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Pressure filtration of Australian bagasse pulp

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Abstract

A one dimensional pressure filtration model that can be used to predict the behaviour of bagasse pulp has been developed and verified in this study. The filtration model uses steady state compressibility parameters determined experimentally by uniaxial loading. The compressibility parameters M and N for depithed bagasse pulp were determined to be in the ranges 3000 kPa to 8000 kPa and 2.5 to 3.0 units respectively. The model also incorporates experimentally determined steady state permeability data from separate experiments in order to predict the pulp concentration and fibre pressure throughout a pulp mat during dynamic filtration. Under steady-state conditions, a variable Kozeny factor required different values for the permeability parameters when compared to a constant Kozeny factor. The specific surface area was 25-30% lower and the swelling factor was 20-25% higher when a variable Kozeny factor was used. Excellent agreement between experimental data and the dynamic filtration model was achieved when a variable Kozeny factor was used.

Introduction

The Australian sugar industry is principally a single commodity producer and has in recent times experienced financial difficulty because of the low world sugar price, recent drought and a rising Australian dollar (Hobson et al. 2006). To increase diversification, the industry is investigating new products that can be made from the fibrous sugarcane residue, bagasse.

Eucalypt pulp is often preferred to bagasse pulp because of the widely held view that it has better filtration properties. Industry experts note that using bagasse pulp reduces paper machine production rates by 25-30%. Bagasse pulp quality is detrimentally affected by the presence of fine and short 'pith' fibres (length < 0.4 mm) (Giertz and Varma 1979; Paul and Kasi Viswanathan 1998). These fibres are liberated by the sugar extraction process and constitute 30-40% of the bagasse. In countries where bagasse pulp is used for paper making, depithing of the bagasse is essential to make pulp of acceptable quality (Atchison 1962). To this end, it is necessary to develop a filtration model specifically for bagasse pulp.

Two parameters affect the filtration properties of fibre beds; compressibility and permeability. Both of these properties vary over time so a model that combines the dynamic compressibility and permeability effects model is required (the one-dimensional pressure filtration model is referred herein as 'the dynamic model') to further understand the behaviour of bagasse pulp.

Compressibility also plays an important role. To the authors knowledge, there is no previous work focussed on quantifying the *steady state* compressibility of bagasse pulp, although there is substantial data for wood pulp (Ingmanson 1952; Ingmanson 1953; Ingmanson et al. 1959; Gren 1972). This study investigates whether there is a difference in the compressibility parameters between Australian bagasse pulp and wood pulp.

In this study, the steady-state compressibility behaviour of pulp was measured using a simple compressibility cell. The pulp mat was initially compressed over a very long time-period to measure the quasi steady state compressibility parameters.

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Permeability is the other important parameter considered in the dynamic model. The steady-state permeability model used in this study is the Kozeny-Carman model. The effect of a variable or constant Kozeny factor, k, will also be investigated in this study.

Once the steady state compressibility and permeability parameters are determined, the dynamic compression behaviour can be predicted. There is no known literature published that verifies a dynamic model for bagasse pulp with its very high loading of short fibres. This study follows the analysis of Landman and co-workers (Landman et al. 1991).

The dynamic behaviour of the pulp is then measured for comparison with the data obtained from the dynamic model.

This study was conducted in four phases

1. Compression tests of depithed bagasse pulp to calculate the steady state compressibility constants, M and N (to be defined later).
2. Steady-state permeability tests of depithed bagasse pulp to calculate the permeability constants (the specific surface area, S_v and swelling factor, α), reported in a previous paper (Rainey et al. 2009)
3. Calculation of the fibre pressure at the top surface of the pulp mat at higher compression rates using the dynamic model. The model uses the physical constants obtained in phases 1 and 2.
4. Dynamic compression testing of depithed bagasse pulp for comparison with the predictions of the dynamic model in phase 3.

The steady state and dynamic compressibility behaviour of several other bagasse pulps were also measured including unfractionated 'whole' Australian bagasse pulp and depithed bagasse pulp from Ledesma Sugar, Pulp and Paper Mill in Argentina.

For comparative purposes, the properties of kraft eucalypt (*Eucalyptus globulus)* pulp, a hardwood pulp with short fibres around 0.8 mm in length, are determined as the benchmark for this study. Finally, the permeability of a kraft pine *(Pinus radiata)* pulp, a long fibre pulp typically 3 mm in length, was measured.

This paper proceeds by presenting the theory for steady state compressibility and permeability behaviour of pulp pads as well as the dynamic model which combines these concepts. The experimental setup and methodology are explained and the results of the steady state compression experiments are compared to each other. Finally, the results of the dynamic compression are compared with the model predictions.

Compressibility and permeability theory for pulp pads

Steady-state compressibility theory

In this study the compressibility equipment was set up so that the pulp could be loaded into a cell and compressed with a permeable top platen which expresses water. This is shown diagrammatically in Figure 1, indicating the pressure on the solid phase, P_s, at the platen. The distance, x, is defined from the top platen.

The hydraulic pressure at the top surface of the pulp mat is negligible so the force on the fibres equals the force exerted on the platen.

The steady-state compression model used in this study is a simple power law model, $P_s = M c^N$, where c is the pulp concentration and M and N are experimental constants. This model is well established and has been used for a long time owing to its simplicity and accuracy (e.g. Ingmanson 1952; Ingmanson et al. 1959; Gren 1972).

In this study quasi steady state behaviour is reached by compressing the pulp mat over a very long time period. During steady state compression, the permeability effects are insignificant. The hydraulic load is negligible compared to the mechanical load, and so the concentration distribution is uniform throughout the bed. The graph of log(P_s) against log(c) is approximately linear. Values of M and N are obtained from the slope and intercept of the linear approximation.

