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Determination of the permeability parameters of bagasse pulp from two different sugar extraction methods

T. J. Rainey, W.O.S. Doherty, R.J. Brown, N.A. Kelson
Queensland University of Technology

D.M. Martinez
University of British Columbia

ABSTRACT

The permeability, the specific surface area and the swelling factor have been determined for Australian bagasse pulp derived from bagasse from two different sugar extraction processes. The sugar extraction process was not found to affect the permeability of the pulp. The results for bagasse pulp are compared to those of eucalypt pulp, which is widely used in Australia for paper manufacture. The fibre length distribution showed a high fraction of small fibres in all of the bagasse pulp samples. Surprisingly, the permeability properties of the bagasse pulp samples were better than that that of eucalypt. It is presumed that this is due to the relatively large fraction of longer fibres in the bagasse pulp compared to the eucalypt pulp.

INTRODUCTION

The Australian sugar industry is a single commodity producer and has recently experienced financial difficulty because of the low world sugar price, poor seasons and a strengthening Australian currency. To increase diversification, the industry is investigating new products that can be made from the fibrous sugarcane residue, bagasse. Bagasse has the potential to partly replace eucalypt which is the hardwood of choice for the production of paper in Australia.

Despite the large quantity of sugar cane grown in Australia, no bagasse is pulped in the country. The main reason is that bagasse pulp has inferior permeability and strength properties compared to plantation eucalypt. This experimental study investigates the permeability properties of Australian bagasse pulp.

Technical Limitations of Bagasse Pulp Preventing its Uptake in Australia

Australian paper manufacturers prefer eucalypt pulp to bagasse pulp because of its better permeability and strength properties. For bagasse pulp, these properties are detrimentally affected by the presence of fine and short "pith" fibres (which are shorter than 0.4 mm). These fibres are liberated by the sugar extraction process and constitute 30-40% of the bagasse (e.g. see [1, 2]).

It is widely held that depithing is essential to make pulp of good quality [e.g. 3]. Considering the wide acceptance by bagasse pulp industry experts that using bagasse pulp reduces paper machine production rates by 25-30% [4, 5], it is interesting to note that there is virtually no published literature available that quantifies the effect of using bagasse pulp on paper production rates nor are there focussed investigations intent on improving bagasse pulp permeability. The only published measurement of bagasse pulp permeability known to the authors was recently performed by El-Sharkawy and co-workers [6, 7].

There have been a number of studies into the related area of bagasse pulp freeness by other researchers as an adjunct to the primary purpose of their work. Paul and Kasi Viswanathan [2]) broadly studied the effects of pith content on the quality of the pulp, which included freeness. Other incidental investigations into bagasse pulp freeness have been performed as part of investigations into bagasse pulp retention [8-12] and investigations into bagasse pulp strength [1, 2, 13-15].

It is thought that the permeability of bagasse pulp depends on the method of juice extraction. The pith is mainly liberated when the sugarcane is initially shredded in the hammermills. However, severe shear forces are exerted on the fibres in the roller mills (typically, there are six roller mills in series), which are located in between the hammermills and the dewatering mill in a factory that uses a milling train. Some factories use diffusion for effective juice extraction. In this process, after cane preparation

in the hammermill and the first roller mill, the prepared cane passes through a diffuser where most of the juice extraction takes place. The diffuser consists of a perforated plate through which the fibrous cane passes and a spray system showers water/juice onto the fibrous material. In the diffuser the juice is heated and lime is added to maintain a pH of about 7 in order to minimise sucrose degradation. The subtle differences in mechanical treatment between milled bagasse and diffuser bagasse may impact differently on the permeability properties of chemical pulps produced from them. The effect that the method of juice extraction has on the permeability properties of bagasse pulp is examined.

The objective of the larger research project is to maximise the permeability of bagasse pulp. This experimental study has two specific objectives: (i) to compare the permeability of milled and diffuser bagasse pulps; and (ii) to quantify the permeability properties of bagasse pulp. In this study, the permeability properties of pulp are measured in terms of the Kozeny Carman specific surface area and the swelling factor. These parameters are measured in a simple permeability cell.

Permeability Theory

The pulp samples are loaded into a rigid cell through which water flows.

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

$$\frac{Q}{A} = \frac{K\Delta P}{\mu \Delta L} \tag{1}$$

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 permeability of the porous material.

