0.0	0	50.0	76,000	5
	37.5	6,750	12.5	19,000	
	25.0	4,500	25.0	38,000	
10	0.0	0	50.0	76,000	6
	37.5	6,750	12.5	19,000	
	25.0	4,500	25.0	38,000	
	Combination by Number Concentration				
5	0.0	0	6.0	9,000	7
	25.0	4,500	3.0	4,500	
	37.5	6,750	1.5	2,250	
	Variation of Finer Particles Concentration Keeping Coarser Particles Concentration Constant				
5	25.0	4,500	6.0	19,000	8
	25.0	4,500	25.0	38,000	
	25.0	4,500	50.0	76,000	

and more coarser particles are retained, the removal of finer particles improves (Figures 5–8). This effect is more prominent at higher filtration rates (Figure 6).

MATHEMATICAL MODELING

The fact that an increase in the ratio of coarser particles of finer particles improves the removal efficiency of finer particles confirms the concept of particle collectors. (The particles attached to the filter grain also participate in filtration action and are termed particle collectors). Therefore the assumption that some of the retained coarser particles in addition to retained finer particles act as "particle collectors" in the removal of finer particles would account for the improvement in removal efficiency of finer particles in the presence of coarser particles.

The modified model for bidimensional particles in the suspension from the monodimensional mathematical model is briefly discussed below. The mathematical model for monodimensional suspension is discussed in detail elsewhere (O'Melia and Ali, 1978).

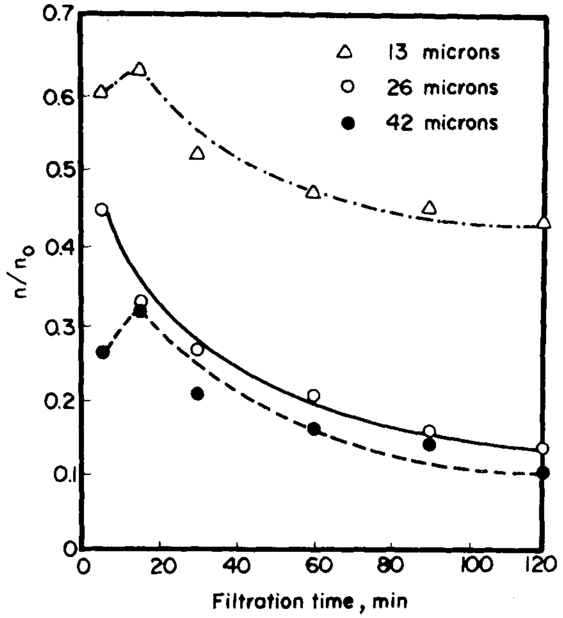

Figure 4. Influence of particle size (V_o = 5 $m^3/m^2{\cdot}h$; d_c = 4 mm; influent concentration = 25 mg/L).

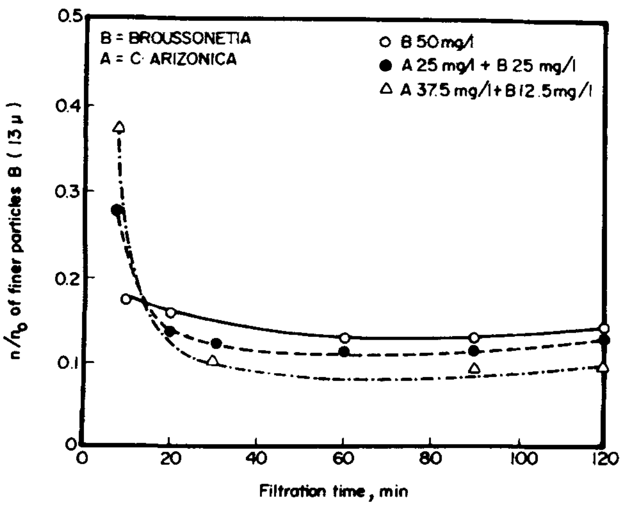

Figure 5. Combination by suspended solids concentration (V_o = 5 $m^3/m^2 \cdot h$; d_c = 2.5 mm).