The pulp concentration can be related to the solidity (that is, the volume solids fraction), which is used in the dynamic model, by $\Phi = \alpha c$ where α is the swelling factor (a constant). The swelling factors for the pulps evaluated in this study are presented in a previous study (Rainey et al. 2009) and values are in the range of 3.2-3.8 cm^3/g.

For this geometry,

$$P_s = m\,\Phi^n \tag{1}$$

where m and n are experimental constants calculated from M and N.

Steady-state permeability theory

The theory of laminar flow through a homogeneous rigid porous media is based on Darcy's law:

$$\frac{Q}{A} = \frac{K\Delta P}{\mu \Delta L} \tag{2}$$

where Q is the volumetric flow rate through a bed of porous material with cross-section area A, ΔP is the frictional pressure drop across the length (ΔL) of the porous media bed, μ is the fluid viscosity which is customarily assumed to be constant and K is the specific hydrodynamic permeability of the porous material.

The permeability of a pulp mat, K, is determined experimentally from Darcy's Law. K is affected by the solidity (volume solid fraction) of the pulp and also the structural arrangement of the mat. These factors are accounted for in the Kozeny-Carman model. The relationship is:

$$K(\phi) = \frac{1}{kS_v^2}\frac{(1-\phi)^3}{\phi^2} = \frac{1}{kS_v^2}\frac{(1-\alpha c)^3}{\alpha^2 c^2} \tag{3}$$

where S_v is the specific surface area, and k is the Kozeny factor. The values for S_v and α which give the best fit for the permeability data can be easily calculated. The inclusion of α allows the permeability to be calculated as a function of concentration directly. This was first used in Robertson and Mason 1939.

The Kozeny factor, k, is often assumed to be constant, 5.55, which is based on work by Fowler and Hertel (Fowler and Hertel 1940). However, Davies (Davies 1952) proposed that k has the following dependence on solidity for fibrous materials,

$$k = \frac{3.5(1-\phi)^3}{\sqrt{\phi}}\left[1 + 57\phi^3\right] \tag{4}$$

This relation was experimentally verified by Ingmanson and co-workers (Ingmanson et al. 1959).

For modelling purposes, the values of S_v and α in equation 3 need to be optimised to make the correlation fit the data. The optimum values of S_v and α are dependant on whether the parameter k is assumed to be constant or whether it varies with concentration. Bagasse pulp requires a lower value for S_v and a higher value for α if a variable k is used rather than a constant k (Rainey et al. 2009). The suitability of a constant k (i.e. k=5.55) versus a variable k (equation 4) is one of the parameters investigated in this study. As will be shown, using a constant or variable k makes no difference in the accuracy of equation 3 under the conditions for steady-state permeability experiments, but it can make a significant difference if it is incorporated into a dynamic filtration correlation.

The dynamic filtration model ('the dynamic model')

Landman and co-workers present analyses of both constant rate and constant pressure one dimensional filtrations using both initially networked and unnetworked suspensions. The principles of the models presented have been applied and further developed by many research organisations both within paper research and for other materials (e.g. Rainey 2009; Martinez et al. 2001; Holmqvist and Dahlkild 2008; Raha 2007). This study follows their analysis of a one dimensional constant rate filtration using an initially networked suspension. Using the definitions in Figure 1, the dimensional form of the governing equation is

$$\frac{d\phi}{dt} = \frac{d}{dx}\left[D(\phi)\frac{d\phi}{dx}\right] - \frac{dh}{dt}\frac{d\phi}{dx} \tag{5}$$

Where

$$D(\phi) = \frac{\phi(1-\phi)K(\phi)mn\phi^{n-1}}{\mu} \tag{6}$$

The dynamic model uses several parameters that can be calculated from steady-state experiments. $K(\Phi)$ is the permeability as predicted by the Kozeny Carman model (equation 3) under steady-state conditions. m and n are compressibility constants determined under steady-state conditions. In an experiment with a platen moving at constant rate, the velocity of the platen, u, is constant and equals dh/dt. This governing equation is subjected to the initial condition $\Phi(x,0) = \Phi_0$ as the solidity is uniform throughout the cell, as well as the following boundary conditions:

Boundary condition at the top platen

$$x = 0,\ u = -\frac{dh}{dt}$$

$$\frac{d\phi}{dx} = 0 \tag{7}$$

Boundary condition at the base (Rainey 2009)

$$x = h,\ u = 0$$

$$\frac{d\phi}{dx} = \frac{dh}{dt}\frac{\mu}{K(\phi)(1-\phi)mn\phi^{n-1}} \tag{8}$$

These equations are non-dimensionalised before being solved. The solution of these equations provides values for Φ over the ranges of x and t.

For comparative purposes, the model predictions for Φ are determined at x=0 for all t and consequently P_s is calculated (equation 1). In the experimental setup, the Instron measures the load on the top platen which is converted to pressure. Validation of the model occurs if the experimental pressure data matches the model predictions for solids pressure at the surface of the pulp mat.

Both a constant k (i.e. k=5.55), and variable k (equation 4) with the relevant values of S_v and α, are investigated for use in the dynamic model.

The dynamic model assumes that 100% of the fibre is retained by the platen.

Experimental procedure

Bagasse pulp preparation

In industrial operations, bagasse is normally moist and wet-depithed prior to pulping in order to remove around 30-35% of the short fine pith fibre as these fibres reduce pulp mat permeability and hence paper production rate. The pretreatment procedure used in this study was intended to minimise degradation during long-term cold storage and also to achieve good permeability properties. Consequently, the total amount of pith removed (around 43%) was higher than normally used by industry.