The conventional Kozeny Carman capillaric permeability model relates pulp bed porosity to permeability

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

where ε is the porosity (i.e., the void fraction), S_v the specific surface area, and k is the Kozeny factor. This model is used in this study because plentiful S_v data exists for wood [e.g. 16, 17]. In this study, S_v is used to compare samples rather than K because it is independent of pulp concentration. Low values of S_v are desired for maximum permeability.

The Kozeny factor takes into account the shape and fibre orientation of the material. In this study, a constant Kozeny factor is used. The value for the Kozeny factor used in this study, k = 5.55, was established by Fowler and Hertel [18]. In another study, the authors investigate the use of a Kozeny factor that varies with porosity.

In the case of pulp fibres in the swollen state, a considerable amount of water occupies the pores of the fibres. If the effective volume of the swollen fibres, i.e. the swelling factor, is α (cm^3/g), then at a concentration, c (g/cm^3), the porosity, ε is

$$\varepsilon = 1 - \alpha c \tag{2}$$

A high value of α indicates good potential for strength generation in refining.

Assuming that the pulp obeys the Kozeny-Carman correlation, inserting equation (2) into (1) and rearranging gives a linear relationship between concentration, c, and a function of permeability, $(Kc^2)^{1/3}$ specifically

$$\left(Kc^2\right)^{1/3} = \left(\frac{1}{k\alpha^2 S_v^2}\right)^{1/3} \left(1 - \alpha c\right) \tag{3}$$

Darcy's permeability, K, is determined experimentally over a range of concentrations, c. S_v and α are determined from the intercept and slope of a graph of $(Kc^2)^{1/3}$ against c.

EXPERIMENTAL PROCEDURE

Bagasse Pre-treatment

Bagasse is normally moist and wet-depithed prior to pulping in order to remove around 30-35 % of the fine pith fibre. The pre-treatment procedure used in this study is intended to maximise the permeability of Australian bagasse pulp and also allows long-term storage. The total amount of pith removed (around 43%) was higher than normally used by industry.

Samples of milled bagasse (species, Q208B) and diffuser bagasse (species, TellB) were collected from CSR Invicta Mill in northern Queensland, Australia. The bagasse samples were washed thoroughly to remove sugar content to prevent the sugar from fermenting. The bagasse was air-dried on a tarpaulin to 10%-15% moisture and placed in a 4°C refrigerator to minimise degradation. This thorough treatment minimises degradation of bagasse for the duration of long research projects.

Bagasse Pulp Preparation

Bagasse pulp samples (80 g-100 g) were produced in a 6×1.5 L cell "flow-through" digester. The equipment is described by Nguyen and Dang [19]. Approximately 50 L of cooking liquor was recirculated through 6 cells containing the fractionated bagasse. The pulping conditions were: 0.4 M sodium hydroxide (approx. 13.8 % Na_2O on oven dry fibre), 0.1 %, anthraquinone, AQ, (on oven dry fibre) at 145 °C for 30 min. The pulp kappa number (i.e., residual lignin content) was 20 which is suitable for making bleached paper.

Eucalyptus globulus (i.e. hardwood) pulp was prepared at Ensis, Melbourne (Australia) using an air-bath reactor. The cooking conditions used to produce the pulp were: 11.75 % Na_2O on oven dry fibre, sulphidity of 25 %, cooking temperature of 165 °C for 2 h. The kappa number of the pulp was around 19.

All pulp samples were screened through a 200 μm slotted Packer screen with water recirculation.

Permeability Testing

The permeability of three different types of pulp was measured:

- Australian milled bagasse pulp
- Australian diffuser bagasse pulp
- Eucalypt pulp

