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Stéphane Couturier[a]; Marc Valat[a]; Jean Vaxelaire[b]; Jean-Rodolphe Puiggali[a]
[a] LEPT-ENSAM UMR 8508 CNRS, Esplanade des Arts et Métiers, Talence, France [b] LGPP (EAD 1932)—ENSGTI, Pau, France

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Liquid Pressure Measurement in Filtration–Compression Cell

Stéphane Couturier,[1,*] Marc Valat,[1] Jean Vaxelaire,[2] and Jean-Rodolphe Puiggali[1]

[1]LEPT-ENSAM UMR 8508 CNRS, Esplanade des Arts et Métiers, Talence, France
[2]LGPP (EAD 1932)—ENSGTI, Rue Jules Ferry, Pau, France

ABSTRACT

Filtration-compression cells are usually used during laboratory tests to describe the behavior of materials submitted to mechanical dewatering processes. Among the parameters measured, the liquid pressure at the surface of the filtration cake is a good indicator of the dewatering evolution. However, in the classically designed cells, the information given by pressure transducer during the expression phase does not confirm the theory. A new design of the piston is proposed and studied in this paper. A pseudo piston is added ahead of the pressure transducer in order to avoid the contact with the solid forming the cake during the expression stage. Experiments were carried out on different compressible materials: talc, kaolin, and activated sludge. Every experiment showed

*Correspondence: Stéphane Couturier, LEPT-ENSAM UMR 8508 CNRS, Esplanade des Arts et Métiers, 33400 Talence, France; E-mail: couturier@lept-ensam.u-bordeaux.fr.

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that the liquid pressure at the surface of the cake reached zero at the end of the dewatering test, even for extremely compressible cakes.

Key Words: Filtration; Expression; Kaolin; Talc; Activated sludge.

INTRODUCTION

Mechanical dewatering by filtration and expression is widely used in different fields (chemical and pharmaceutical industry, wastewater treatment, etc.). For a given suspension, the filtration rate and the amount of liquid removed in filtration and compression stages are governed by cake properties. At laboratory scale, relevant parameters for filtration and compression can be obtained from experiments performed in a filtration–compression cell (FCC).

Some improvements can be carried out on the classical FCC in order to estimate additional parameters such as liquid pressure at the cake surface[1–3] or along the cake thickness.[4–7] Similarly, specific apparatuses designed to study the behavior of compressible materials during expression allowing liquid pressure measurement have been developed.[8] An accurate measurement of the liquid pressure is important because it gives the true pressure applied during filtration and allows a better determination of the transition between filtration and compression. According to Novak *et al*.[2] the normalized liquid pressure is "*an excellent indicator of the extent of dewatering by expression*."

Several works, recently published, report pressure data obtained with experimental setups with a pressure transducer mounted flush with the piston face.[9,10] The objective of this work is to show that liquid pressure measurement performed with a similar setup may induce error in the measure during expression. In that way, a comparison of the results obtained from two different experimental setups is presented. In one apparatus (FCC1) the pressure transducer was located at the surface of the piston. In the other (FCC2) a solid disk (designated as pseudo piston) was added ahead of the piston (and its pressure transducer) in order to prevent contact between the membrane of the pressure transducer and solid particles. The cell FCC2 was designed to measure the true hydraulic pressure at the cake surface during the entire mechanical separation and to demonstrate clearly that an experimental setup such as FCC1 is not suitable for measuring hydraulic pressure during expression. The experiments were carried out during filtration and expression in order to

show that the modified experimental setup (FCC2) allows a measurement of the effective liquid pressure regardless of the compressibility of the cake.

THEORETICAL BACKGROUND

In cake filtration operations, the solid particles accumulate at the surface of a filter medium, forming a cake. The filterability of this cake and its ability to express the liquid are essential parameters of the separation process. They largely depend on the cake structure, which is fixed by the operating conditions and the suspension properties. For compressible materials, the local structure (notably the porosity) is nonuniform and a profile of pressure can be observed through the cake thickness. The evolution of the porosity is currently characterized by a constitutive equation (which relates the porosity to the compressive stress in the cake) and a relationship between the compressive stress (p_s) and the liquid pressure (p_l). This relationship has been derived from momentum balances[11,12] on the liquid and the solid. As the acceleration and inertial forces can generally be neglected[6] the momentum balances change to a pair of stress balances. The derivation of these balances has frequently neglected the viscous and gravity forces. It leads to:

$$\frac{dp_s}{dx} = -\frac{dp_l}{dx} \tag{1}$$

and the integrated form:

$$p_s + p_l = P_{app} \tag{2}$$

where P_{app} is the pressure applied on the suspension. p_s is the structure stress resulting from a compressive force divided by the cross-sectional area.