The depithed bagasse pulp samples (80 g - 100 g) were produced in a 6×1.5 L cell digester at the Australian Pulp and Paper Institute (APPI, Melbourne). Fifty litres of soda anthraquinone (AQ) cooking liquor was recirculated through six cells containing the bagasse. The pulping conditions were: 0.4 M sodium hydroxide (approx. 13.8% Na_2O on oven dry fibre), 0.1% AQ, (on oven dry fibre) at 145°C for 30 min. The pulp kappa number was 20. After pulping, the samples were washed thoroughly to remove residual chemicals.

Quasi steady state compressibility testing

A simple compression cell was fabricated from stainless steel and mounted to an Instron 5500R capable of a maximum load of 100 kN although for this study the load applied did not exceed 5 kN. Photographs of the assembly is shown in Figure 2. The cell is 100 mm in height, the platen is 10 mm thick, resulting in a total possible working height of 90 mm. The platen is fitted with a shamband and Teflon ring to prevent water flowing around the platen, and the platen is drilled with thirty 6 mm holes for the water to evacuate (see Figure 2).

Pulp samples were disintegrated to 0.9% consistency. The barrel of the compressibility cell was removed from the base and suspended on a screen of 100 mesh. The disintegrated pulp was added to the barrel of the compressibility cell and the bulk of the water was allowed to drain through the mesh. Once the desired height of pulp in the barrel was reached, the barrel, the supporting screen and the loaded pulp could be transferred to the base and bolted in. The pulp mat remained saturated during the transfer; in practice, this was easy to achieve. The platen of the compressibility cell is then connected to the Instron, ready to commence the compression experiment (see Figure 2).

The amount of pulp fibre required to create a pulp pad to the top of the barrel depended on the amount of fine material in the sample but typically was 20 g to 30 g (dry basis). For most experiments, the initial pulp concentration was between 0.03 g/cm^3 and 0.045 g/cm^3. The pulp concentration was calculated from known quantity of pulp fibre and working volume of the barrel which was determined by the height of the platen at a given moment in time.

For all of the compressibility tests, the platen finished compressing the pulp mat at 15 mm above the base of the cell. The platen was lowered very slowly over 300 min at a constant rate of 0.25 mm/min (that is, 75 mm over 300 min). The wood pulp samples and the Argentinean bagasse pulp were compressed several times to obtain average values of M and N. The Instron load and time were logged. The load on the platen was recorded by the Instron and converted to pressure. The measured load was reduced by the frictional resistance between the Teflon seal and the barrel. This was typically 2.5 – 4.5 kPa which is measured by compressing the cell when loaded with water.

Steady-state permeability testing

The bagasse pulp samples were measured for their permeability properties, specifically S_v and α, as a function of Darcy's permeability constant K, using both a constant and variable k in a previous study (Rainey et al. 2009).

In the previous study, pulp permeability was measured in a simple experimental cell (i.e. the 'permeability cell') shown in Figure 3. The experimental cell was 41 mm in internal diameter and loaded with 30 g (dry basis) of pulp from a 0.9% consistency slurry. A clear Perspex tube was filled with pulp and attached to a constant head tank. Water ran from the head tank until steady state flow was achieved. The flow-rate was measured with a bucket and stopwatch. The pressure drop was measured by two manometers and the height of pulp in the cell was determined in order to calculate the pulp concentration. Darcy's permeability constant, K, was calculated using equation 2 from this information for the given pulp concentration in the cell.

The pulp concentration in the cell was varied by maintaining a pool of water above the pulp pad and applying compressed air, always ensuring the fibres remained saturated. The concentration was varied from its initial concentration, typically 0.06 g/cm^3, to its final concentration, typically around 0.15 g/cm^3. The final concentration was limited by the compressibility properties of the pulp.

According to equation (3), plotting pulp concentration, c, against $(Kc^2)^{1/3}$, provided a linear correlation, allowing the specific surface area, S_v, and the swelling factor, α, to be calculated. These values for S_v and α were then used in equation 3 and hence equation 5 to predict K for the given pulp concentration, c, at a particular point in time during dynamic pulp filtration.

Dynamic filtration modelling

The governing equation was non-dimensionalised, programmed in the language Fortran 77 and compiled. The resolution of the output was 100 increments in height, h, and time, t. The experimental compressibility constants M and N for each pulp sample were converted to m and n for use in the dynamic model (equation 5). Similarly, the experimentally determined permeability constants S_v and α were used in the dynamic model. Hence, the four physical constants from steady-state experiments, m, n, S_v and α are inputs for the program which runs the dynamic filtration model. Other inputs into the model include the initial pulp concentration and the platen speed. The program outputs the solidity throughout the height of the cell for many discreet time intervals. For comparison with the experimental data, the predicted solidity at the top platen is determined and converted to fibre pressure using equation 1. The dynamic model predictions using both a constant k (i.e. k=5.55) and a variable k (equation 4) can then be compared with experimental data obtained in the next phase.

Dynamic compressibility testing

In the final experimental phase, the compression speed was increased by 100 times in most instances to 25 mm/min (that is 75 mm over 3 min) and the load on the platen is recorded and converted to the average pressure over the platen.

For the dynamic compressibility testing, the compression cell was loaded to 75 mm in depth, leaving 15 mm clearance to the platen, and compressed to 15 mm. The lower initial height of the pad is required for the dynamic testing because the calculated values of the compressibility constants are valid over the limited range of pressures used in the quasi steady state testing.

