THE INFLUENCE OF SEDIMENTATION DURING DOWNWARD CAKE FILTRATION

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ABSTRACT

Data for near incompressible cake formations with simultaneous settling are presented. Aqueous calcite suspensions exhibiting similar median particle size, but different size distributions, were filtered over a range of constant pressures. For each experiment the time dependent history of filtrate removal and the particle size distributions of cake samples at different spatial positions were measured. These data were compared with predictions from a new mathematical model that divides cake formation into a range of discrete time steps. Cake growth due to filtration and sedimentation were considered to proceed simultaneously, but separately, with the additive results predicting the change in cake thickness during a time step. Account was taken of the changing effects of suspension concentration on settling rate and the transient influence of size distribution on specific cake resistance.

The model is shown to quantitatively predict the influence of feed particle size distribution on cake formation and filtrate removal rates and favourable comparisons are made with values recorded in experiments. For the experimental conditions investigated, sedimentation is shown to contribute up to one third of the cake resistance in a filtration test. At lower pressures and with wider size distributions, larger particles from the feed tended to accumulate near the filter medium and in some cases a minimum cake resistance was observed toward a mean cake height. For higher pressures, however, the effect of particle sedimentation in filtration was reduced and cakes formed with near uniform median size through the cake height.

KEYWORDS

Filtration modelling; Sedimentation; Pressure filtration; Cake formation; Particle size distribution.

INTRODUCTION

It is thought that sedimentation of particles during dead-end filtration can contribute to cake formation as well as the rate at which filtrate is extracted and several authors have previously investigated the phenomenon through a combination of experiment and theory[1-9]. They generally agree that sedimentation influences filtration performance to an extent dependent on filter orientation, the properties of the feed mixture and, to a lesser extent, the septum characteristics. This paper attempts to quantify some effects of sedimentation in downward, incompressible, dead-end filtration. Experimental data are compared with predictions from a new model that divides the filter cell/feed suspension into a number of individual layers and treats filtration and sedimentation as separate, but additive, processes.

EXPERIMENTAL PROCEDURES AND CHARACTERISATION

The conventional apparatus used in the filtration experiments is shown in Figure 1. All filtrations were performed in the downward direction with 5% w/w suspensions of calcite dispersed in double distilled water to yield clear filtrates.

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In a test the (78.5 cm^2 area) stainless steel filter cell was initially filled with suspension. After a minimum, but fixed time delay, the filtration pressure was set to a constant value within the range 25-300 kPa and the filtrate valve opened to begin an experiment. Cake formation proceeded with the cumulative volume of filtrate being recorded as a function of time until the suspension within the cell was just exhausted. The filter cell was subsequently separated and samples of filter cake where taken to establish porosity by loss of weight on drying. Further samples of cake were taken in an attempt to quantify any spatial variations in particle size distribution with distance above the septum. It was generally difficult to take representative samples from the relatively thin filter cakes formed (<25 mm) and most experiments were restricted to up to three size measurements through the cake height. Typical data showing aspects of experimental repeatability are shown in Figures 2 and 3 and these, as well as subsequent results, confirmed the near incompressible nature of the calcite system previously observed[10,11].

The filter medium was Primapor, a polyurethane coated cloth supported by a 2:1 twill weave substrate. The medium had a thickness of 1.3 mm, a mean flow pore size of 4.3 μm as measured by Coulter Porometer and a permeability of 2.7×10^{-13} m^2 as measured by water permeation.

The size and size distributions of the filter cake samples and challenge suspensions were determined using a Malvern MasterSizer laser light scattering instrument; the results are summarised in Table 1. Two different batches of calcite solids were used and in their unground states the rhomboidal shaped particles exhibited median sizes of 11.7 μm and 9.6 μm respectively and relatively wide size distributions when dispersed. Suspensions with different median sizes were produced by wet grinding in a ball mill and over the period of 72 h a median size of 2.7 μm could be produced (e.g. grind 4). In some cases, two individual size distributions were mixed in appropriate proportions to give a, different size distribution, bimodal suspension of similar median size to one of the wet grinds (e.g. compare mix 1 with grind 1).