Figure 1 shows a schematic diagram of the experimental equipment assembly used to obtain the permeability data. The main feature of the permeability apparatus is a permeability cell made from a Perspex tube with ID of 41 mm and height of 300 mm. The cell has an airtight seal at the top. A rubber bung is connected to the manual valve, and the bottom is supported by reinforced screen of 100 mesh. The pulp mat, that is formed when a pulp suspension passes through the cell, rests on the screen. The cell is connected to two manometers to measure the pressure drop (Δp) across two positions on the pulp mat (distance Δl).
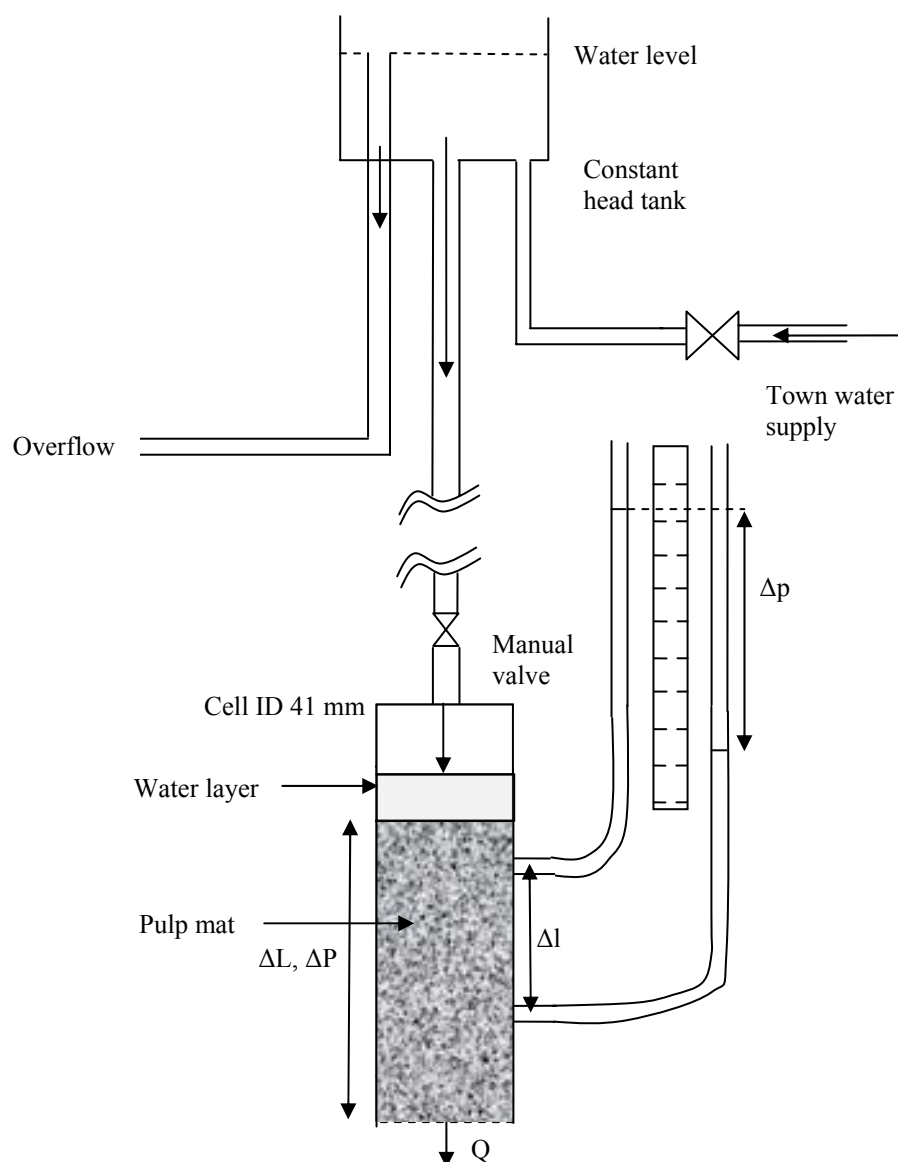
Figure 1   Schematic diagram of the apparatus used for permeability measurements

Exactly 30 g of dry pulp equivalent (i.e. around 130 g of wet pulp at the given dry substance, typically 22% - 24%) and 3 L of distilled water was added to a disintegrator to make a pulp slurry of 0.9 % consistency. 2 L of this slurry was then slowly poured into the disassembled permeability cell to form a saturated mat. The slurry was vigorously agitated as it was added to the cell to ensure uniform layering of the pulp fibres in the cell.

The town water supply valve to the constant head tank was opened until the tank overflowed and a constant head was maintained above the manual water valve. The permeability cell was connected to the constant head water tank and the manual water supply valve. The water supply valve was opened and water flowed from the constant head tank through the cell. The manual valve was adjusted so that the height of water in the top manometer was around 600 mm. (typically 5-15 min). The pulp mat height (ΔL) was recorded. This height was typically between 230 mm-260 mm. The flowrate of the water through the cell was measured (Q) with a measuring cylinder and a stopwatch and the difference in water height between the two manometers was recorded in order to obtain Δp. The pressure drop Δp applies over the distance between the two manometers, Δl. $\Delta p/\Delta l$ between the two manometers is used to determine the average pressure gradient over the height of the pulp mat, $\Delta P/\Delta L$ which is required for the calculation of permeability using Darcy's Law.