Results

Results of quasi steady state compressibility testing

The pressure was plotted as a function of concentration on a log-log scale and the compressibility factor, N was determined from the slope of the linear approximation and the compressibility factor, M was determined as the exponent of the abscissa intercept (see Figure 4 for example). The linear approximation is suitable; hence the power law steady state compression model is suitable for bagasse pulp.

M was found to vary significantly between samples, and was typically in the range 3000 kPa to 8000 kPa however N was less volatile and was typically 2.5 to 3.0 units.

Table 1 is a summary of the compressibility constants M and N obtained from the quasi steady state compressibility experiments and used in the dynamic model. Australian bagasse pulps A-J are all depithed bagasse pulps with subtle differences in preparation conditions. The compressibility parameters for wood pulp determined by previous workers has been recalculated in terms of the definitions of M and N used in this study. The results for eucalypt and pine from this study are very similar to the findings by previous workers for wood pulp. Gren and Hedstrom (Gren and Hedstrom 1967) report N and M over the full range of kappa numbers for chemical pulps, from 2.22 for a fully bleached pulp to 2.37 for a 100 kappa pulp whilst Ingmanson reports N between 2.66 and 3.17. Gren and Hedstrom note that this is due to the different compression range used in their experiments.

Results of steady-state permeability testing

The optimised values for S_v and α for both a constant and variable Kozeny factor are reproduced from Rainey and co-workers (Rainey et al. 2009) in Table 2. The values for S_v and α in Table 2 are used in the dynamic model.

The S_v values for the depithed bagasse pulp pads were typically 1400 cm^{-1} to 2300 cm^{-1}, lower than for eucalypt pulp (2480 cm^{-1}) meaning they were more permeable (i.e. higher K). It was found that the bagasse pulp that was produced was more permeable than eucalypt pulp pads. Removing the pith was extremely beneficial for improving the permeability. S_v for the unfractionated material was very high (20200 cm^{-1}).

The values for α were similar for the depithed bagasse pulp as for eucalypt (around 3.2 cm^3/g to 3.9 cm^3/g). The unfractionated bagasse pulp was much lower, 1.11 cm^3/g. The unfractionated bagasse pulp contained a large amount of short round pith particles (derived mainly from parenchyma material in the plant) which have a lower propensity to swell than slender pulp fibres which are predominant in the depithed bagasse pulp samples (these fibres are derived from schlerenchyma material).

For the Australian bagasse pulps, when variable k is used in the calculation of S_v the value of S_v is about 400 cm^{-1} on average lower than when it is calculated with constant k. The variable k requires values of S_v and α that are 25%-30% lower in order to make the model (equation 3) fit the data. Table 2 shows that the α values obtained with variable k were 20%-25% higher than the values obtained with constant k. The estimate of S_v was accurate to +/-10% but the accuracy of the estimate for α was only accurate to +/-25%.

The values of S_v and α presented in Table 2 obtained using a constant and variable Kozeny factor were inserted back into the Kozeny-Carman model and compared with the original experimental data (shown in Figure 5 for three different types of bagasse pulp). The Kozeny-Carman model with either a constant or a variable k reasonably predicts the experimental permeability data over the concentration range used in the steady-state experiments, but it will be shown that they do not perform equally well in dynamic filtration conditions.

Extrapolating the permeability model slightly above the concentration range used in the permeability cell shows that the model predicts higher permeability with a variable Kozeny factor than with a constant factor (Rainey et al. 2009). This is important in a dynamic experiment when a large mechanical force is used to increase the pulp concentration beyond this range.

Results of the dynamic model

The output from the dynamic model provides the solidity as a function of position within the cell as well as time. An example of the output for Australian bagasse pulp is shown in Figure 6. The solidity is initially constant through the cell Figure 6a but during the initial phase of the experiment, the solidity increases more rapidly at the top platen than lower in the cell Figure 6b. The pulp pad is initially very loosely held together so when the platen initially moves, the pulp at the top of the pad is compressed but the pulp at the bottom of the pad is unaffected until later in the experiment when the stress is transmitted from the top of the pad to the bottom.

In order to verify the dynamic model, the fibre pressure P_s at the top platen was calculated from Φ at the top platen using equation 1 (that is, from data similar to that presented in Figure 6b). These results are presented in Figure 7.

Results of dynamic compressibility testing and comparison with predicted values

Figure 7 and Figure 8 shows the experimentally determined pressure at the top platen compared to P_s calculated from the dynamic model. It was found that for all pulp samples, the best agreement with experimental data occured when using a variable Kozeny factor (equation 4) rather than a constant Kozeny factor. The optimum values for S_v and α that were determined during the permeability experiments were for a concentration range up to a maximum of 0.15 g/cm^3 (dry basis). This maximum pressure was limited by the equipment and air pressure that was available. The final pulp concentration during the compression experiments was slightly higher (0.15 g/cm^3 to 0.25 g/cm^3) than during the permeability experiments. For the dynamic experiments, it was required to extrapolate the permeability model (equation 3) to these higher concentrations. Consequently the variable k performed better than a constant value for k.

The bagasse pulp samples and the pine pulp sample had very good agreement between the experimental data and the model predictions. The eucalypt pulp had fair agreement. The reason for the poorer performance in predicting the the behaviour of eucalypt pulp is not known.

Two samples had poor agreement between the dynamic model and experimental data; the pulp made from whole (i.e. unfractionated) bagasse. These pulp samples have the highest fine fibre content and deviation from the dynamic model is thought to be caused by incomplete retention of fine fibre by the platen.

