Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

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To cite this Article Leu, Wenfang and Tiller, Frank M.(1983) 'Experimental Study of the Mechanism of Constant Pressure Cake Filtration: Clogging of Filter Media', Separation Science and Technology, 18: 12, 1351 — 1369
To link to this Article: DOI: 10.1080/01496398308059930
URL: http://dx.doi.org/10.1080/01496398308059930

SEPARATION SCIENCE AND TECHNOLOGY, 18(12&13), pp. 1351-1369, 1983

Experimental Study of the Mechanism of Constant Pressure Cake Filtration: Clogging of Filter Media

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ABSTRACT

Failure of data taken in pilot plant filtration of liquefied coal to fit conventional analysis led to research summarized in this paper. Historically, the effect of migrating fine particles in cake filtration has been ignored in theoretical treatments. In usual development, the total resistance to flow has been broken into cake resistance R_c and medium resistance R_m. Experimentors have only measured the total resistance and have assumed that R_m remained constant. In this investigation, a filter with seven probes was empolyed to measure the individual resistances. Medium resistance is found to increase with time and mass of dry cake per unit area due to migration of fine particles into the interestices of a filter medium.

INTRODUCTION

Cake filtration is an important operation within the domain of solid-liquid separation which can be divided into four stages of pre-treatment, thickening, solid separation, and post-treatment. Two major problems encountered in cake filtration are (1) how to improve filtration cycle rates, and (2) how to reduce liquid content of

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filter cakes. The latter problem has been approached with hydraulic (Tiller and Horng, 1983) and mechanical (Shirato, Murase, and Hayashi, 1982) methods. The rate of filtration depends upon the pressure drop, viscosity, and the resistances of both cake and medium. Conventional theoty has assumed that medium resistance R_m is constant and average cake resistance α_{av} is a unique function of its initial value α_o and the pressure drop across the cake Δp_c. However, both laboratory data and industrial practice indicate that medium resistance changes with time.

Throughout the history of experimentation in filtration, the pressure drop across both cake and medium has been measured rather than across the cake alone. Consequently, it has been impossible experimentally to separate medium from cake resistance. In the past, utilization of a model which assumes R_m is constant has permitted calculations of both R_m and R_c. If the model should prove inadequate, calculated values of individual resistances would be in doubt. Little attention has been focused on the critical question of constancy of R_m and the effect of its possible variation in theoretical formulations. Notebaert, Wilms, and van Haute (1975) and Tiller, et al. (1981) have addressed themselves to the question by developing models employing variable R_m. Ultimately, experiments which permit separation of the resistances are necessary to theoretical progress.

It was the objective of experimentation in this phase of investigation to measure pressure drops across both medium and cake and thereby separate the respective resistances. Hydraulic pressure variations in cakes were measured so that the entire profile from cake surface to the medium could be obtained. Okamura and Shirato (1955), and Willis, Shen, and Gray (1974) used probes to measure local hydraulic pressure in filter cakes. However, they did not focus on the variation of medium resistance.

REVISIONS OF FILTRATION THEORY

Classical techniques for interpretation of constant pressure data have been shown to be frequently in error (Tiller, Crump, and Ville, 1980). Basic assumptions which have been shown to be incompatible with experimental data include

(1) Increase in medium resistance not only during the first few seconds of a given filtration operation but throughout the entire process.

(2) Variation in local cake resistance due to deposition of small particles migrating through the pores

Cake properties can be profoundly affected by migration of fines. Analysis of filtration data of liquefied coal from the Wilsonville Pilot Plant has shown the effect of deposition of asphaltenic colloids in an already formed cake (Tiller and Leu, 1982). Filtration theory was further modified in order to account for structural changes due to clogging of flow channels by submicron particles (Tiller, et al., 1981). An understanding of the basic phenomena involved in such operations as liquefied coal filtration requires an analysis of the internal flow mechanisms.