Unfortunately, according to different authors the definition of the liquid pressure was not similar.[8] For example Tiller[13] has introduced the liquid pressure as the force acting on the liquid phase divided by the cross-sectional area ($p_l =< p_l >$), while Willis and Tosun[11] consider the intrinsic liquid pressure, which is derived by an averaging of the liquid phase volume ($p_l = < p_l >^l$). According to Whitaker,[14] Chase *et al.*,[7] and Slattery (in Ref.[15]) this intrinsic pore pressure is the one measured by a pressure transducer.

The relationship between those two defined pressures is:

$$\langle p_l \rangle = \varepsilon \cdot \langle p_l \rangle^l \tag{3}$$

Consequently, great care is necessary with the use of the pressure equation in order to avoid misunderstanding or erroneous results.

As expression occurs, the distribution of the liquid pressure changes in the cake. The profile tends to be flat when the consolidation is complete (Fig. 1), and the liquid pressure at the top of the cake reaches the atmospheric pressure (which is the pressure at the surface of the filter medium when the filter resistance is neglected).

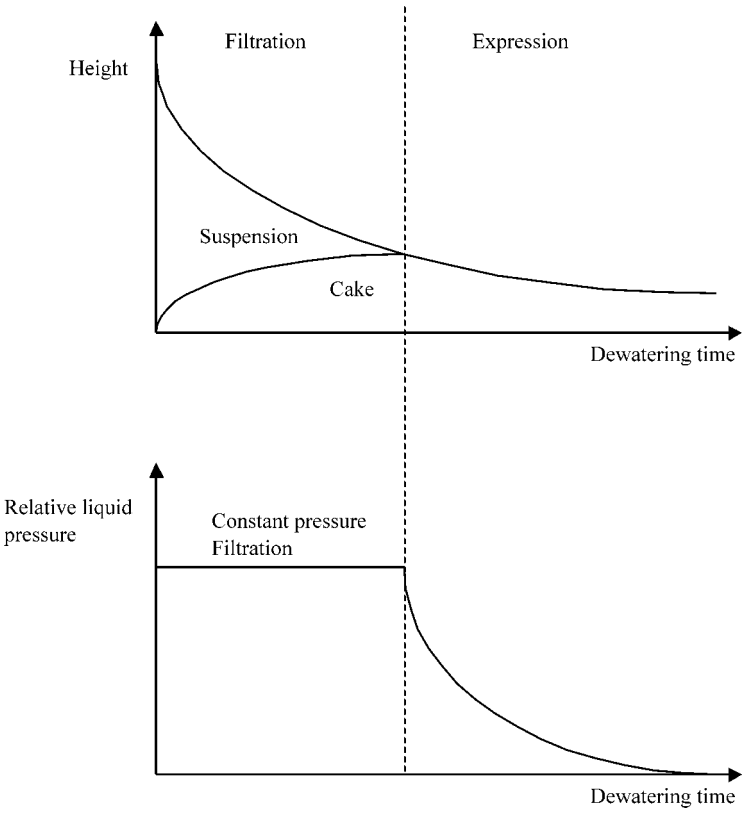

Figure 1. Evolution of cake height and relative liquid pressure during filtration and expression.

An unexpected behavior for extremely compressive materials has been reported by Sorensen *et al*.[1] and Novak *et al*.[2] They experimentally showed that the measured liquid pressure at the cake surface remained high even after a long period of expression. They explained this behavior by the formation of a nonpermeable skin at the cake/medium interface. However, according to their experimental setup (no pseudo piston), a contact between some solid particles and the transducer diaphragm may perturb the measurement and could explain the previous observation.

MATERIALS AND METHODS

Particles and Suspensions Properties

Two types of aqueous suspensions, talc and kaolin, were used for this study. These materials were chosen according to the different compressibility of their cakes to examine the effect of compressibility. Some properties of the solids and suspensions are listed in Table 1. Kaolin and talc were supplied by Merck, France, and Luzenac, and France, respectively.