Conclusions

The steady-state compressibility parameters, M and N, for depithed bagasse pulp pads were determined using a simple uniaxial compressibility cell. In the experiments the rate of compression was constant. M was determined to be 3000 kPa to 8000 kPa and N was determined to be 2.5 to 3.0 units.

The permeability parameters of bagasse pulp pads were determined in separate steady-state permeability experiments. The permeability parameters S_v and α used in equation 3 depend on whether the value for k is assumed to be constant or whether it varies with concentration according to equation 4. If a variable k is used, the value of S_v is 25%-3% lower and the value of α is 20%-25% higher.

The dynamic filtration model incorporated the steady-state compressibility and permeability parameters, M, N, S_v and α. The dynamic filtration model provided excellent prediction of the fibre pressure of a compressed pulp mat made from depithed bagasse pulp at high compression rates where the dynamic effects were significant. It is particularly accurate for a depithed bagasse pulp at high compression rates. It was less accurate for a pulp pads made from unfractionated bagasse pulp or eucalypt pulp.

The dynamic model gave excellent predictions when a variable Kozeny factor was used because the permeability model (equation 3) could be extrapolated beyond the pulp concentration range used in the steady-state permeability experiments. The optimised specific surface area was 25%-30% lower using a variable Kozeny factor, whilst the swelling factor was 20%-25% higher.

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Nomenclature

A is the cross sectional area of a porous bed for use with Darcy's Law, cm^2
c is pulp concentration, g/cm^3
h is the height of the pulp mat in the compressibility cell, cm
K is Darcy's permeability constant, cm^2
k is the Kozeny factor, -
ΔL is the height of a bed of porous material for use with Darcy's Law, cm
M is a compressibility constant, kPa, used in the expression $P_s=Mc^N$
m is a compressibility constant, kPa, used in the expression $P_s=m\,\Phi^n$
N is a compressibility constant, -, used in the expression $P_s=Mc^N$
n is a compressibility constant, -, used in the expression $P_s=m\,\Phi^n$

ΔP is the pressure drop across a bed of porous material for use with Darcy's Law, mPa
Q is the flowrate through a porous material for use with Darcy's Law, cm^3/s
S_v is the specific surface area of pulp fibre (cm^2/cm^3)
t is time, min
x is the distance from the top platen, cm

Greek letters
α is the pulp swelling factor, cm^3/g
μ is the liquid viscosity, mPa.s
Φ is the solidity (i.e. volume solids fraction), -

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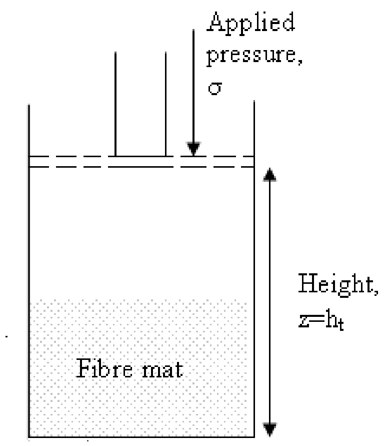
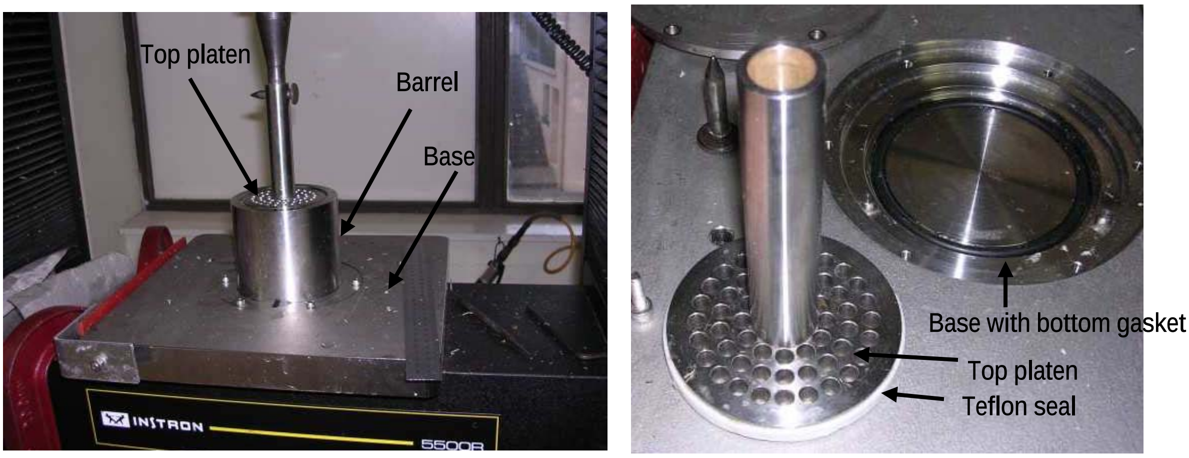


Figure 1 **Sketch of the compressibility cell**



(a) (b)

Figure 2 **Photographs of (a) the loaded compressibility cell with the barrel fixed onto the base and (b) the top platen and the base of the cell when the cell is dismantled**