The filtration equation which is derived from Darcy's law can be expressed in the resistance form (Tiller and Crump, 1977)

$p/\mu q$	$= \alpha_{av} w_c$	$+ R_m$	
total	cake	medium	
Resistance	resistance	resistance	(1)
R	R_c	R_m	

where p is applied pressure, μ is liquid viscosity, q is superficial velocity dv/dt, v is volume of filtrate per unit area, α_{av} is average specific resistance, w_c is mass of dry cake per unit area, and R, R_c and R_m are total, cake, and medium resistance respectively. Eq. (1) can be applied to any kind of cake filtration, not just constant pressure filtration.

For constant pressure filtration if $c\alpha_{av}$ and R_m are constant, integrating Eq. (1) with respect to time yields the well-known parabolic relation between v and t which can be placed in the form

$$t = \mu c \alpha_{av} \frac{v^2}{2} + \mu R_m v \tag{2A}$$

or

$$pt/\mu v = p/\mu q_{av} = \frac{\alpha_{av}}{2} w_c + R_m \tag{2B}$$

where c is a pseudo-concentration defined as dry cake mass per unit filtrate volume, and $q_{av} = v/t$ is the average superficial velocity. Equation (2) is valid only when c, α_{av}, and medium resistance R_m are constant. Constancey of c and α_{av} requires that pressure drop across the cake Δp_c be constant. For constant-pressure *filtration*, Δp_c can be constant only if $R_m = 0$. Thus mutually exclusive assumptions are involved in the derivation of Eq.(2). Its limitations have been discussed by Tiller, Crump, and Ville (1980).

In the textbook approach, assumption of constant R_m, c and α_{av} leads to two linear plots of $p/\mu q$ and $pt/\mu v$ vs. w_c in accord with

Eqs. (1) and (2). The p/μq plot has twice the slope and the same intercept as the pt/μv plot as shown in Fig. 1.

Typical curves for p/μq vs. w_c generated with various assumptions involved in constant pressure filtration theory are presented in Fig. 2. The shapes of the curves depend upon assumptions concerning the magnitude of R_m, the variation of R_m and α_{av} due to particle migration, and the effect of pressure drop across the cake. Even in constant pressure filtration, the pressure drop across the cake Δp_c is not constant. It is given by

$$\Delta p_c = p - p_1 = p - \mu q R_m \tag{3}$$

At the start of filtration, $\Delta p_c = 0$; and α_{av} has its initial value α_o. As the rate decreases, Δp_c and, consequently, α_{av} increase. Thus the supposed straight lines in Fig. 1 are initially curved. However, the time involved in the curved portion is frequently

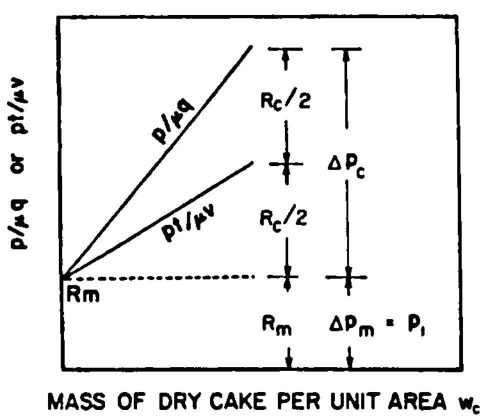

Fig. 1. Resistance plots of p/μq and pt/μv vs. w_c derived from conventional filtration theory.