The particle size distribution was measured by a diffraction laser method. Figure 2 confirms the presence of fine particles in kaolin powder characteristic of dewatering problems.[16]

Apparatus

A diagram of the apparatus used to run the filter experiments is shown in Figs. 3 and 4. They are cylindrical stainless steel chambers with internal diameter of 70 mm. In order to limit the effects of side wall friction, only cakes with an average thickness of 15 mm were formed to maintain a low cake thickness to cell diameter ratio.[17] A perforated disk was located at the bottom of the cylinder in order to support the filter medium. A polymeric filter cloth (Fyltis, France, ref 25841 AN) was used for the experiments.

Table 1. Properties of talc and kaolin suspensions.

Variable	Talc	Kaolin
ρ_s (kg·m^{-3})	2350	2600
d_{50} (μm)	15.13	5.73
s (kg/kg)	0.23	0.23

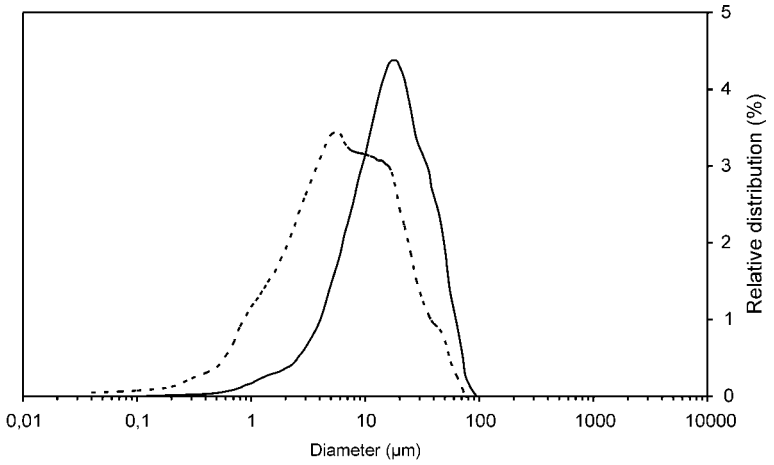

Figure 2. Particle size distribution: talc (—); kaolin (···).

The pressure was applied to the piston by a hydraulic system in the setup FCC1 and by pressurized air in FCC2. In both cases the pressure was measured by a transducer located at the bottom of the piston but in FCC2 a pseudo piston (Fig. 4) was added in order to avoid contact between the solid in the cake and the diaphragm of the transducer. The clearance between the pseudo piston and the cylinder enables liquid continuity. The suspension fills the space between the piston and the pseudo piston to completely saturate the cell at the beginning of experiments. This dead volume was not taken into account during the experiments. Then the same initial concentration of the suspension can be ensured in both cells. However this volume must not be taken into account for the measurement of the final cake liquid content. It is important to remove it by a weak vacuum system at the end of each experiment. This modified setup enables one to measure the intrinsic pore pressure since no continuous solid matrix is in contact with the transducer diaphragm during the entire experiment (filtration and expression).

The pressure transducers were piezoresistive OEM pressure transducers with a flush, gap-free welded diaphragm ($\phi = 19$ mm) (Keller, France, Series 10 FL). A high-sensitivity piezoresistive silicon chip was used for pressure sensing. The chip was protected against ambient influences by stainless steel housing sealed with a concentrically corrugated diaphragm. The housing is filled with silicone oil to ensure the transfer of the pressure from the flush diaphragm to the sensing component.