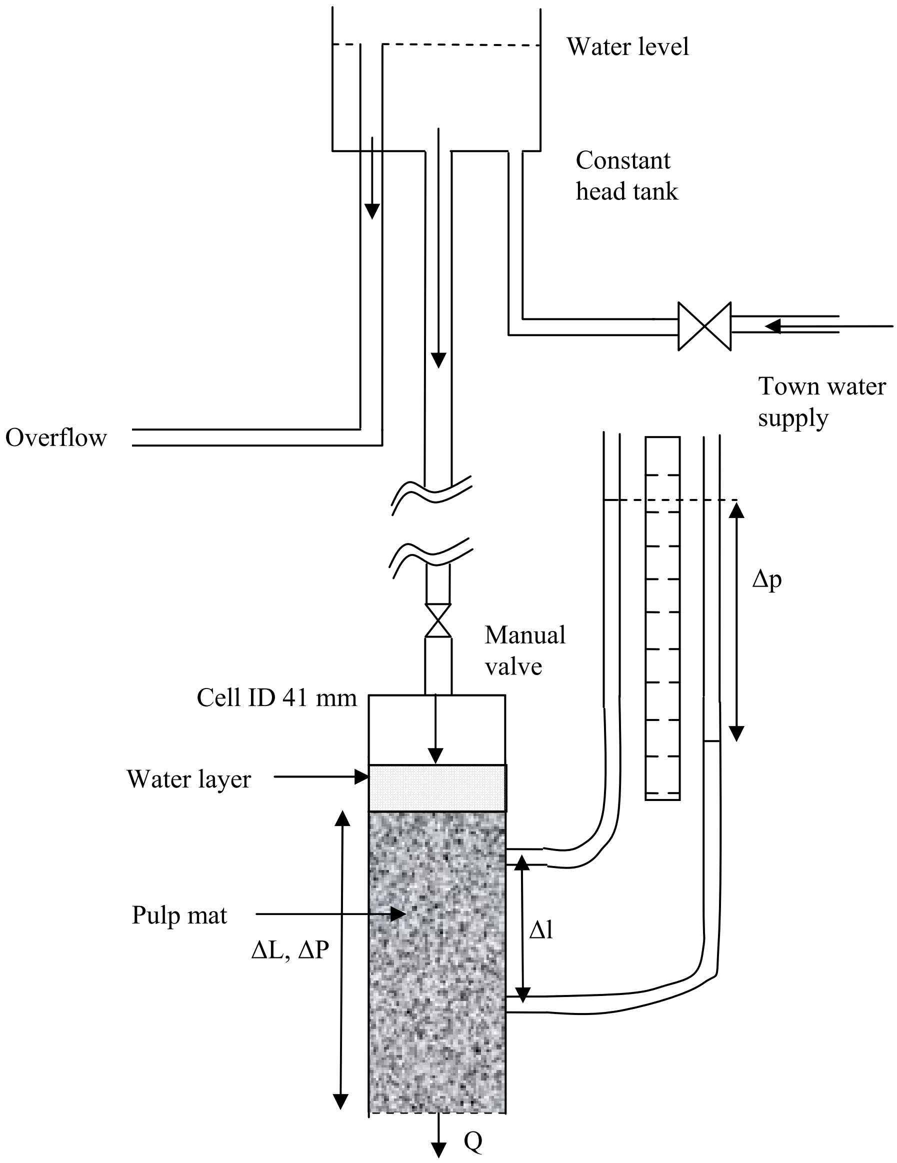


Figure 3 Schematic diagram of the apparatus used for steady-state permeability measurements (Rainey et al. 2009).

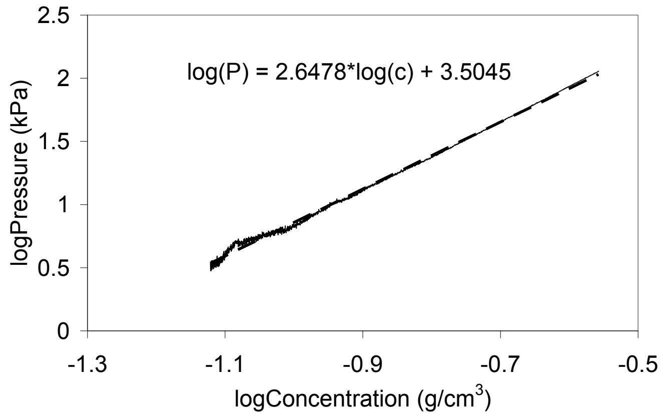


Figure 4 **Plot of the log of platen pressure against the log of pulp concentration for a sample of bagasse pulp (experimental data is shown as the thin solid line and the linear approximation is shown as the thick dashed line)**