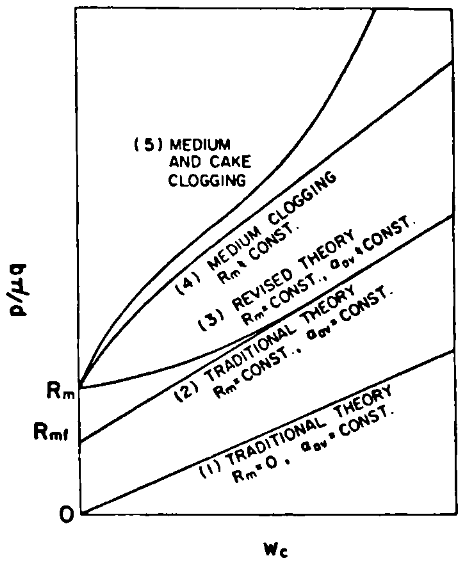

Fig. 2. Resistance plots of p/μq vs. w_c summarizing revised filtration theory.

measured in seconds; and only the straight portion is reported. We now discussed the various curves in Fig. 2.

Case I: Negligible Medium Resistance

If medium resistance R_m is negligible, then α_{av} is constant from the start of filtration because $\Delta p_c = p$. The resistance plot is simply a straight line through the origin as line (1) in Fig. 2. In this one case, conventional and revised filtration theory coincide.

Case II: Constant Medium and Cake Resistances

If both R_m and α_{av} are constant, the two straight lines in Fig. 1 result. The p/μq vs. w_c plot from Fig. 1 is also shown as line (2) in Fig. 2 and is marked "traditional theory". The majority of experimental values of α_{av} and R_m reported in the literature have been obtained from plots like those in Fig. 1. The value of α_{av} is obtained from the slope of the straight line and R_m from the intercept. As the first portion should be curved, values of R_m and α_{av} may be in error when determined by the conventional methodology unless the total resistance $R = p/\mu q$ is large compared to R_m. The ratio $R/R_m = p/\mu q R_m$ ought to have a value in a range close to ten.

Case III: Constant Medium Resistance and Variable Cake Resistance

In a first stage revision of traditional theory (Tiller, Crump, and Ville, 1980), α_{av} was treated as variable while R_m was still regarded as constant. Interpretation of data was prinicipally based upon Eq. (1) which represents instantaneous as opposed to average rates over the entire run. The average filtration resistance is calculated by

$$\alpha_{av} = \frac{p/\mu q - R_m}{w_c} \tag{4}$$

This value of α_{av} corresponds to Δp_c as given by Eq. (3). It should be noted that α_{av} calculated from Eq.(4) is not the slope of the $p/\mu q$ vs. w_c curve.

A $p/\mu q$ vs. w_c curve with increasing slope is generated as curve (3) in Fig. 2. The curve approaches a straight line as w_c increases. The intercept of the curve is medium resistance R_m while the intercept of the tangent to the curve is regarded as a false medium resistance R_{mf}. According to the revised theory, the false medium resistance R_{mf} can never be negative. For highly compressible materials R_{mf} approaches zero but never takes on negative values.

Case IV: Medium Clogging

In a second stage revision (Tiller, et al., 1981) medium clogging phenomenon was considered; and R_m was treated as variable with respect to time. Notebaert, et al. (1975) proposed that the medium resistance increases gradually and then reaches a constant value $R_{m\infty}$. One empirical method for expressing medium resistance at any instant is

$$R_m = R_{m\infty} - (R_{m\infty} - R_{mo})e^{-jw_c^2} \tag{5}$$

where R_{mo} is the resistance of clean medium, and j is a constant parameter. The product jw_c^2 controls the rate at which R_m approaches its ultimate value. Equation (5) depends upon the crude assumption that the degree of clogging is a function of the mass of cake deposited. Presumably j depends on the penetration and deposition of fine particles.

Medium clogging results in a raising of the $p/\mu q$ plot by the increase of R_m. The effect decreases with time and frequently results in a curve like (4) in Fig. 2.

Case V: Medium and Cake Clogging

In the third stage revision (Tiller, et al., 1981), both medium and cake clogging phenomena were taken into account. If migration of fine particles through a filter cake occurs, the fundamental assumption that local specific filtration ressitance is a unique function of p_s (Tiller and Leu, 1980) is incorrect. The average specific filtration resistance for clogged cake may be assumed to take the form

$$\alpha_{av}(\text{clogged cake}) = \alpha_{av}(\text{non-clogging cake})f(w_c) \quad (6)$$

where $f(0) = 1$ and $df/dw_c > 0$. The functional form of $f(w_c)$ may vary substantially depending on the complex phenomena of fine particle miigration.

