

SURFACE FORCE EFFECTS ON FILTER CAKE CHARACTERISTICS

J. DUECK, D. PUREVJAV and Th. NEESSE

Department of Environmental Process Engineering and Recycling, University of Erlangen – Nuremberg, Paul-Gordan-Str. 3, 91052 Erlangen, Germany.

In order to validate a filtration model that accounts for the particle interactions within filter cakes, filtration experiments with a quartz suspension were carried out. The bonding energy of the particles was varied using the electrolytes NaCl, MgCl₂ and AlCl₃ via the different valencies of the counter ion. The measured filter cake porosities and permeabilities show a remarkable correspondence to measured zeta-potentials and adhesive forces. Despite some differences between the experimental results and the model equations, the principal validity of the theoretical expectations was confirmed. The model considerations can be helpful in providing a deeper understanding of the influence of electrolytes and how they act as coagulants in fine particle filtration.

Keywords: Coagulation; filter cake; particle-particle-interaction; permeability; porosity; specific bonding energy.

INTRODUCTION

Fine particle cake filtration is influenced by particle interactions that depend on the physico-chemical conditions at the particle-liquid interface. These particle interactions lead to agglomeration and further to a loosened compressible filter cake with enlarged porosity.

The influence of the pH and ionic strength of the coagulants and the zeta-potential in the liquid phase on fine particle filtration has been the subject of experimental investigations by different authors¹⁻⁵. Currently, there is no physically based filtration model that considers these parameters. Earlier papers by the authors⁶⁻¹² presented a porosity model of a compressible filter cake that took account of interparticle forces. The subject of this paper is the validation of the model by filter cake filtration experiments with variation of the interparticle forces.

Porosity Model of a Compressible Filter Cake

The elementary cell of a compressible filter cake is assumed to be a hollow spherical agglomerate (Figure 1). The compressibility of such a cake that consists of rigid particles

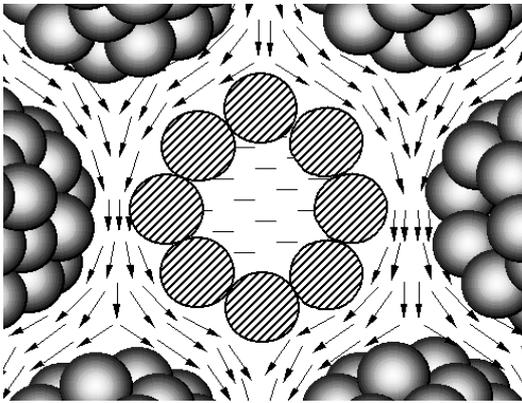


Figure 1: Schematic structure of a fine-grained filter cake cell.

is caused only by the loosening due to particle agglomeration. The agglomerates are assumed to form a random packing with the filtrate flow around the agglomerates, whereas the liquid within the agglomerates is assumed to be stagnant. The size of the agglomerates depends on the adhesive force between two particles and on the drag force due to the filtrate flow.

On the basis of this model, a relative filter cake porosity function for pressure filtration has been derived⁶:

$$s = \frac{\varepsilon - \varepsilon_0}{1 - \varepsilon_0} \approx \exp \left[- \left((4\Delta E)^{\frac{1}{3}} \varphi(\varepsilon)^{\frac{1}{3}} \Delta p^{\frac{1}{3}} L^{\frac{1}{3}} d_p^{\frac{2}{3}} \right) \right] \quad (1)$$

where $\varepsilon_0 \approx 0.4$ is the porosity of the dense packing of mono-disperse rigid spheres, $\varphi(\varepsilon)$ is the porosity function^{13,14}

$$\text{e.g., } \varphi(\varepsilon) = \frac{(1-\varepsilon)^2}{\varepsilon^3} \quad \text{or} \quad \varphi(\varepsilon) = \varepsilon^{-5.5}$$

Δp is the filtration pressure drop, L is the filter cake thickness, d_p is the particle size or for polydisperse cakes, the mean Sauter diameter, d_{32} , respectively and ΔE is the specific bonding energy of the particle.