Great care was taken to ensure that the pulp mat was constantly saturated with water by maintaining a pool of water above the pulp mat at all times. If the pulp mat dries out, the fibres contract and the pulp mat would no longer be evenly distributed across the cross section of the cell and channelling of water could occur.

Once these measurements at the lowest flowrate were recorded, the flowrate of water through the cell was increased by adjusting the position of the water valve until the height of water in the top manometer equilibriated at around 900 mm. Increasing the flowrate and pressure compresses the pulp mat slightly (typically 2 mm). The values for Δp, ΔL and Q were recorded. Finally the flowrate of water through the cell is further increased by adjusting the position of the water valve until the height of water in the top manometer was around 1200 mm and values for Δp, ΔL and Q were noted.

Once these experiments are completed the supply of water to the cell is turned off and water is immediately purged from the manometers to avoid water back flushing into the permeability cell which would otherwise disrupt the uniformity of the pulp mat.

Another 500 mL of pulp slurry is then added to the permeability cell following the same procedure described for the initial 2 L of slurry. Values for ΔL, Q, and Δp were again obtained. Finally the remaining 600 mL of pulp slurry (typically 120 g of wet pulp fibre and 3 litres of water make around 3.1 L of slurry) is added to obtain additional permeability data at higher pulp concentrations.

Once all of the pulp slurry was added to the cell, the pulp mat was compressed to heights of 210 mm, 180 mm and 150 mm using compressed air. The tubing connecting the permeability cell to the water valve was detached and connected to a compressed air line. At this point, the pulp mat is very compressed (>0.1 g/cm^3) and a pool of water above the pulp mat is easily maintained as the compressed air is turned on. The pool of water above the pulp mat allows the fibres to remain saturated, preventing them from drying and shrinking which can lead to channelling.

It was observed during the permeability experiments that at high pulp concentrations (i.e., >0.1 g/cm^3) repeatable results were readily obtained since it was easier to avoid channelling than at low concentrations. Obtaining repeatable results was more challenging in the low concentration range between 0.06-0.08 g/cm^3. At these low concentrations, the following problems were occasionally encountered: (i) channelling; (ii) pulp slurry entrained in the manometer lines; and (iii) difficulty in visually determining the interface between the pulp mat and the water layer. At lower concentrations, the data obtained was continuously checked and if channelling or turbulence took place the calculated permeability K, was obviously far too high and subsequently the datum was rejected. As the manometer tubes were transparent it allowed for the observation of pulp entrainment.

Fibre Length Analysis

A Kajaani FS100 unit was used to measure the fibre length distribution of each pulp sample.

RESULTS

Three different types of pulp were tested and the S_v and α values were determined from the Kozeny-Carman model. Table 1 shows the estimates of specific surface area, S_v, and the swelling factor, α, for all the pulp samples investigated in this study. Optimum values for S_v and α were determined for both constant and variable Kozeny factors using a least squares regression method.

The average S_v was found to be 1741 cm^{-1} for milled bagasse pulp and that for diffuser bagasse pulp was found to be 1963 cm^{-1}. A Student's t test found no significant statistical difference in the S_v values using a 95% confidence interval.

The S_v for eucalypt pulp was found to be 2480 cm^{-1} which is outside the experimental variation for the bagasse pulp samples. The value for eucalypt pulp is consistent with the findings of earlier workers studying hardwoods [16, 17].

Table 1   Summary of permeability parameters obtained with the Kozeny-Carman model

Sample number	Fibre Type	Specific surface area, S_v (cm^{-1})	Swelling factor, α (cm^3/g)
1	Milled	1540	3.44
2	Milled	1423	3.27
3	Milled	1572	3.84
4	Milled	1823	3.33
5	Milled	1827	3.38
6	Milled	2265	3.10
Average milled		*1741*	*3.39*
7	Diffuser	1524	3.52
8	Diffuser	1394	3.61
9	Diffuser	2171	3.20
10	Diffuser	2763	3.00
Average diffuser		*1963*	*3.33*
11	Eucalyptus Globulus	2481	3.38

The S_v for Australian bagasse pulp was lower than that for eucalypt, indicating higher permeability. Given that replacing eucalypt pulp with bagasse pulp normally reduces production rates [4, 5], this is quite surprising. It is thought that a high amount of pith was removed by washing and cooking in the "flow-through" digester which dramatically increased the pulp permeability.