The curve of $p/\mu q$ vs. w_c may initially have a section of decreasing slope followed by an inflection point and a region of increasing slope as curve (5) in Fig. 2. Severe cake blinding will lead to a tangent line with a negative intercept.

EQUIPMENT

A flow diagram of experimental equipment is shown in Fig. 3. A pressure filter originally designed by Masterton (1980) and subsequently modified was used in this study. The pressure filter, consists of a transparent plexiglass cylinder with inner diameter 153mm. Two sheets of Whatman #1 filter paper supported on a porous stone served as the filter medium. Seven 1/16" stainless steel probes were located at intervals of 3.0 mm from the filter medium. Probe #1 at the interface of cake and medium measured the pressure drop p_1 across the medium separately.

Even with Probe #1 located as close as possible to the medium, precise determination of p_1 is difficult to accomplish. Although we are unable to estimate the accuracy of the measurements, we believe

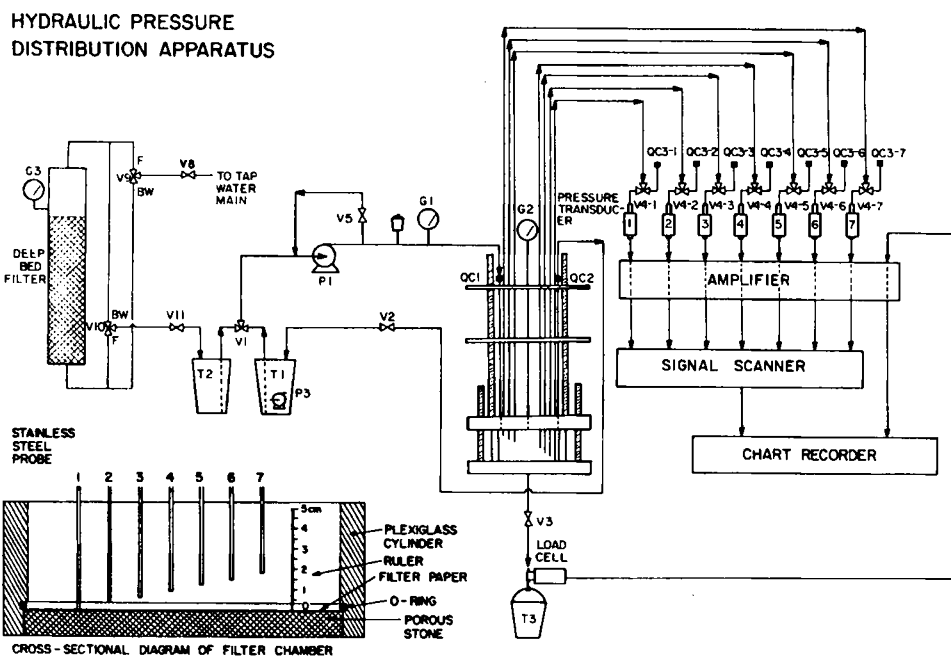

Fig. 3. Flow diagram of the equipment for measuring hydraulic pressure distribution.

Fig. 3. Flow diagram of the equipment for measuring hydraulic pressure distribution.

that the procedure leads to an improved understanding of filtration. The probes were located in a vertical position (1) in order to be parallel to flow paths and (2) to permit change of depth.