MODELLING

The modelling of filtration with simultaneous sedimentation was based on a previously proposed concept[4,12]. The filter cell/suspension was vertically divided into (typically) 100 layers as shown in Figure 4 and the previously measured particle size distribution of the feed suspension divided into between 25 and 45 size classes of known frequency.

At t = 0 s the solids concentration in each layer is equal to the feed concentration (c_0) with size distribution (d) and thus the number, size and starting position of all the particles in each layer is known. For a time interval, Δt, between t = 0 and t_{max} s, it is considered that filtration and sedimentation can be treated independently with the contributions to cake formation from each process being subsequently additive to give the overall filtration performance within the time interval.

For cake formation via sedimentation, particles within a layer are assumed to travel a distance (x_s) as given by the Richardson-Zaki correction to the Stokes equation where:

$$x_s = \Delta t \frac{d_p^2 g \left(\rho_s - \rho_l\right)}{18\mu} \left(1 - V_s\right)^{4.65} \tag{1}$$

and d_p is the diameter of a particle, g the acceleration due to gravity, ρ_s and ρ_l are the solid and liquid densities respectively, μ the liquid viscosity and V_s the volume solids concentration. Particles of different diameter settle differentially as appropriate to new layers and those travelling sufficiently far to contact either the filter medium at the bottom of layer 1 (in time interval 1) or the top of the cake become fresh cake whose additional thickness (Δh_s) is:

$$\Delta h_s = \frac{V_{sc}\left(1+e\right)}{A} \tag{2}$$

where e is the cake voids ratio, A the filter area and V_{sc} the particle volume joining the cake in Δt s.

For cake formation via filtration, the mass solids concentration (s_{chal}) and median size of the particles ($(d_{p,50})_{chal}$) challenging either the filter medium (in time interval 1) or the existing cake is determined. As the number and size of particles within each layer is known, the median of the distribution can be readily calculated and the challenge solids concentration is given by:

$$s_{chal} = \frac{\left(V_{sl}/V_l\right)\rho_s}{\left(V_{sl}/V_l\right)\left(\rho_s-\rho_l\right)+\rho_l} \tag{3}$$

where V_{sl} is the volume of particles in a layer and V_l the total volume of a layer. The average specific resistance of the cake generated by freshly joining particles ($\alpha_{av,chal}$) is given by:

$$\alpha_{av,chal} = \left(\alpha_{av,chal}\right)_{t=0}\left(\frac{\left(d_{p,50}\right)_{t=0}^{2}}{\left(d_{p,50}\right)_{chal}^{2}}\right) \tag{4}$$

and the effective feed concentration (c) is a function of s_{chal}. The volume of filtrate generated during the time interval Δt (i.e. ΔV) is determined by iteration of equation (5), which is a form of the general filtration equation, such that the RHS of the expression has a value equal to Δt:

$$\Delta t = \Delta V\left(\frac{\mu R}{A\Delta p}+\frac{\mu\alpha_{av,chal}c_{chal}\Delta V}{2A^2\Delta P}+\frac{\mu}{A^2\Delta P}\sum_{n=0}^{n=t-\Delta t}\left(\left(\alpha_{av,chal}\right)_n\left(c_{chal}\right)_n\left(\Delta V\right)_n\left(1+\frac{\left(\Delta h_s\right)_n}{\left(\Delta h_f\right)_n}\right)\right)\right) \tag{5}$$

where R is the filter medium resistance, Δp the filtration pressure and the additional cake thickness due to filtration alone (Δh_f) is subsequently given by:

$$\Delta h_f = \frac{\Delta V\left(1+e\right)}{A\left(\frac{\rho_s}{\rho_l}\left(\frac{1}{s_{chal}}-1\right)-e\right)} \tag{6}$$

The total added cake thickness is $\Delta h_s + \Delta h_f$ and the new positions of particles within the filter cell after Δt are determined as x_s is known and all particles are assumed to translate vertically downwards by an amount proportional to the amount of extracted filtrate where $x_f = \Delta V/A$.

In the above manner calculations proceed to give a predicted time – filtrate flow rate data sequence and the particle size distributions throughout the cake height. In a typical simulation the error in the solids mass balance was <0.5%.