In order to further investigate the relationship between fibre length and permeability, the fibre length distribution for each type of pulp was measured. The results are shown in Figure 2. It can be observed that the fraction of fibres shorter than 0.4 mm in length is approximately 30% higher for each of the bagasse pulp samples than that for the eucalypt pulp. However, bagasse pulp has more fibres greater than 1.3 mm in length. The relatively large fraction of small bagasse fibres has not reduced the permeability of bagasse below that of eucalypt. The authors propose that this is due to the presence of a significant fraction of bagasse fibres longer than 1.3 mm.
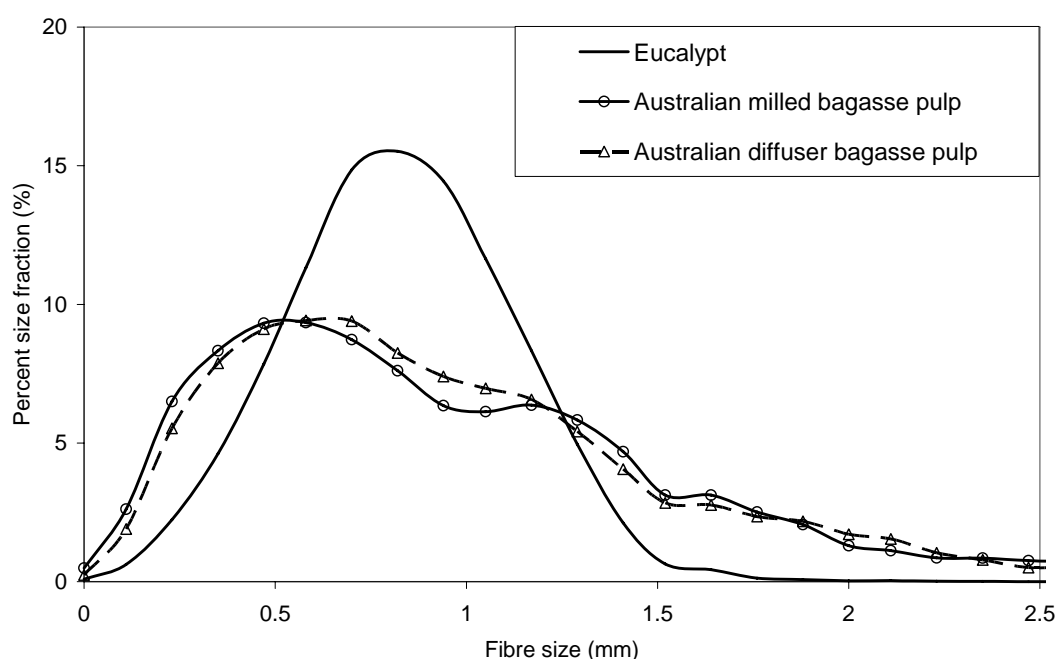

Figure 2   Fibre length distribution of Australian bagasse pulps and eucalypt pulp

The mean value of α for pulps derived from the milled bagasse material is 3.39 cm^3/g compared to 3.33 cm^3/g for pulps derived from diffuser bagasse material. This is statistically insignificant. The α values for the Australian bagasse pulps derived from either milled or diffuser bagasse material were not very different from eucalypt (3.38 cm^3/g). This suggests Australian bagasse pulp has reasonable prospects for strength generation through refining.

CONCLUSIONS

The permeability properties of Australian bagasse pulp have been measured and reported. Pulp derived from Australian bagasse has been produced in the laboratory with higher permeability than eucalypt pulp, despite a higher overall fine fibre content. As a word of caution, further physical property testing needs to be undertaken to establish whether the improvement in the quality of Australian bagasse pulp is truly comparable to eucalypt pulp.