EXPERIMENTAL RESULTS

Data Acquired

In most constant pressure filtrations reported in the literature, volume vs. time and the liquid content of the final cake are the data usually obtained. In addition, we measured cake thickness and hydraulic pressures (Fig. 4) as functions of time. Thickness

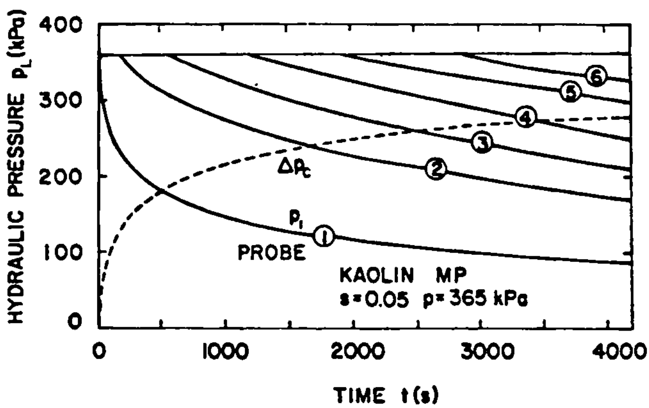

Fig. 4. Hydraulic pressure vs. time for 5% kaolin MP at 365 kPa.

vs time permits calculation of the average porosity. Knowledge of the pressure profile allows R_m to be separated from R_c.

Pressure Drops across Cake and Medium

At the beginning of filtration, all of the applied filtration pressure p was used to overcome the medium resistance. As filtration proceeded, the cake thickness increased, and the pressure drop across the cake rose gradually. The pressure drop across the cake Δp_c is calculated by $\Delta p_c = p - p_1$ where the hydraulic pressure at the medium-cake interface p_1 was measured during the experiment. Figure 4 shows the variations of p_1 and Δp_c with time. The quantity p_1 dropped relatively fast at the beginning of filtration. However, the initial value of R_m/α_{av} was approximately 7 (units of kg/m^2) whereas a more typical value might be 0.5. Because of the large value of R_m, the pressure drop across the medium decreased slowly; and Δp_c never exceeded 75% of the applied pressure.

Increase in Medium Resistance

The medium resistance was calculated by means of $R_m = p_1/\mu q_1$. Figure 5 shows R_m became larger as t and w_c increased. Medium resistance was doubled in about 1500 s. Beyond 1500 s the rate of increase dropped. The medium resistance ranged from 5.20 to 11.38 $(10^{11})\ m^{-1}$ and the average specific flow resistance α_{av} changed from 0.781 and $1.17(10^{11})$ m/kg over the period of 50 min.

The experimental results R_m vs. w_c as shown in Fig. 5 can be adequately fitted by Eq. (5) in the form

$$R_m = 10^{11}(11 - 5.7e^{-0.01w_c^2}) \tag{7}$$

Calculated values according to Eq. (7) are also shown on Fig. 5.

The increase of R_m was indicative of medium clogging phenomenon. Fine particles migrated into the interstices of the filter medium

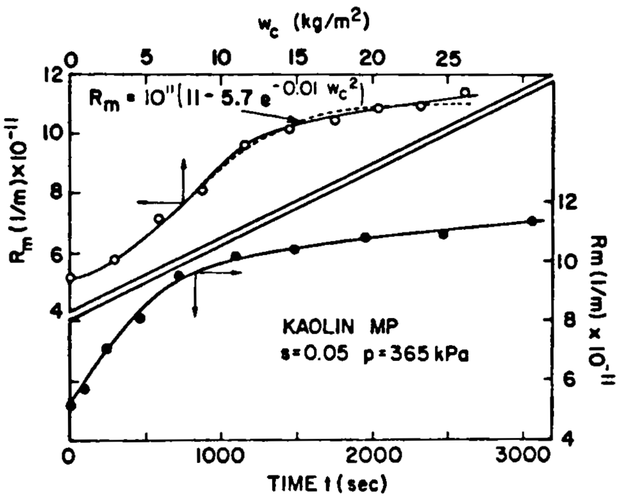

Fig. 5. Medium resistance vs. time and dry solid mass per unit area for 5% kaolin MP at 365 kPa.

and resulted in an increase of medium resistance. Measurement of turbidity supported this explanation. The slurry was composed of kaolin MP and prefiltered tap water with an average turbidity of 0.35 NTU (Nephelometic Turbitity Units, 1 NTU = 0.25 ppm). However, turbidity of the filtrate was found to be as high as 19 NTU. This was a strong evidence that fine particles passed through and were deposited in the pores of the filter medium.