In filtration practice ΔE is modified by adding coagulants and flocculants for aggregation of the fine particles. Thus, only particle attraction and positive values of ΔE are of interest.

For the experimental validation it seems to be useful, to rewrite Equation (1) in the following form:

$$\begin{aligned} S_L &\equiv \ln \left[\ln \frac{1}{S} \right] & (2) \\ &= m_p \ln \Delta p - m_L \ln L + 2m_d \ln d_p - m_E \ln(\Delta E) + \ln(a) \\ &= \ln a + n \ln F \end{aligned}$$

where in accordance with Equation (1) the parameter n must be 1/3.

In a more generalised form it is suggested that:

$$S = \exp(-aF^n) \quad (3)$$

F is a dimensionless characteristic filtration number, corresponding to the ratio of the drag force and adhesion force at the critical particle of the agglomerate:

$$F = \frac{\Delta p d_p^2}{\Delta E L} \quad (4)$$

and n is an empirical constant.

Starting with Equation (2) the permeability, P_C of the filter cake can be written as follows⁸:

$$\frac{P_0}{P_C} = (1 - \exp(-aF^n))^2 \quad (5)$$

Here P_0 is the permeability of a densely packed cake and

$$P_L = \ln \left[\ln \left(1 - \sqrt{\frac{P_C}{P_0}} \right)^{-1} \right] = \ln a + n \ln F \quad (6)$$

Initial measurements of porosity and permeability of the filter cake for a quartz (glass) suspension in distilled water have been reported⁷⁻¹⁰, in which the pressure drop, particle size and cake height were varied.

During the experiments the interparticle forces were kept constant by using distilled water. In the calculations for the quartz/water interface the theoretical value was assumed¹⁴.

According to the presented results (Figure 2), the values of the coefficients are all about 0.45, instead of the value 1/3 predicted by Equation (1). However, the linearity of the plots shown in Figure 2 underlines the principal validity of the model.

PARTICLE INTERACTION IN THE FILTER CAKE

The adhesive force, F_H results from the superposition of two components:

$$F_H = F_A + F_R \quad (7)$$

The interparticle attractive force, F_A is taken to be^{14,15}:

$$F_A = \frac{A}{6h^2} d_p \quad (8)$$

where A is the Hamaker constant (olc) and $h \approx 0.4$ nm is the distance between the adhering particles.

In accordance with the DVLO-theory¹⁵ we can assume for the repulsive force F_R :

$$F_R = \frac{4\pi e^2}{kT} \psi_0^2 \frac{c_\infty}{\kappa} \exp[-\kappa h] d_p \quad (9)$$

with

$$\kappa = \sqrt{\frac{e^2 \sum (c_\infty)_i z_i^2}{\epsilon kT}} \quad (10)$$

where e is the elementary charge, k the Boltzmann constant, T the temperature in Kelvin, ψ_0 the surface potential, $(c_\infty)_i$ the ionic concentration of the suspension and z the valency of the counter ion.

Both forces, F_A and F_R , are proportional to the particle size, d_p . Thus, the specific bonding energy, $\Delta E = F_H / d_p$ [N m⁻¹] can be understood as a characteristic measure of the physico-chemical state of the suspension and thus of the filter cake as well.

The surface potential, ψ_0 of quartz (SiO₂) in pure water is negative and can be determined approximately by zeta-potential measurements.

PRESSURE FILTRATION EXPERIMENTS

In order to verify the influence of the specific bonding energy, ΔE on cake porosity, ϵ and permeability, P_C , filtration experiments with a standard compression cell⁷ have been carried out. The porosity was determined with a special sensor that detected the filter cake height⁷. The permeability was determined by the well-known t/V -method¹⁴.

All experiments were carried out using a constant volume of a 10 % by weight quartz suspension and an acting pressure drop of 3 bar.