This study indicates that there is no difference in the final pulp permeability properties as measured by specific surface area, S_v, between bagasse from a mill and from a diffuser. Australian bagasse has reasonable prospects for pulp strength generation through refining, as measured by the swelling factor.

This is the first experimental study into the permeability properties of bagasse pulp and fills this gap in the literature. Successfully producing bagasse pulp with very high permeability properties justifies further work in this area. Normally bagasse pulp has been expected to have poorer permeability than eucalypt pulp. The underlying cause of the superior permeability of the Australian bagasse pulp produced in this study is not fully understood. Slight differences in the fibre length distribution or differences in the fibre physical properties such as stiffness are proposed as possible causes.

ACKNOWLEDGEMENTS

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
K is Darcy's permeability constant, cm^2
k is the Kozeny factor, -
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)

Greek letters
α is the pulp swelling factor, cm^3/g
ε is the pulp porosity, - (between 0 and 1)
μ is the liquid viscosity, mPa.s (cP)

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Determination of the permeability parameters of bagasse pulp from two different sugar extraction methods

T. Rainey, W. Doherty, R. Brown, N. Kelson (QUT)

M. Martinez (UBC)

Background

- Australian sugar industry under hardship
  - Low world sugar price, drought, rising $A
  - Investigation into value added products

- Bagasse is much cheaper than eucalypt (25% of cost) and already collected

- Environmental benefit- reducing burden on hardwood plantation/old growth (i.e. "tree free")

Background (cont.)

- Bagasse not used to make pulp in Australia because

  - Large economy of scale & supply constraints
  - Remoteness of bagasse to existing pulp mills
  - Pulp inferior to eucalypt pulp
    - Inferior drainage properties- reduces machine speed 25-30%
    - Inferior strength properties due to mechanical damage and fibre morphology
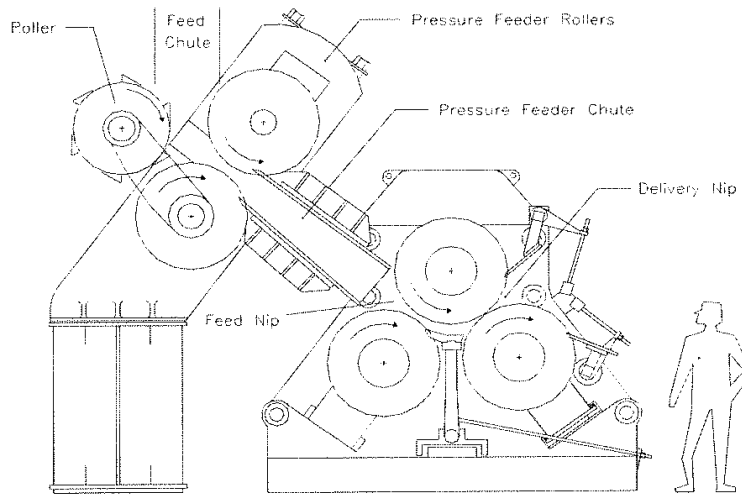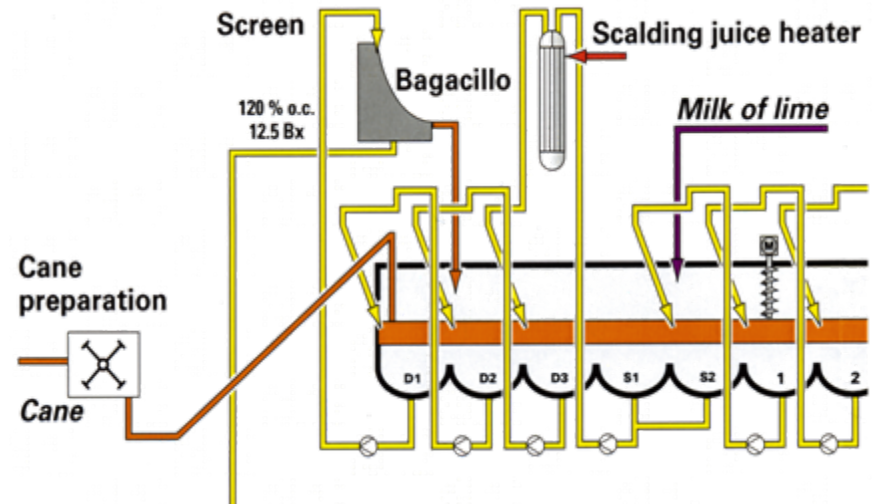
Background (cont.)