Resistance Plot

Plots of $p/\mu q$ and $pt/\mu v$ vs. w_c are shown in Fig. 6. The lines have been drawn so that the slope of $pt/\mu v$ vs. w_c line is exactly half of the slope of $p/\mu q$ line. Figure 6 is similar to Fig. 1 in which the conventional constant pressure filtration theory was illustrated. According to Eqs. (1) and (2), plots of $p/\mu q$ and $pt/\mu v$ vs w_c are straight lines when R_m and α_{av} are constant.

As experimental results fit the straight lines perfectly, we may draw the wrong conclusion that all the assumptions involved

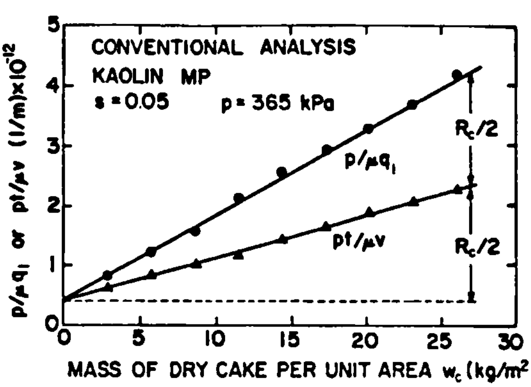

Fig. 6. $p/\mu q$ and $pt/\mu v$ vs. w_c for 5% kaolin MP at 365 kPa.

in conventional theory are valid. In normal practice of the past a constant value of $\alpha_{av} = 1.38(10^{11})$ m/kg at a pressure of 365 kPa would have been reported from the slope of the resistance plot. This value is about 19% too high as compared to $\alpha_{av} = 1.17(10^{11})$ m/kg calculated at a Δp_c of 266 kPa and time of 3050 seconds. On the other hand, if we take the intercept of $4.50(10^{11})$ m^{-1} as R_m, the constant value is about 13% to 60% lower than the actual medium resistance which ranges from 5.20 to $11.38(10^{11})$ m^{-1}.

If R_m were constant, the resistance plot would have a concave shape initially with an increasing slope as time proceeds as shown in Fig. 2. However, this curvature can be offset by the clogging effect and a straight line results. This shows the danger involved in using the method of conventional data analysis. It is only through measurement of Δp_c and the pressure drop across the medium that erroneous conclusions can be avoided.

Effect of Pressure

Figure 7 depicts effect of filtration pressure on the change of medium resistance with 5% kaolin MP. At 665 kPa, R_m changed from 7.0 to $8.7(10^{11})$ m^{-1} in 3000 s; while at 365 kPa, R_m changed from 5.2 to $11.3(10^{11})$ m^{-1} in the same period of time. Increase in medium resistance was more significant under lower filtration pressure.

At a higher pressure, more fine particles are forced into the interstices of the filter medium at the start of filtration. Therefore, the "clean" medium resistance at t = 0 was higher for higher pressures. However, as the cakes formed at high pressure were more

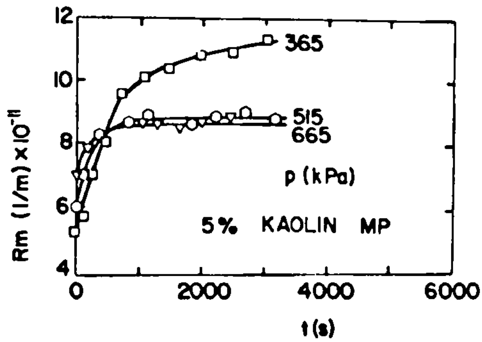

Fig. 7. Medium resistance vs. time for 5% kaolin MP at 365, 515, 665 kPa.

resistant and had smaller pores, fewer particles were able to migrate through the cake into the medium than at lower pressure. Turbidities for the filtrate collected at 365 and 665 kPa were 19 and 13 NTU which supported the above explanation.