RESULTS AND DISCUSSION

Typical experimental data for the downward filtration of a range of suspensions are shown in Figure 5. It is evident that, as expected, with a raised filtration pressure the filtration rate also increased. For a fixed pressure, however, a bimodal suspension made from a mix of two size distributions (i.e. mix 1) always produced less filtrate than an equivalent test with a suspension produced from a single wet grind (i.e. grind 1). This phenomenon was confirmed through the calculated average specific cake resistances (α_{av}) and porosities (ε) where at 100 kPa, for example, α_{av} = 2.1x10^{10} m kg^{-1} and ε = 0.68 for grind 1 and α_{av} = 3.3x10^{10} m kg^{-1} and ε = 0.67 for mix 1. These findings were mirrored by corresponding experiments with 'grind 3' and 'mix 2' suspensions where the calculated differences in α_{av} between otherwise identical tests could approach an order of magnitude.

Also shown on Figure 5 are model predictions of filtration performance. In most cases the model predicted the experimental data well and this was confirmed with similarly good predictions for the other available filtration data. To use the model it was necessary to assume a specific cake resistance due to the first particles deposited on the filter medium (designated $(\alpha_{av,chal})_{t=0}$). As $\alpha_{av,chal}$ varies in a known manner according to eqn. (4), the simulations facilitated a measure of the contribution to overall cake resistance by sedimented particles and Figure 6 shows an example of such data that corresponds to the information in Figure 5. It is evident that as the filtration pressure is raised, and the filtration rate is consequently increased, so the contribution to cake resistance due to sedimentation is reduced. The result is also intuitive, as a raised pressure results in less time being available for particles to sediment before the filtration is complete. In all cases the predicted influence of sedimentation is greater for 'mix 1' suspensions, presumably due to the greater proportion of larger particles in the feed (see Table 1).

Experimental measurements and theoretical predictions of particle size within filter cakes are shown in Figures 7-10.

Comparisons of Figures 7 and 8 show reasonable agreement between experiment and theory, although the experimental difficulties associated with taking representative samples of filter cakes inevitably contributes to some of the apparent differences. At the 100 kPa pressure represented by Figure 7, both the experimental data and the theoretical prediction suggest that the median particle size in the cake increases marginally with cake height. For corresponding experimental conditions in Figure 8 and a feed composed of the mix of two individual size distributions, both the experiment and model indicate a larger particle size toward the bottom of the filter cake adjacent to the medium and a similarly reduced particle size toward the top. These conditions arise as a consequence of particle sedimentation toward the medium. However, the model also predicts a maximum median particle size some way up the cake height with this corresponding to a minimum in the local cake resistance. Some authors[4,6] have previously reported results that support such a prediction and attribute the phenomenon to the differential settling of different particle size classes as well as the changing concentration of particles that challenge the cake surface with time.

Figures 9 and 10 show the experimentally measured effects of filtration pressure on the particle size distribution within filter cakes. With the suspension designated 'grind 3' and a filtration pressure of 50 kPa, the cake formed through its height with an almost constant median particle size close to the median size of the feed suspension. Raising the pressure had little effect as the measured particle size changed by a negligible amount. For the suspension designated 'mix 2', which comprised a mix of the two size distributions 'unground 2' and 'grind 4', the observed effects of filtration pressure are more marked. For the given experimental conditions and the lower pressure of 50 kPa, there was a sufficiently long time available for larger particles to sediment and result in a larger median size toward the bottom of the cake. At the higher pressure of 500 kPa the time available for sedimentation during the filtration was much reduced and the contribution to cake resistance from particle sedimentation was significantly lowered. Here, cake formed with near constant median size through the cake height that was again close to the median size of the feed. These findings confirm the data presented in Figure 6.

CONCLUSIONS

The preliminary work presented in this paper quantifies some of the effects of particle sedimentation that can occur during dead-end filtration. It is evident that sedimentation may

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contribute a significant proportion of the cake resistance that is present during downward filtration and that the influence is reduced as the:

- filtration pressure/rate increases
- size of particles in the feed becomes smaller
- distribution of the feed becomes narrower.