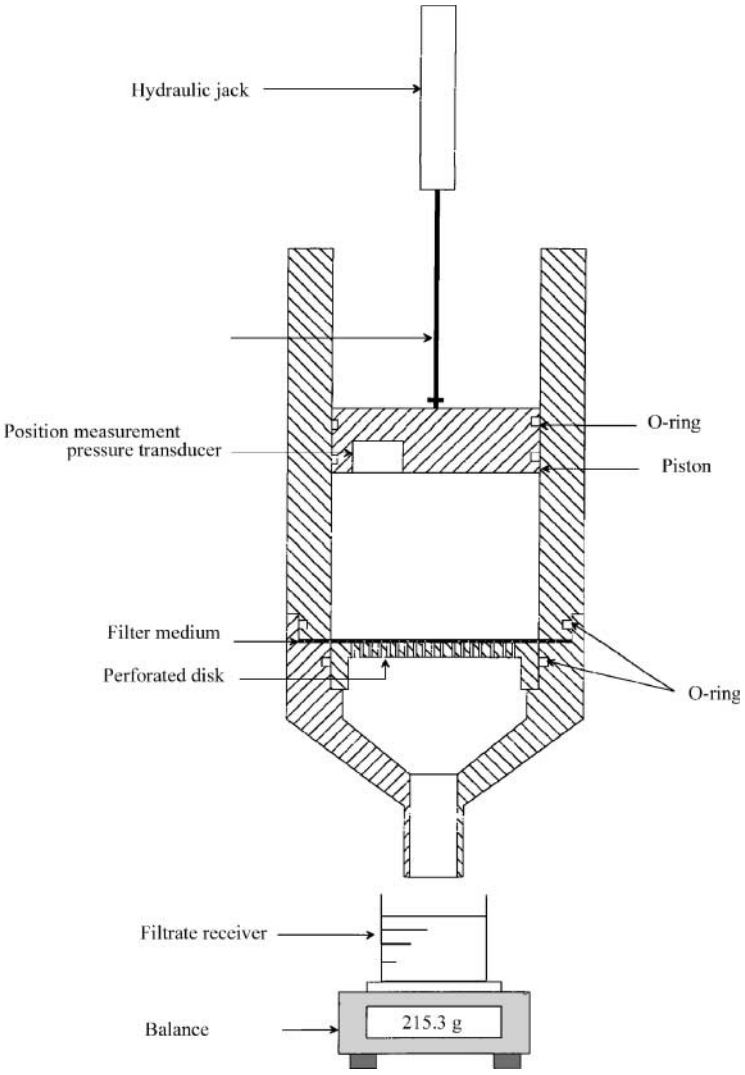

Figure 3. Schematic diagram of the filtration–compression cell FCC1.

Liquid pressure at the surface of the cake, mass of filtrate, and piston height were automatically recorded on a personal computer. The residual moisture content of the cake at the end of an experiment was measured by drying at 105°C and weighing.

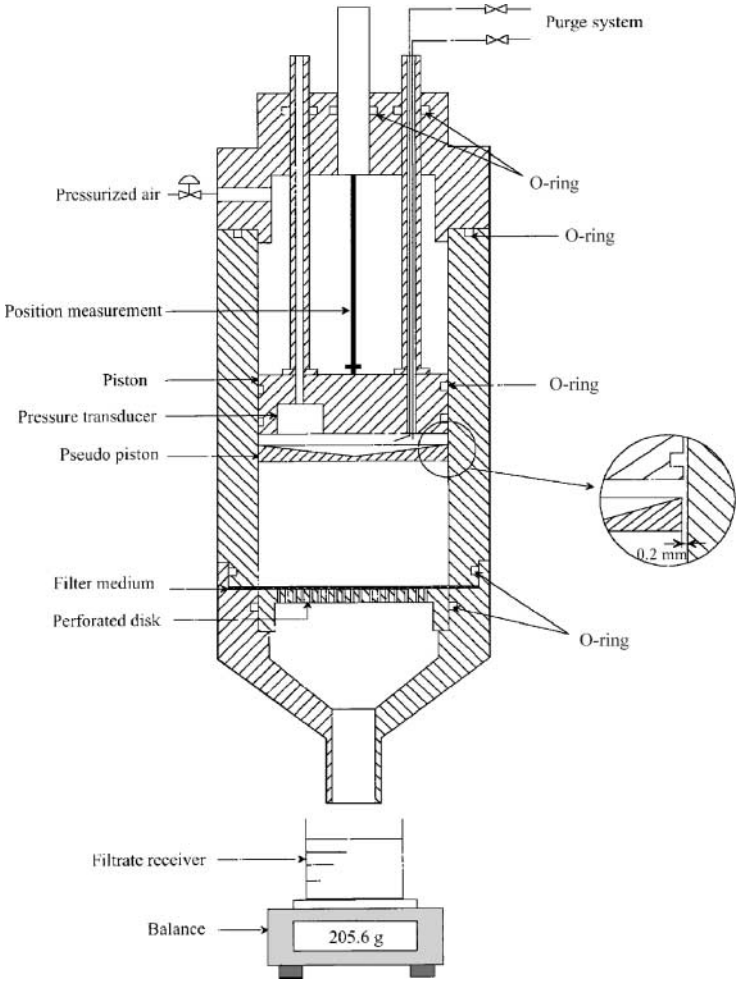

Figure 4. Schematic diagram of the filtration–compression cell FCC2.