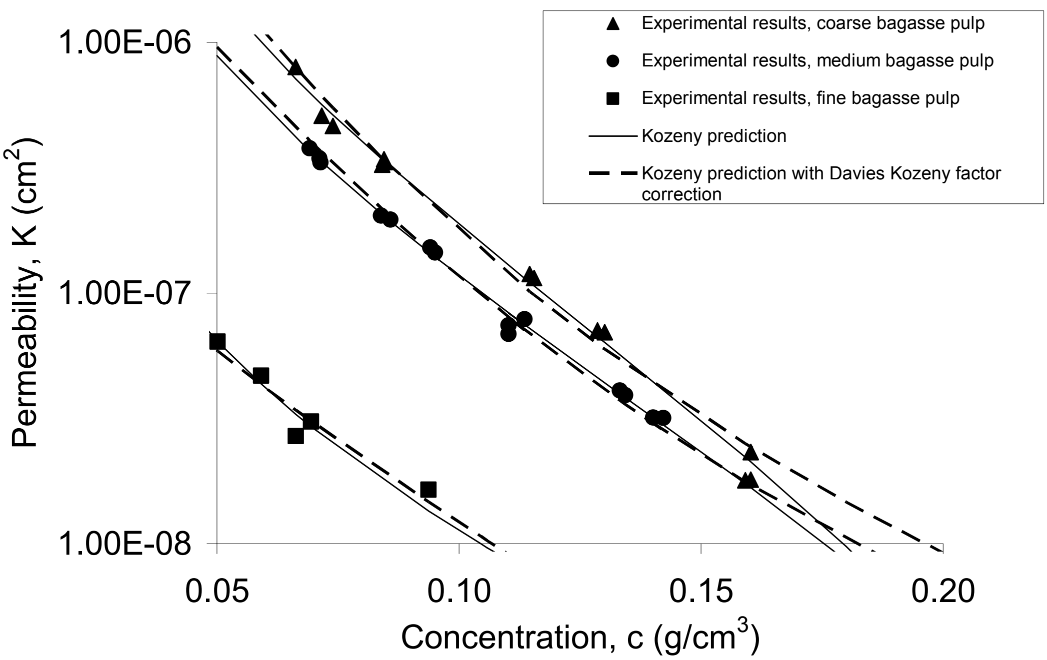


Figure 5 **Comparison of the Kozeny-Carman model with experiment data with both a constant and variable Kozeny factor (Rainey et al. 2009).**

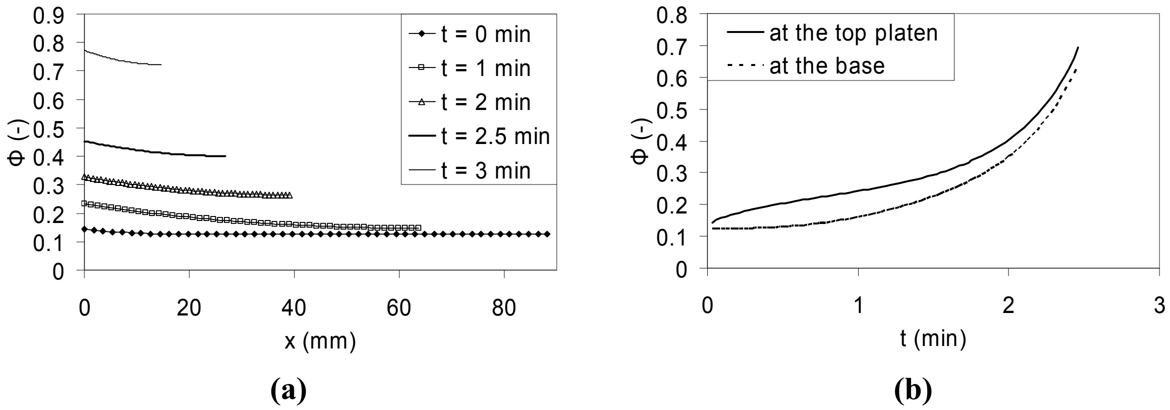


Figure 6 **Output from the dynamic model for Sample A: (a) graph of Φ as a function of depth below the platen; (b) graph of Φ as a function of time**

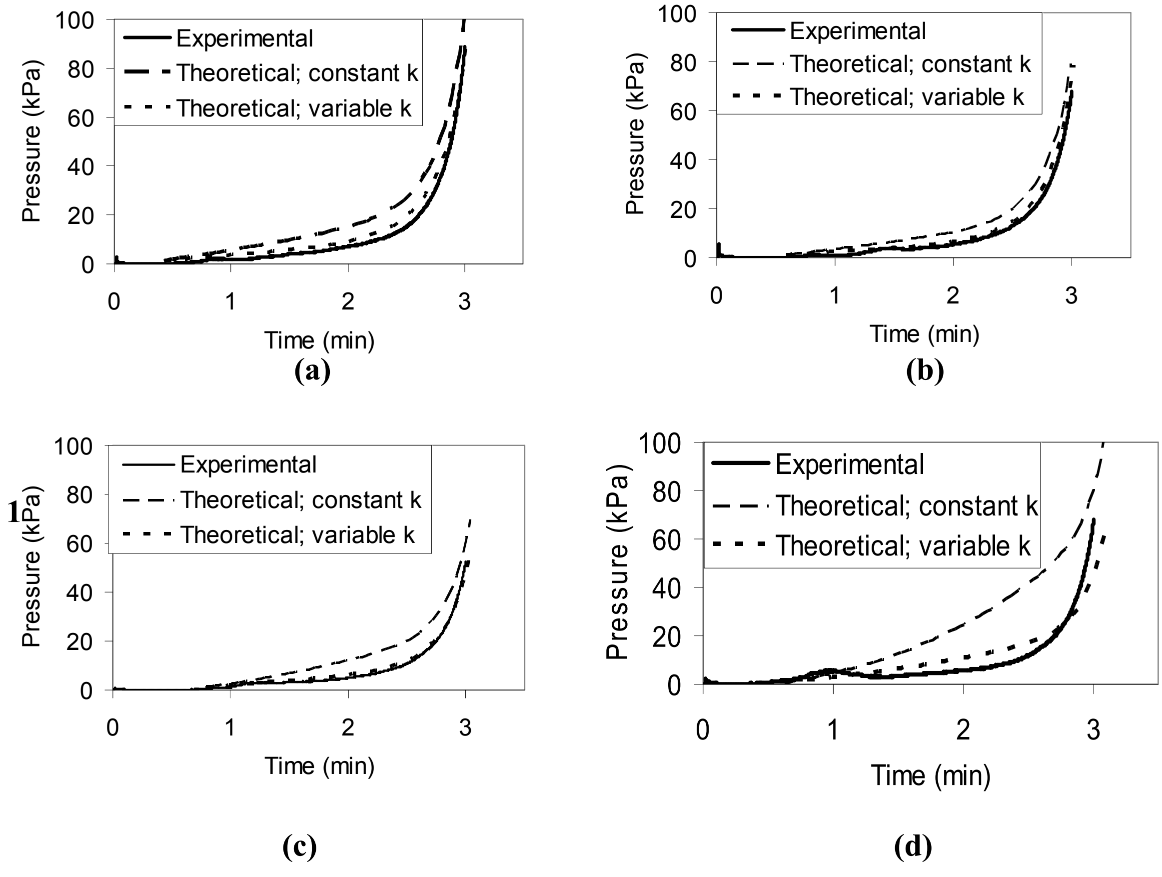
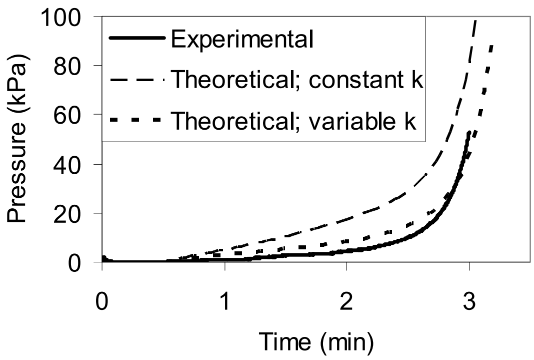
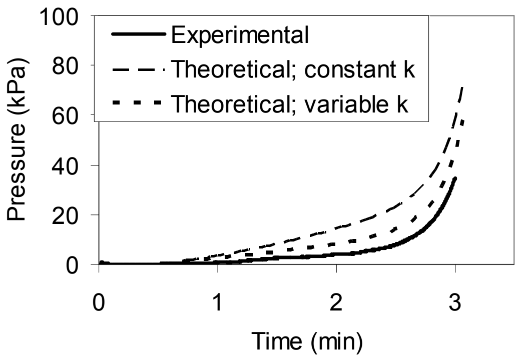