Whilst the 'layer' model has been shown to predict filtration performance and particle size distributions in downward filtration, the author believes that the approach can be adapted and used to investigate other aspects of filtration. The influence of filter orientation is of obvious interest. However, examination of cake formations over different pressure and flow regimes are equally as important as is the extension of the model to include the compression of already formed cake layers. The latter is potentially difficult, although fundamentally necessary to provide a more complete understanding of cake filtration.

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FIGURES AND TABLES

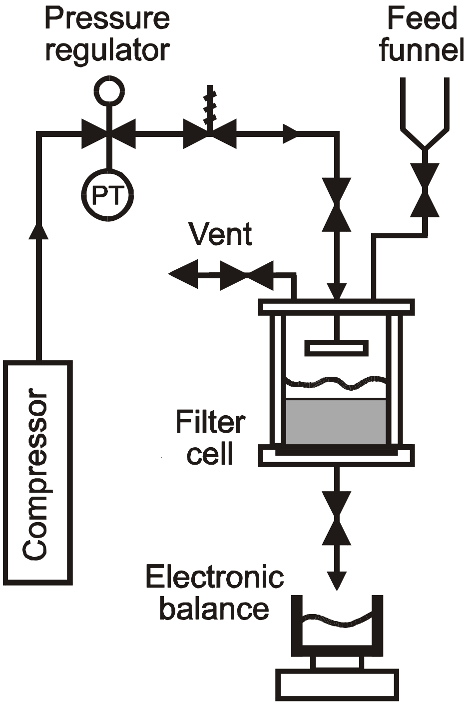

Figure 1: Schematic of the dead-end filtration apparatus.

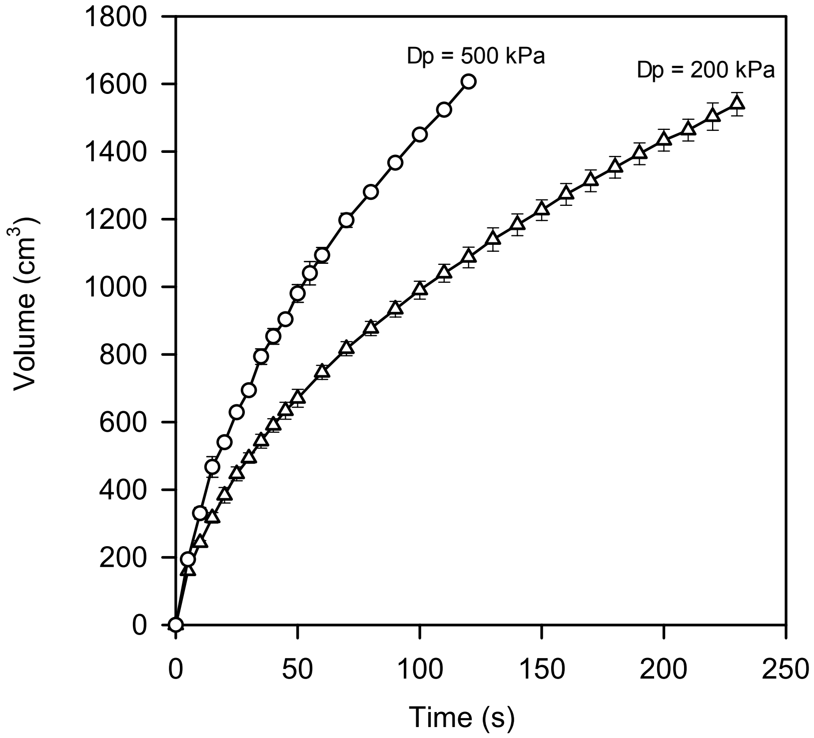

Figure 2: Typical variations between repeat filtration tests; unground 2.