EXPERIMENTAL RESULTS

Material Characterization

The compressibility properties of the materials were measured in a compression–permeability cell (CP cell).[18,19] Such measurements enable

the generation of some relationships between solidosity (ε_s) and specific resistance (α) and compressive stress. Experimental data are usually correlated by power-law functions[19,20]:

$$\alpha = \alpha_0 \left(1 + \frac{p_s}{p_a}\right)^n \tag{4a}$$

$$\varepsilon_s = \varepsilon_s^0 \left(1 + \frac{p_s}{p_a}\right)^\beta \tag{4b}$$

where ε_s^0, p_a, β, n, and α_0 are empirical constants.

The experimental results and the fitted curves are presented in Fig. 5 for the talc and the kaolin suspensions. The fitting parameters are given in Table 2.

According to the classification given by Tiller and Yeh,[21] results obtained show that talc cake is moderately compressible (n = 0.48), whereas kaolin cake (n = 1.17) is highly compressible. Reported compressibility coefficients for kaolin range between 0.37 and 0.85 (Table 3). However, the diversity of values found in the literature indicates that constitutive parameters vary strongly from one kaolin to another and make any comparison irrelevant.

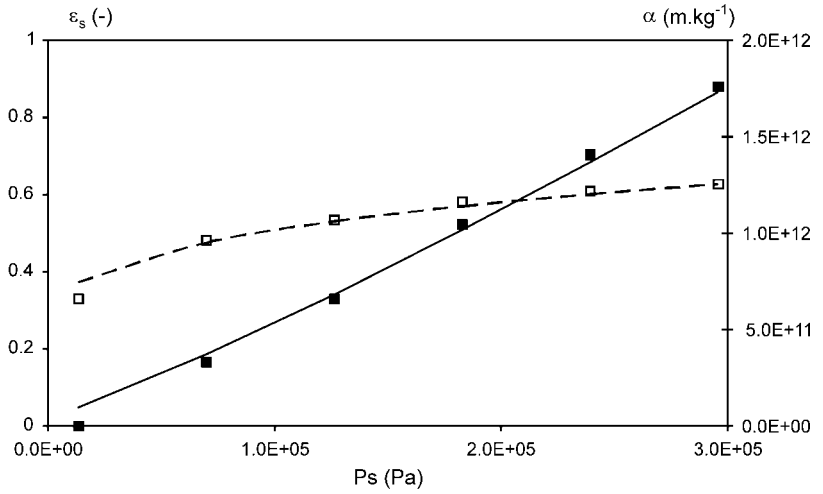

Figure 5. Constitutive relationships obtain from CP cell measurement for kaolin cakes. α vs. p_s, (□) CP data; (–) fitting with Eq. (4a). ε_s vs. p_s, (■) CP data; (– –) fitting with Eq. (4b).

Table 2. Constitutive equation parameters.

Parameter	Kaolin	Talc
β (–)	0.21	0.15
n (–)	1.17	0.48
P_a (Pa)	1.25×10^4	6.20×10^3
ε_s^0 (–)	0.32	0.34
α_0 (m·kg^{-1})	4.10×10^{10}	1.02×10^{10}

Constant Filtration–Expression Experiments: Influence of the Pseudo Piston

First some experiments were carried out in order to verify that the pseudo piston does not modify the filtration and expression process. Normalized filtrate volume (V_N = filtrate volume divided by filtrate volume at the end of experiment), normalized height (h_N = position of the interface piston/suspension divided by the cake height at the end of experiment), and reciprocal flow rate [$t/(V_N)$] versus normalized volume are reported in Fig. 6 for two applied pressures.

The introduction of these dimensionless variables was necessary in order to properly compare the data obtained on both experimental setups FCC1 and FCC2. Due to the suspension filling the space between the piston and the pseudo piston, it was difficult to accurately fix the initial sample volume to be dewatered. Moreover, the number of seals involved in FCC2 increases wall friction, so it was difficult to apply the same pressure from one experiment to another. For FCC1, the volume of suspension purged during the placement of

Table 3. Parameters for constitutive equations found in literature for kaolin.