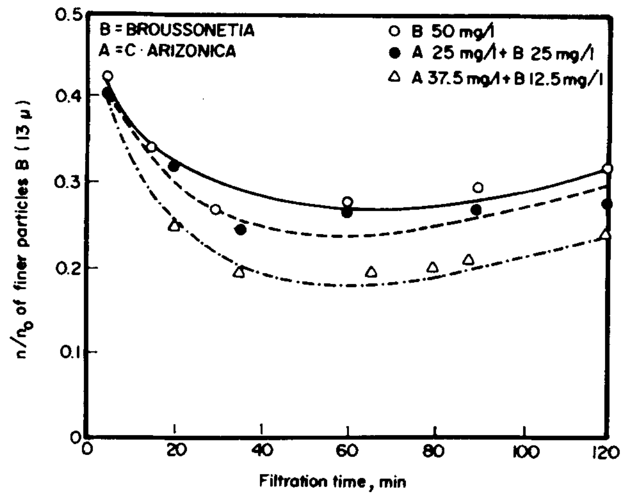

Figure 6. Concentration by suspended solids concentration (V_o = 10 $m^3/m^2 \cdot h$; d_c = 2.5 mm).

The assumption that a fraction (γ) of coarser particles (which participate as particle collectors when coarser particles alone are filtered in the same conditions) acts as particle collectors in addition to finer particle collectors to remove the finer particles in the suspension leads to the following equation:

$$\eta^*_{r1}(l,t) = \alpha_1\eta_1 + N_1(l,t)\eta_{p1}\alpha_{p1}\left(\frac{d_1}{d_c}\right)^2 + \gamma N_2(l,t)\eta_{p2}\alpha_{p2}\left(\frac{d_2}{d_c}\right)^2 \tag{1}$$

Here

$$N_1(l,t) = \alpha_1\eta_1\beta_1 V_0 n_1(l,t)\frac{\P d_c^2}{4} \tag{2}$$

$$N_2(l,t) = \alpha_2\eta_2\beta_2 V_0 n_2(l,t)\frac{\P d_c^2}{4} \tag{3}$$

Therefore Eq. 1 can be rewritten as

$$\eta^*_{r1}(l,t) = \eta_{r1}(l,t) + \gamma(\eta_{r2}(l,t) - \alpha_2 n_2(l,t)) \tag{4}$$

where

$$\eta_{r1}(l,t) = \alpha_1\eta_1 + \alpha_{p1}\eta_{p1}N_1(l,t)\left(\frac{d_1}{d_c}\right)^2$$

$$\eta_{r2}(l,t) = \alpha_2\eta_2 + \alpha_{p2}\eta_{p2}N_2(l,t)\left(\frac{d_2}{d_c}\right)^2$$

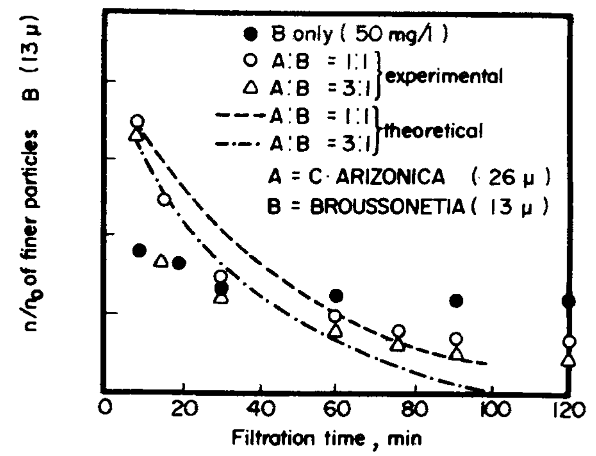

Figure 7. Influence on n/n_o of finer particles by coarser particles in combination (V_o = 5 $m^3/m^2 \cdot h$; d_c = 2.5 mm).