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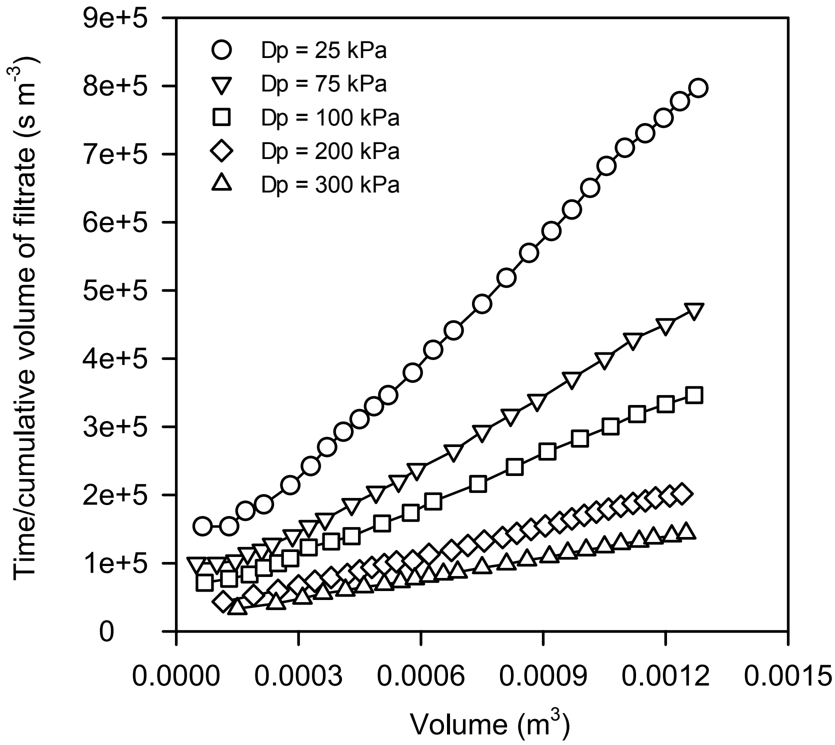

Figure 3: Sequential variation of experimental data with filtration pressure; grind 1.

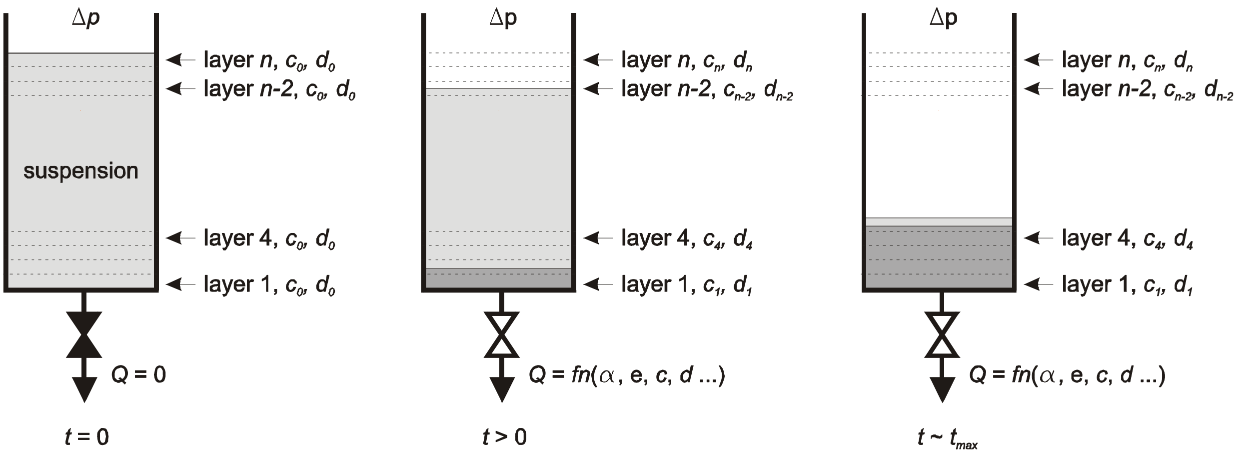

Figure 4: Schematic of the model for filtration with simultaneous sedimentation.