Parameter	Tiller and Leu[20]	Tien et al.[8]	Stamatakis and Tien[22]	Tiller and Horng[23]	Reichman and Tomas[24]
β (–)	0.09	0.17	0.09	0.09	0.20
n (–)	0.37	0.85	0.40	0.55	0.76
P_a (Pa)	1.3×10^3	8.7×10^4	1.2×10^3	1.9×10^4	1.6×10^5
ε_s^0 (–)	0.27	0.34	0.27	0.32	0.38
α_0 (m·kg^{-1})	4.50×10^{11}	5.47×10^{11}	4.00×10^{11}	1.10×10^{11}	1.08×10^{12}

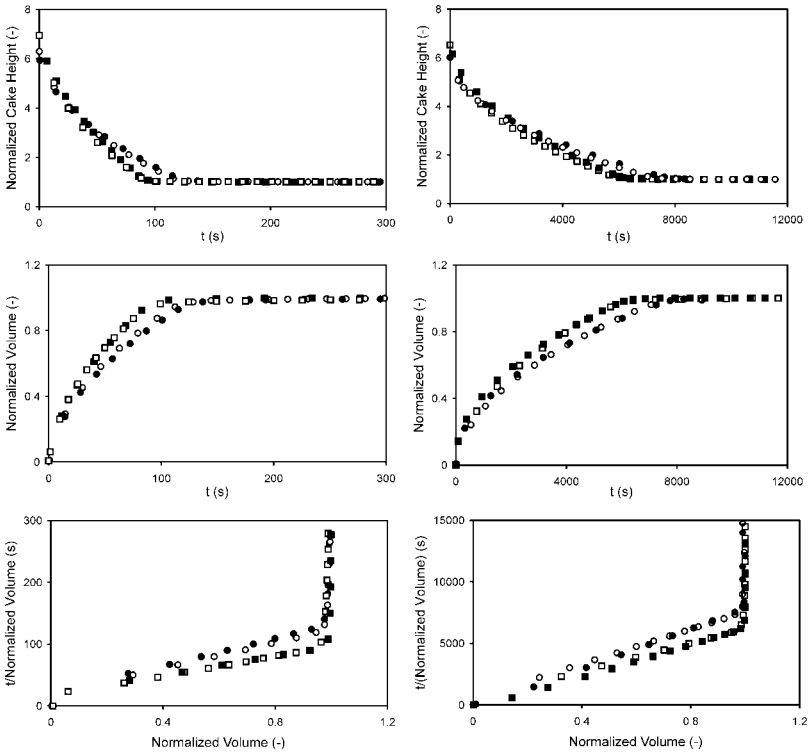

Figure 6. Comparison of filtration curves obtained with FCC1 and FCC2 for talc (a) and kaolin (b); 5 bar: FCC1 (■), FCC2 (□); 3 bar: FCC1 (•), FCC2 (○).

the piston in contact with sample is relatively small compared to FCC2, which has a system of purge requiring a larger initial volume of suspension.

The results reported in Fig. 6 for the two suspensions show that the pseudo piston has no significant effect on the constant-pressure filtration and expression process. Both cakes have the same properties (Table 4).

Liquid Pressure Measurements

As previously mentioned, similar results in terms of volume of filtrate and cake thickness have been obtained in the two different cells. However, significant discrepancy could be observed according to liquid pressure measurements (Fig. 7).

Table 4. Properties of 3-bar dewatered cakes.

	Talc		Kaolin	
	FCC 1	FCC 2	FCC 1	FCC 2
α ($m \cdot kg^{-1}$)	4.4×10^{10}	4.6×10^{10}	3.8×10^{12}	3.3×10^{12}
ε (–)	0.52	0.52	0.54	0.53
Solid content (%)	70	70	68	69

In FCC1, normalized liquid pressure (p_N = liquid pressure measured at the piston/cake interface divided by the constant applied pressure) at the cake surface did not reach zero, even after a long period of expression. The more compressible the materials, the higher the residual liquid pressure recorded. With pseudo piston (FCC2), p_N at the surface of the cake continuously fell to zero, attesting that the expression was complete.