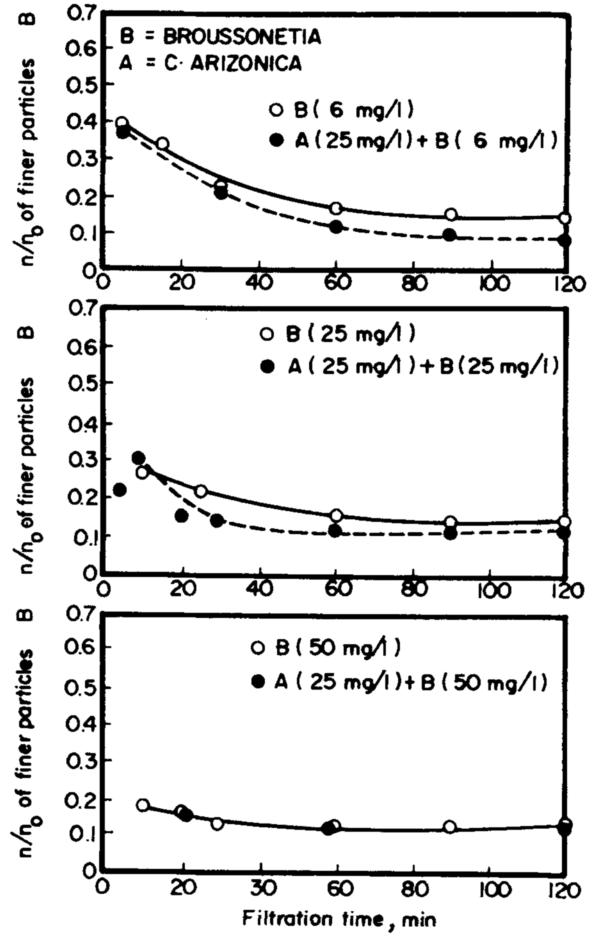

Figure 8. Concentration of coarser particles are kept constant (V_o = 5 $m^3/m^2 \cdot h$; d_c = 2.5 mm).

From the mass balance of finer particles, one obtains

$$\frac{\partial n'_1(l,t)}{\partial t} + V_0\frac{\partial n'_1(l,t)}{\partial l} + \frac{3}{2}\frac{(1-f)}{d_c} \cdot V_0 \cdot n'_1(l,t)\eta^*_{r1}(l,t) = 0 \tag{5}$$

The concentration of finer particles at any time and depth of filter can be obtained from Eqs. 1, 2, 3, and 5 using the finite-difference method. Details are presented elsewhere (Vigneswaran, 1980).

MODEL VERIFICATION

The values of $\alpha\eta$ and $\alpha_p\beta$ were calculated separately for coarser and finer particles from monodimensional particle filtration experimental results and were used in a modification of O'Melia's model for filtration of bidimensional particle suspensions to calculate the improvement of removal efficiency of finer particles.

Although the experimental curves of the bidimensional particles in suspension could not be fitted exactly to the theoretical curves, the introduction of an additional factor, $\gamma(= 0.7)$ demonstrated the improvement of finer particle removal efficiency in the presence of coarser particles (Figure 7).

CONCLUSIONS AND PRACTICAL APPLICATIONS

Although this study was performed for a simple case of bidimensional particles in suspension, the experimental observations and the theoretical formulations could be extended to suspensions of particles in a wide range of sizes. The improvement in removal efficiency during the contact flocculation-filtration process can be explained qualitatively and modeled mathematically in the same approach.

NOTATION

d_c = diameter of filter grain
d_p (or d) = diameter of particle
f = porosity
l = depth
N = number of particle collectors
n = number concentration of suspended particles
n_1' = number concentration of finer particles in the presence of coarser particles
t = filtration time
V_o = filtration rate

Greek Letters

α = particle-to-filter grain attachment coefficient
α_p = particle-to-particle attachment coefficient
β = fraction of retained particles that act as particle collectors
γ = constant
η = contact efficiency of a filter grain
η_p = contact efficiency of a particle collector
η_r = removal efficiency of a single collector
η_{r1}^* = removal efficiency of finer particles in the presence of coarser particles when they are in combination in the suspension

Subscripts

1 = finer particles
2 = coarser particles

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Measuring Adsorption Rates from an Aqueous Solution

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Adsorption kinetics of organic solutes in the aqueous phase has been the subject of considerable attention in recent years. Generally, the purpose of such experiments is to determine pore diffusion coefficients for designing industrial equipment to be used in pollution control. Laboratory apparatus is usually a stirred constant-volume tank; and when determining pore diffusion coefficients from concentration-time data, it is necessary to consider the effects of external diffusion resistance as well as possible deviations from the concept of ideal mixing. Below we report briefly on results with three different designs of experimental apparatus.

The differential equations, the initial and the boundary conditions for the constant-volume adsorption rate problem, have been given by Komiyama and Smith (1974). Because the isotherms determined for the systems investigated below are nonlinear, a numerical solution was required. We prefer to go into details of our numerical solution in a later paper in connection with a larger volume of experimental results. This note is concerned primarily with the choice of proper equipment. The numerical procedure permitted a comparison of calculated and experimental adsorption uptake curves $\gamma(t)$.

$$\gamma(t) = \frac{c(t) - c_0}{c_\infty - c_0} \tag{1}$$

Diffusion coefficients were varied to obtain a minimum standard deviation between calculated and experimental uptakes.

$$\frac{\sum_1^n (\gamma_{\text{exp}} - \gamma_{\text{cal}})^2}{n - 1} = \text{min!} \tag{2}$$

We have measured adsorption kinetics for an aqueous solution