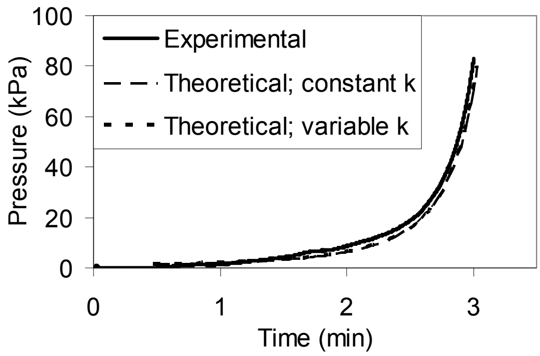
Figure 7 **Comparison of the dynamic model with experimental data for bagasse pulp (constant and variable k) (a) Sample D; (b) Sample A; (c) Sample F; (d) Sample J. Compression rate 100 mm/min.**



(a)



(b)



(c)

Figure 8 **Comparison of the dynamic model with experimental data for (a) Argentinean bagasse pulp, (b) eucalypt pulp and (c) pine pulp (constant and variable k). Compression rate 100 mm/min.**

Table 1 **Table of values for the compressibility factors N and M found in this study and by previous workers**

This study		
Sample number	**N**	**M (kPa)**
Aust. bagasse pulp A	2.83	7645
Aust. bagasse pulp B	2.60	3317
Aust. bagasse pulp C	2.94	8041
Aust. bagasse pulp D	2.66	4985
Aust. bagasse pulp E	2.68	3962
Aust. bagasse pulp F	2.72	6090
Aust. bagasse pulp G	2.61	3727
Aust. bagasse pulp H	2.56	3784
Aust. bagasse pulp I	2.72	4490
Aust. bagasse pulp J	2.65	3192
Average	*2.70*	*4920*
Whole bagasse pulp	2.74	4960
Argentinean bagasse pulp	2.82	8445
Eucalypt pulp	2.43	4774
Pine pulp	2.47	6009

Previous studies		
Sample description	**N**	**M (kPa)**
Unclassified wood pulp at moderate levels of compression (Gren and Hedstrom 1967)	2.22-2.37	Not provided
Wood pulp (Ingmanson et al. 1959)	2.66	1448
Beaten wood pulp (Ingmanson 1952; Ingmanson 1953)	3.12	2952
Beaten wood pulp (Ingmanson 1952; Ingmanson 1953)	3.14	3164
Unbeaten wood pulp (Ingmanson 1952; Ingmanson 1953)	3.17	3480
Unbeaten wood pulp (Ingmanson 1952; Ingmanson 1953)	3.14	3188

Table 2 **Permeability parameters obtained from the Kozeny-Carman model with both a constant and variable Kozeny factor (Rainey et al,. 2009)**

Sample name	Specific surface area S_v (cm^{-1}) constant k factor	Specific surface area S_v (cm^{-1}), variable k factor	Swelling factor α (cm^3/g), constant k factor	Swelling factor α (cm^3/g), variable k factor
Aust. bagasse pulp A	1420	1270	3.27	3.49
Aust. bagasse pulp B	1570	1500	3.84	3.94
Aust. bagasse pulp C	1540	1390	3.44	3.67
Aust. bagasse pulp D	1520	1370	3.52	3.75
Aust. bagasse pulp E	1400	1200	3.61	3.93
Aust. bagasse pulp F	1820	1660	3.33	3.52
Aust. bagasse pulp G	1830	1730	3.38	3.50
Aust. bagasse pulp H	2260	2080	3.10	3.25
Aust. bagasse pulp I	2760	2510	3.00	3.17
Aust. bagasse pulp J	2170	2090	3.20	3.27
Whole bagasse pulp	20200	5760	1.11	2.47
Bagasse pulp from Argentina	2100	2010	3.58	3.67
Eucalypt pulp	2480	2360	3.38	3.51
Pine pulp	327	320	7.17	7.60