The significant differences observed between FCC1 and FCC2 were related to the nature of pressure measured during the expression stage. Due to the pseudo piston the pressure measured in FCC2 is the pore liquid pressure (intrinsic phase average pressure for the liquid phase) at the surface of the cake. In a classical configuration as FCC1 the pressure transducer diaphragm measures a stress that is the contribution of both the pore liquid pressure and a stress generated by the solid network (Fig. 8).

The residual pressure observed in the classical setup (FCC1) with highly compactible cakes was previously attributed to the formation of a thin skin at the cake/medium interface that absorbs most of the pressure drop across the cake.[21,25] It is not the purpose of our paper to discuss the existence of such phenomena intuitively pointed out by Tiller and Green[26] and experimentally observed in terms of porosity profiles[27] or liquid pressure profiles.[28] However, the experiments carried out during this study suggest that the liquid pressure measured in several previous works was not exactly hydraulic pressure.

To confirm this result a highly compactible material was considered. A flocculated activated sludge coming from a municipal wastewater treatment plant (Villeneuve sur Lot, France) was dewatered in the cell FCC2. Liquid pressure measurements at the surface of the cake clearly allow understanding the physical behavior (Fig. 9). Normalized liquid pressure at the surface of the cake must reach zero unless the skin becomes totally nonpermeable.

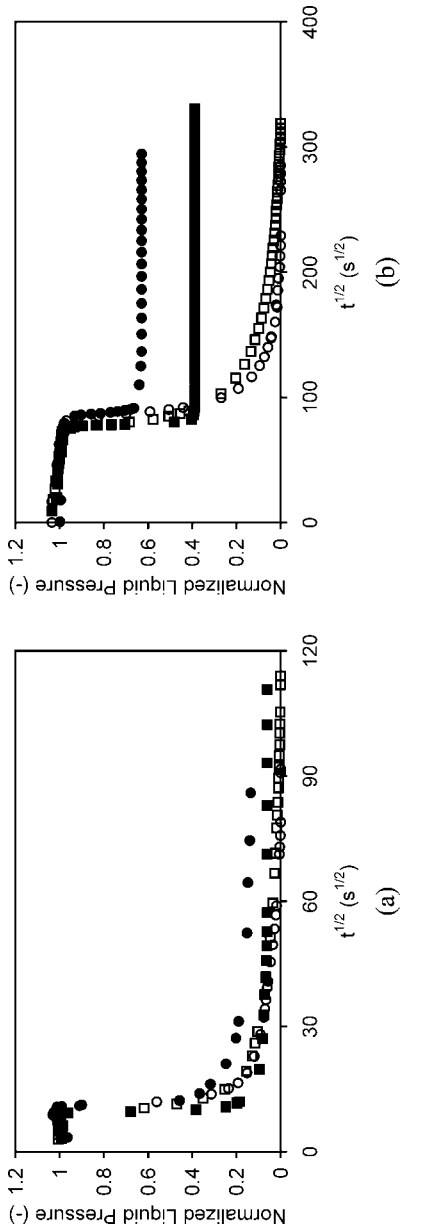

Figure 7. Evolution of the normalized liquid pressure obtained with FCC1 and FCC2 for talc (a) and kaolin (b); 5 bar: FCC1 (■), FCC2 (□); 3 bar: FCC1 (●), FCC2 (○).

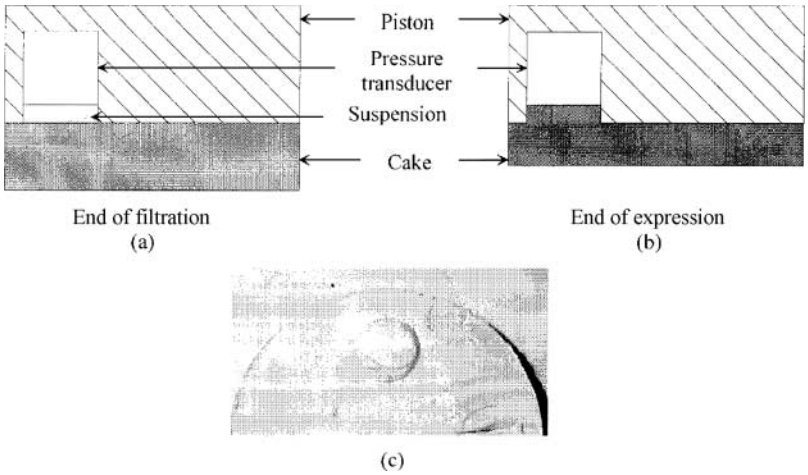

Figure 8. Schematic behavior of highly compressive cake at the end of filtration (a) and expression (b); picture of a kaolin cake deliquored with FCCI (c).