Effect of Slurry Concentration

As shown in Fig. 8, the medium resistance for filtering the kaoline MP slurry with s = 0.15 was much higher than filtering the other two slurries with s = 0.10 and 0.05. Because of cake formed by the slurry with s = 0.15 was more open, there were more opportunity for fine particles to migrate. Therefore, more serious medium clogging was encountered.

Effect of Compressibility

The behavior of attapulgite, a very compressible material, was also investigated. Highly compressible materials generally have open structures with porosities in the 0.90 range. They frequently exhibit

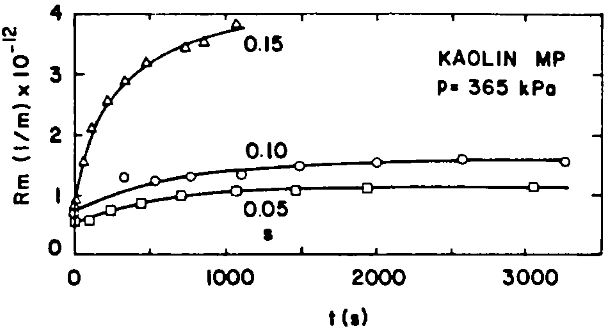

Fig. 8. Medium resistance vs. time for 5, 10, and 15% kaolin MP at 365 kPa.

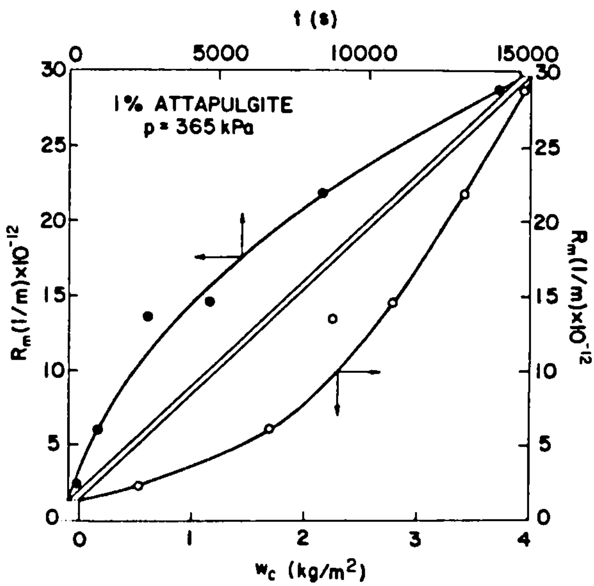

Fig. 9. Medium resistance vs. time and dry solid mass per unit area for 1% attapulgite at 365 kPa.

substantial surface activity and may form loose combinations with water. Painchaud (1978) showed that increasing pressure on attapulgite in a compression-permeability cell resulted in a steep rise in medium resistance. The cake was assumed to have deformed under pressure and passed into the interstices of the medium.

At a filtration pressure of 365 kPa, the pressure drop across the cake was only 155 kPa after seven hours. The filter medium consumed a large fraction of the pressure drop. The medium resistance changed from 1.5 to $29(10^{12})$ m^{-1} in about four hours as shown in Fig. 9. Migration of attapulgite particles into the medium was more significant as compared to kaolin MP and caused a twenty-fold increase in medium resistance in four hours.