The particle interaction was varied by addition of the electrolytes NaCl, MgCl₂ and AlCl₃ to the quartz suspension. The particle size distribution (mean Sauter-diameter, $d_{32} = 2.8$ mm) of the suspension was not influenced by the electrolytes (Figure 3). Therefore, before starting the filtration no coagulation had occurred.

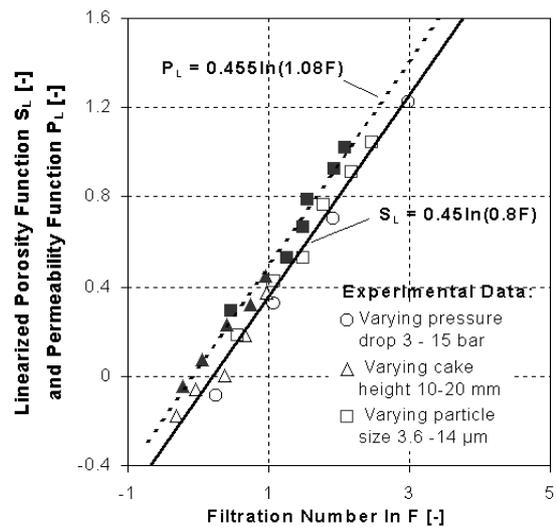


Figure 2: Comparison of theoretical porosity and permeability (Equations (2) and (6)) with experimental data as a function of the dimensionless filtration number, F .

RESULTS

The complete results are summarised in Figure 4. Figure 4a presents results of the experiments with values taken from the literature¹⁴. It illustrates that the zeta-potential decreases with increasing concentration of the counter ions Na⁺, Mg²⁺ and Al³⁺, where Na⁺ and Mg²⁺ only lead to double layer compression. In the case of Al³⁺ a positive counter charge can be observed after reaching the zero-point of charge.

In accordance with Equations (7) and (9) lower zeta-potentials must result in a reduction in the repulsive force, F_R and consequently in an increase in the adhesive force F_H . Adhesive force measurements at a plate/sphere arrangement using the centrifuge method¹⁶ confirmed these theoretical expectations (Figure 4b).

Figure 4c shows the experimentally determined cake porosities for varying electrolyte concentrations and for counter ions of different valency. These porosity curves show a remarkable correspondence with the measured adhesive forces shown in Figure 4b.

The permeability curves in Figure 4d show the same behaviour, which is in accordance with the previously presented model based on Equation (5).

The rapid increase in the adhesive force, porosity and permeability curves occurs at a critical coagulation concentration, c_S , where the attractive forces and the potentials of these forces and the repulsive forces as well as the corresponding potentials are equal¹⁵. According to the Schulz-Hardy-rule for the critical coagulation concentration, c_S the following is valid:

$$c_S \sim z^{-6} \tag{11}$$

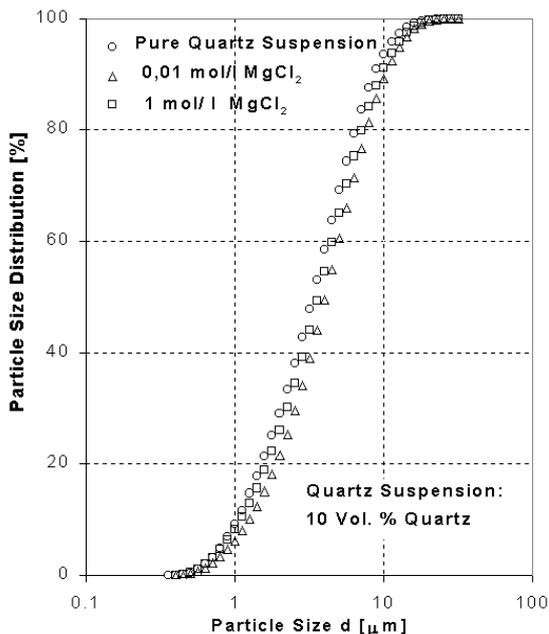


Figure 3: Particle size distribution of quartz particles in a 10% by volume quartz suspension for different electrolyte concentrations (MgCl₂).