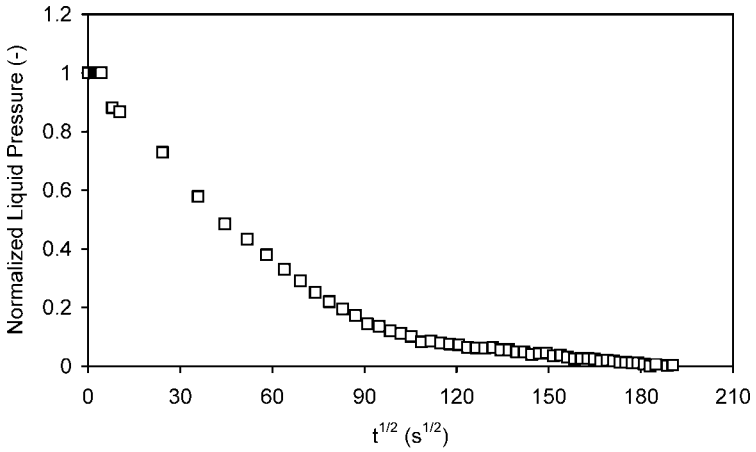

Figure 9. Normalized liquid pressure at the surface of the cake for flocculated waste-activated sludge dewatered with FCC2 at constant pressure ($P_{appl} = 1$ bar, $s = 0.02$).

TECHNICAL REMARKS

This study pointed out different problems related to the difficulty of carrying out identical experiments on two different experimental setups.

In the first series of experiments (not presented in this paper) filtration curves obtained were shifted. Presence of air bubbles trapped between the perforated disk and the filter cloth in FCC1 provoked an apparent increase of the medium resistance. To solve this problem, the perforated disk, the filter, and the bottom of the cells were carefully filled with water before each experiment.

Moreover, the specific design of FCC2 (pseudo piston) led to air bubbles trapping at the bottom of the pseudo piston. In this case, the expression was longer than in FCC1. Liquid content of cakes dewatered in FCC2 was lower than with FCC1. The excess of filtrate recovered corresponded to a volume of air pushed into the cake. Using the weak vacuum system, possible bubbles could be removed during the placement of the pseudo piston at the top surface of the sample.

CONCLUSION

Using filtration–expression cells, liquid pressure was measured at the surface of the sample during the whole process. Several materials with different compressible behaviors were studied. This work presents a newly designed FCC with a pseudo piston that enables the measurement of the true liquid pressure at the surface of a filtration cake. Experimental data clearly showed that even for extremely compressible materials, normalized liquid pressure at the top surface of the cake fell to zero during expression.

This paper also presents experiments carried out in two laboratories. Significant experimental work was necessary to obtain similar results between the two cells (under the same operating conditions). Indeed, it often seems hazardous to compare the different experimental data provided by the literature.

It appears that the use of a pseudo piston is an interesting way to study filtration and expression, even for highly compressible materials.

NOTATION

d_{50}	median diameter, μm
h_N	normalized cake height = cake height/cake height at the end of experiments

n	compressibility coefficient, Eq. 4a
p_a	empirical constant, Eq. 4a–4b, Pa
P_{appl}	filtration pressure, Pa
p_l	hydraulic pressure, Pa
$< p_l >$	phase average pressure for the liquid phase, Pa
$< p_l >^l$	intrinsic phase average pressure for the liquid phase, Pa
p_N	normalized pressure = Pressure/P_{appl}
p_s	compressive stress, Pa
s	solid particle mass fraction in the suspension, (kg of dry solid/kg of water)
S	liquid content, %
t	time, s
V_N	normalized filtrate volume = filtrate volume/filtrate volume at the end of experiments

Greek Letters

α	cake specific resistance, $m \cdot kg^{-1}$
α_0	value of α in unstressed cake, Eq. 4a, $m \cdot kg^{-1}$
β	empirical constant, Eq. 4b
ε	porosity
ε_s	solidosity (volume fraction of solids)
ε_s^0	value of ε_s in unstressed cake
ρ_s	solid density, $kg \cdot m^{-3}$
ϕ	diameter of transducer diaphragm

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