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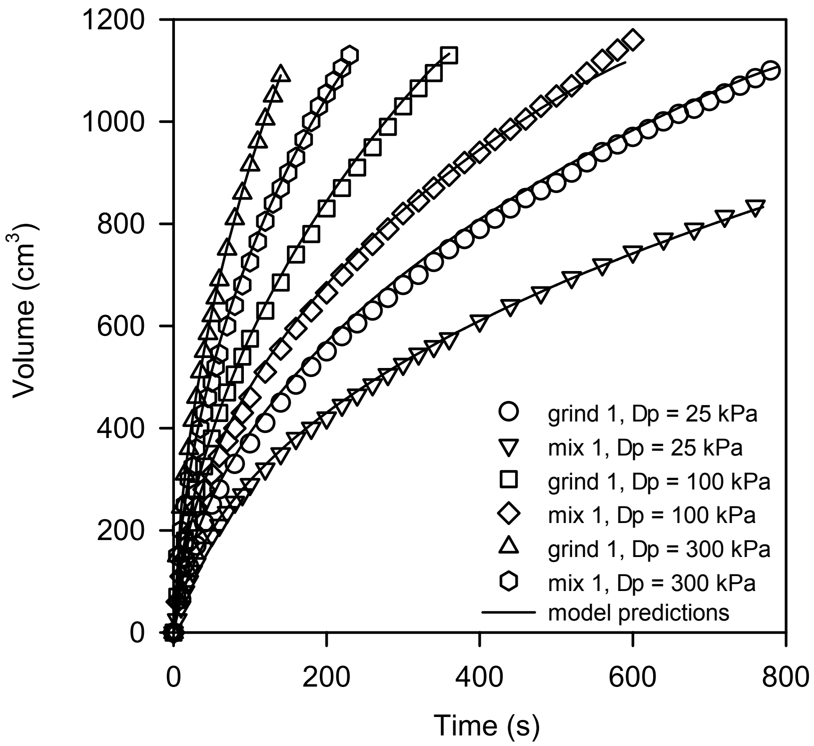

Figure 5: The effects of particle size distribution on filtration performance.

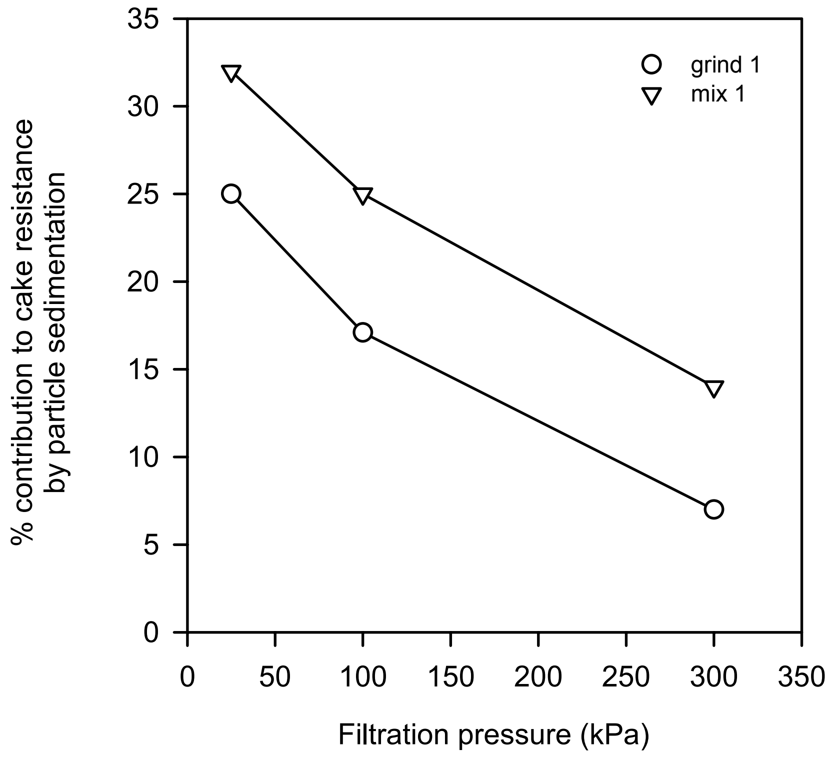

Figure 6: Predicted contributions of particle sedimentation to cake resistance as a function of filtration pressure.