The measurements shown in Figure 5 reflect this law with an experimentally determined power coefficient of 6.3 instead of 6 as determined by Equation 11.

In order to validate our model (Equations (2) and (5)) the quantities S_L and P_L were calculated, using the data shown in Figure 4c and 4d. The result is shown in Figure 6.

Due to the linearity of the plots shown in Figure 6 an agreement with the model was concluded and a quantitative agreement was established. However, in comparison to the data shown in Figure 2 some differences are obvious. According to Equations (2) and (5), the parameter n should have the same value for the porosity and the permeability function ($n = 0.33$). Furthermore, the porosity and permeability do not increase strongly enough with increasing filtration number, F , which corresponds to the electrolyte concentration. The determined n -values of 0.12

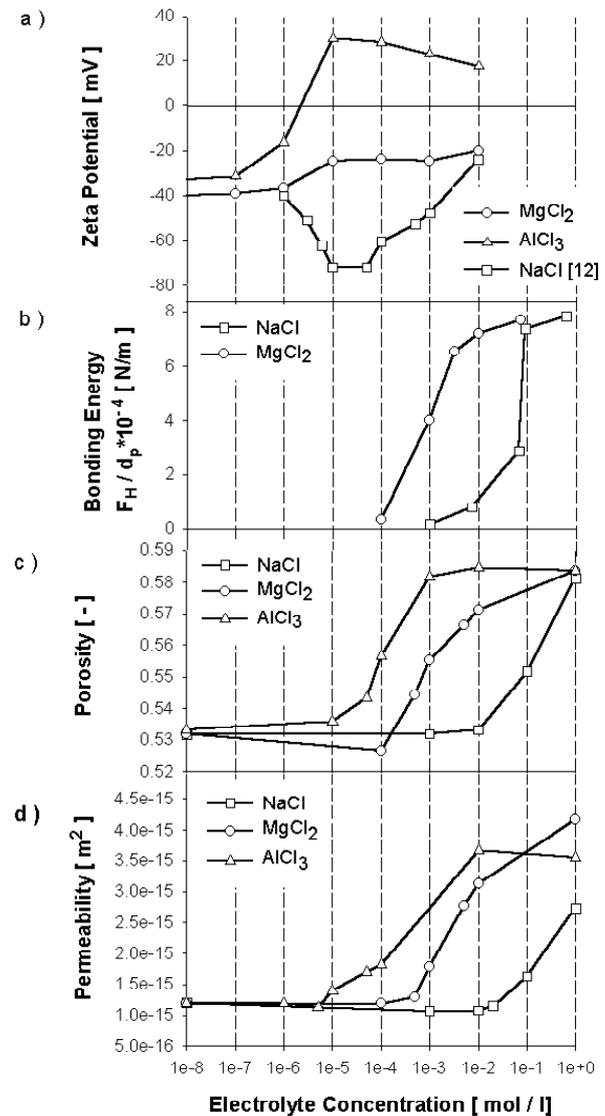


Figure 4: Characteristic filtration parameters as a function of the electrolyte concentration.

and 0.19 are too low in comparison with what they were expected to be. Therefore, model refinements seem to be necessary. Further investigations will need to consider the pressure dependency of the adhesive forces.

SUMMARY

The previously published porosity model for fine-grained filter cakes which considers interparticle forces and agglomeration effects has been verified by comparing the predictions with experimental results. The experiments were carried out with three electrolyte types of different ion valency by varying their concentration. With regard to the porosity and permeability of filter cakes, a qualitative agreement between the theoretical predictions and the experimental data has been achieved. The results validate the use of cationic electrolytes as coagulants in filtration practice.