NOTATIONS

c Concentration, mass of dry cake per unit volume of filtrate, kg/m^3

j Constant parameter in the Eq. (5), m^4/kg^2

p Applied filtration pressure, Pa

p_L Hydraulic pressure at distance x from medium, Pa

p_1 Hydraulic pressure at interface of medium and cake, Pa

Δp_c Pressure drop across the cake, Pa

q Superficial velocity of liquid, m/s

q_{av} Average superficial velocity defined as v/t, m/s

R Total resistance in filtration, including cake resistance R_c and medium resistance R_m, 1/m

R_c Cake resistance, 1/m

R_m Medium Resistance, 1/m

R_{mf} False medium resistance, 1/m

R_{mo} Resistance of clean medium, 1/m

$R_{m\infty}$ Ultimate medium resistance, 1/m

s Mass fraction of solids in the slurry, (-)

t Time, s

v Filtrate volume per unit filtration area, m^3/m^2

w_c Mass of dry solids per unit area, kg/m^2

Greek Letters

α_{av} Average specific filtration resistance, m/kg

α_o Initial specific filtration resistance at $p_s = 0$, m/kg

μ Viscosity of liquid, kg/m•s

ACKNOWLEDGEMENT

The authors wish to express their appreciation to the Office of Basic Energy Sciences of the U.S. Department of Energy for a Grant DE-AS05-81ER-10946 which has enabled them to investigate fundamentals of solid-liquid separation. Special thanks go to Roy Priest, master machinist, and John Lehman, electronics technician, who were instrumental to construction of the apparatus. Alfred Ling assisted in taking data.

REFERENCES

1. F. R. Masterton, Pressure Profiles through Filter Cakes, Master Thesis, Univ. of Houston, Houston, TX (1980).

2. F. F. Notebaert, D. A. Wilms, and A. A. van Haute, A New Deduction with a Larger Application of the Specific Resistance to Filtration of Sludges, Water Res., 9, 667-673 (1975).

3. S. Okamura, and M. Shirato, Liquid Pressure Distribution within Cakes in the Constant Pressure Filtration, Kagaku Kogaku (Japan) 19, 104-110 (1955).

4. B. P. Painchaud, An Experimental Study of Filtration Properties of Soils, An Unpublished Internal Report, Univ. of Houston, Houston, TX (1978).

5. M. Shirato, T. Murase, and N. Hayashi, Expression Theory and Its Practical Utilization, Proceedings of World Filtration Congress III Sponsored by the Filtration Society (Downingtown, PA), p. 280-287, Uplands Press Ltd., Croydon, England (Sept., 1982).

6. F. M. Tiller, R. Chow, W. H. Weber, and O. Davies, Clogging Phenomena in the Filtration of Liquedfied Coal, Chem. Eng. Prog., 77, 61-68 (Dec., 1981).

7. F. M. Tiller, and J. R. Crump, Solid-Liquid Separation: An Overview Chem. Engr. Prog., 73, 65-75 (Oct. 1977).

8. F. M. Tiller, J. R. Crump, and F. Ville, A Revised Approach to the theory of Cake Filtration in Fine Particles Processing, Proceedings of the International Symposium on Fine Particles Processing (Las Vegas, NV, 1980), v. 2, 1549, Amer. Inst. Mining, Meta., and Petro. Engrs. Inc., New York, NY (1980).

9. F. M. Tiller and L. L. Horng, Hydraulic Deliquoring of Compressible Cakes, Part 1: Reverse Flow in Filter Presses, AIChE J., 29, 297-304 (1983).

10. F. M. Tiller and W. Leu, Basic Data Fitting in Filtration, J. Chinese Inst. Chem. Engr., 11, 61-70 (1980).

11. F. M. Tiller and W. Leu, Solid-Liquid Separation for Liquefied Coal Industries, Final Report for EPRI Research Project RP-1411-1 (Sept. 1978-Dec 1982), Univ. of Houston, Houston, TX (Submitted in Dec. 1982, in press).

12. M. S. Willis, M. Shen, and K. J. Gray, Investigation of Fundamental Assumptions Relating Compression-Permeability Data with Filtration, J. Chem. Eng. (Canada), 52, 331-336 (1974).