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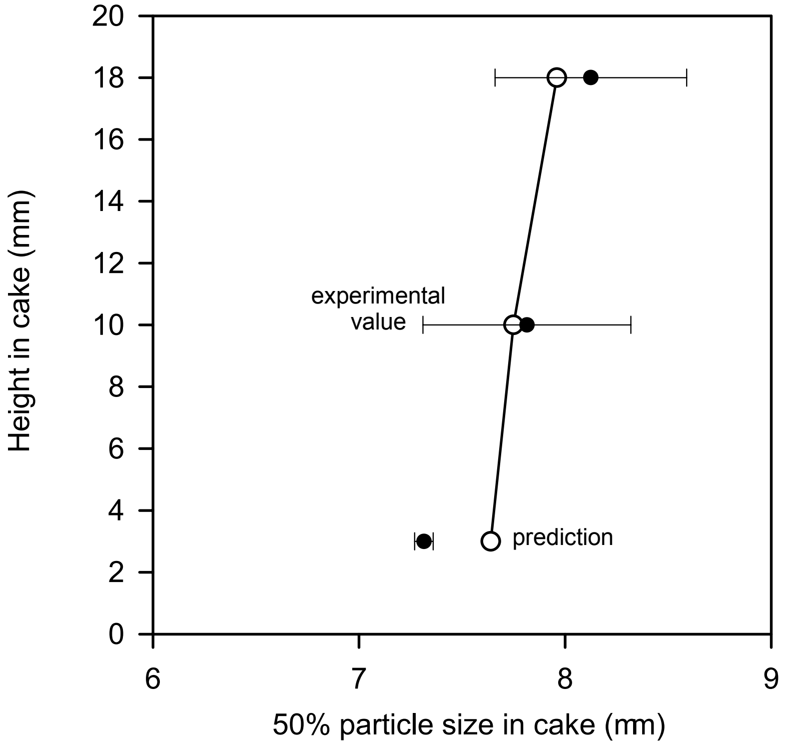

Figure 7: Experimental and theoretical particle sizes in a filter cake; grind 1, Δp = 100 kPa.

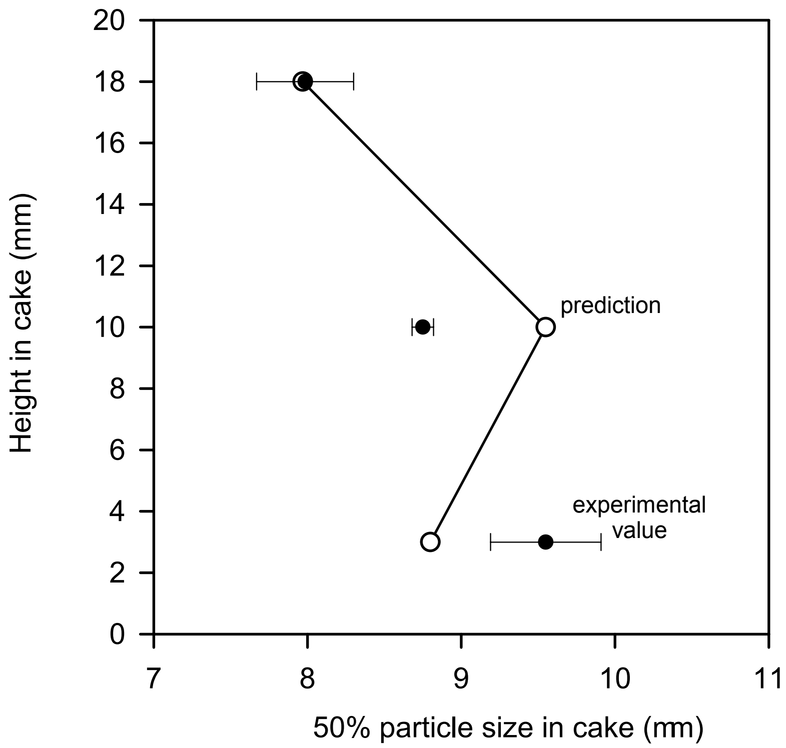

Figure 8: Experimental and theoretical particle sizes in a filter cake; mix 1, Δp = 100 kPa.