NOMENCLATURE

A	Hamaker constant (J)
C_s	Critical coagulation concentration (mol l^{-1})
c_∞	Ion concentration in the solution (mol l^{-1})
d_A	Agglomerate diameter (m)
d_p	Particle diameter (m)
d_{32}	Sauter diameter (m)
e	Elementary charge (c)
F	Filtration number (-)
F_a	Attractive force (N)
F_B	Born's repulsive force (N)
F_H	Adhesive force (N)
F_r	Repulsive force (N)
F_s	Drag force (N)

h	Distance between particles in agglomerate (m)
k	Boltzmann's constant (J K^{-1})
L	Filter cake thickness (m)
n	Empirical constant (-)
P_C	Permeability of loosened filter cake (m^2)
P_0	Permeability for (m^2)
T	Temperature (K)
v	Filtration velocity (m s^{-1})
Z_i	Valency of the ion for i^{th} component in the electrolyte (-)
ψ_0	Surface potential (V)
χ	Debye length (m)
σ	Size of molecule (m)
ε	Porosity of the filter cake (-)
ε_0	Porosity of a random dense packing (-)
$\varphi(\varepsilon)$	Porosity function (-)
ΔE	Free specific surface energy (N m^{-1})
Δp	Pressure drop across the filter cake (N m^{-2})
η	Dynamic viscosity ($\text{kg m}^{-1} \text{s}^{-1}$)

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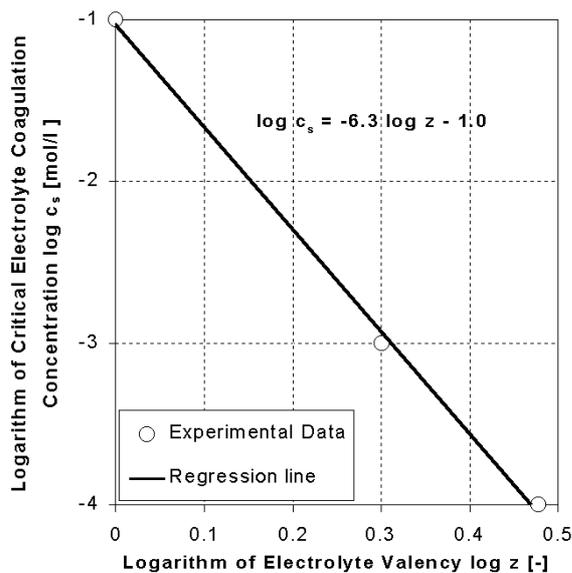


Figure 5: Critical electrolyte coagulation concentrations as a function of the electrolyte's ion valency, showing agreement with the Schultz-Hardy rule.

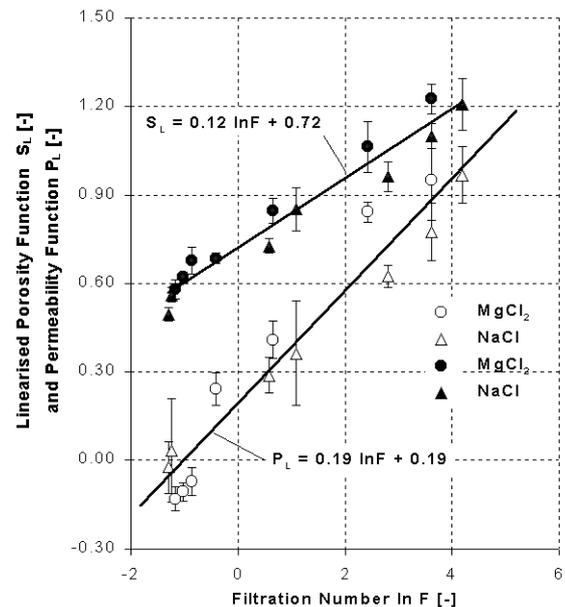


Figure 6: Correlation between relative filter cake porosity function, S_L , relative permeability, P_L , and the filtration number $\ln F$, for varying electrolytes (NaCl and MgCl_2) and concentrations.

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ADDRESS

Correspondance concerning this paper should be addressed to Johann Dueck, Department of Environmental Process Engineering and Recycling, University of Erlangen – Nuremberg, Paul-Gordan-Str. 3, 91052 Erlangen, Germany, or via email to johann.dueck@rzmail.uni-erlangen.de.