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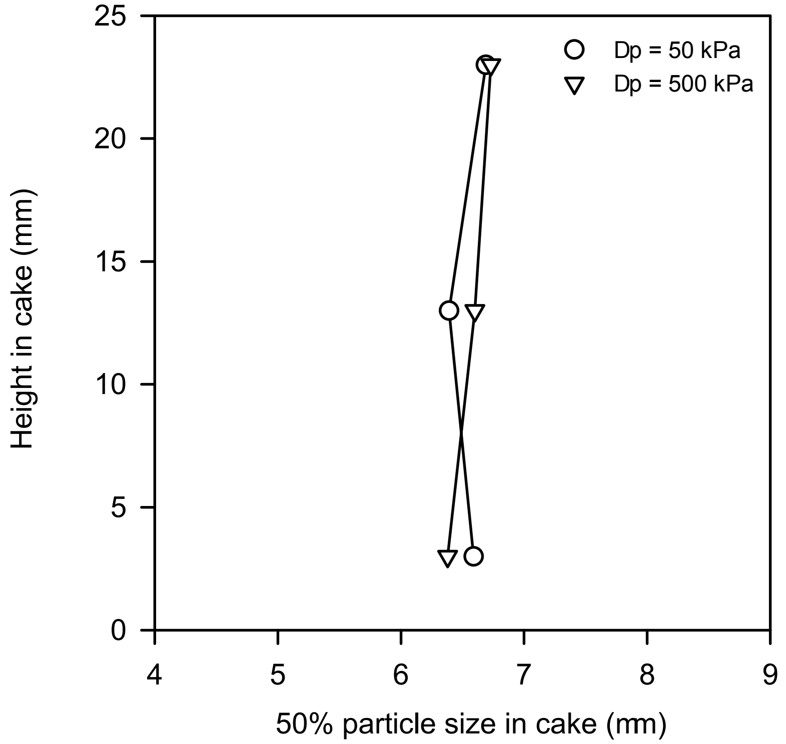

Figure 9: The effects of filtration pressure on the measured particle size in a filter cake; grind 3.

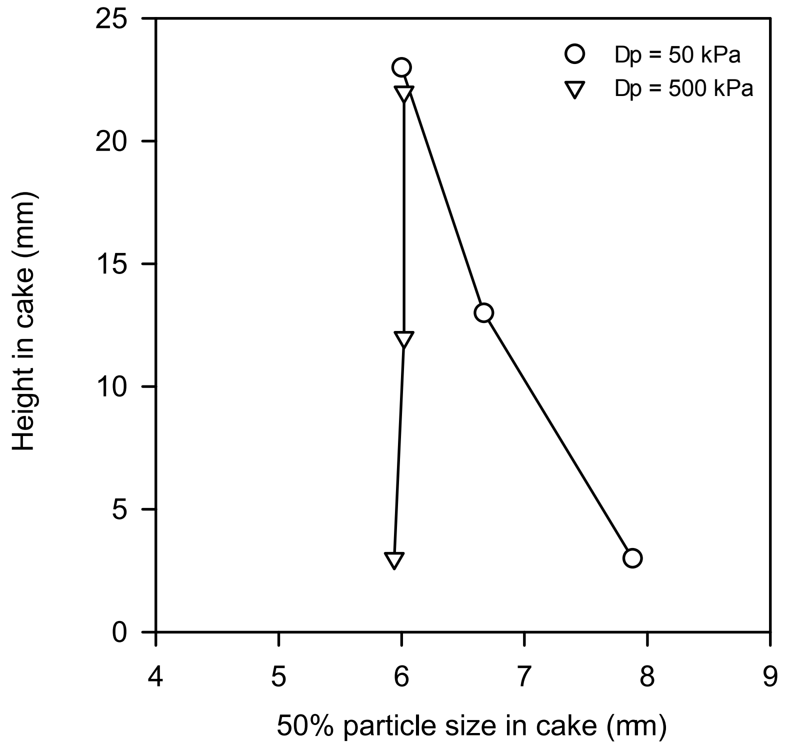

Figure 10: The effects of filtration pressure on the measured particle size in a filter cake; mix 2.

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Suspension pretreatment	Designated name	10 % size (μm)	50 % size (μm)	90 % size (μm)
none	unground 1	2.42	11.66	26.10
wet grind 1.5 h	grind 1	0.84	7.47	14.03
wet grind 48 h	grind 2	0.62	4.22	6.74
unground 1 + grind 2	mix 1	0.85	7.65	21.89
none	unground 2	0.40	9.55	28.26
wet grind 6 h	grind 3	0.36	6.28	14.37
wet grind 72 h	grind 4	0.20	2.65	6.44
unground 2 + grind 4	mix 2	0.36	6.35	24.06

Table 1: Particle size data for the calcite suspensions.

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