Sugarcane
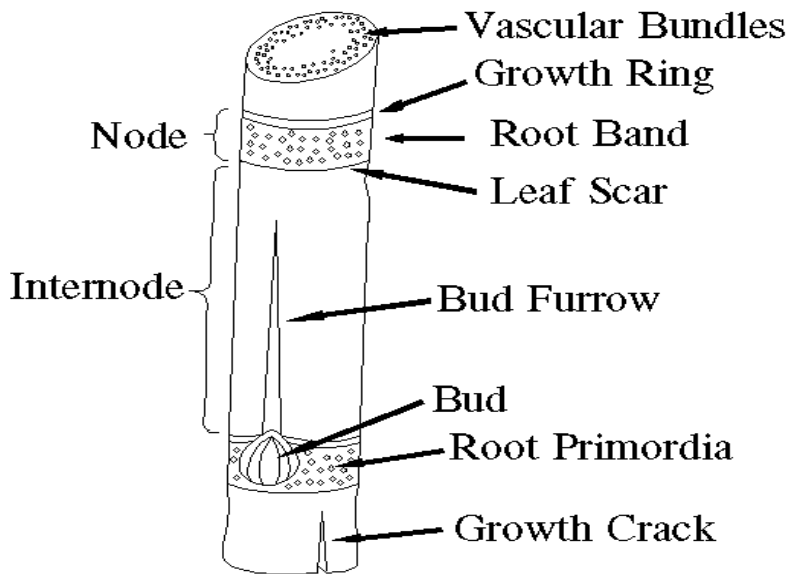
Australian bagasse
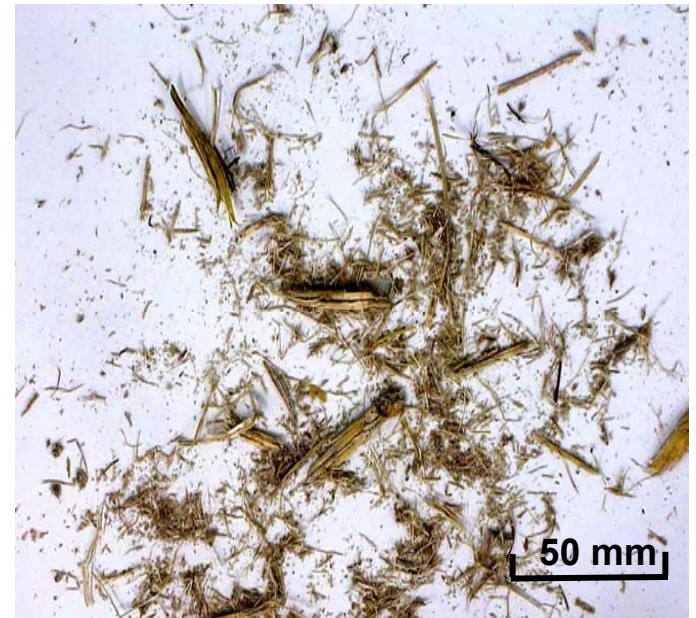
[1] J. D. Miller and R. A. Gilbert Sugarcane Botany: A Brief View, University of Florida, IFAS, edis.ifas.ufl.edu/SC034 viewed 15/5/08

Sugar mill

Diffuser

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ISSCT Workshop "Further energy extraction by optimized energy concept"
Nov. 21-24, 2006; Veracruz, Mexico

Research objectives

- To quantify the permeability of bagasse pulp
  - Little bagasse pulp permeability data in literature (only one study)
- To identify options for improving permeability

Research question

- Is there a difference in pulp permeability between milled and diffuser bagasse?

Permeability theory

- ## Darcy's Law

  Q is flowrate

  A is cross-sectional area

  K is the permeability constant

  ΔP is the pressure drop

  ΔL is the length of porous material

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

  K dependant on concentration

- ## Kozeny-Carman model

  ε is the porosity

  k is the Kozeny-Carmen constant

  S_v is the specific surface area

$$K = \frac{1}{kS_v^2} \frac{\varepsilon^3}{(1-\varepsilon)^2}$$

  Compare S_v over a wide concentration range

  Low S_v is good

Permeability theory (cont.)

Incorporating swelling factor, α, gives an indication of the prospects for strength generation

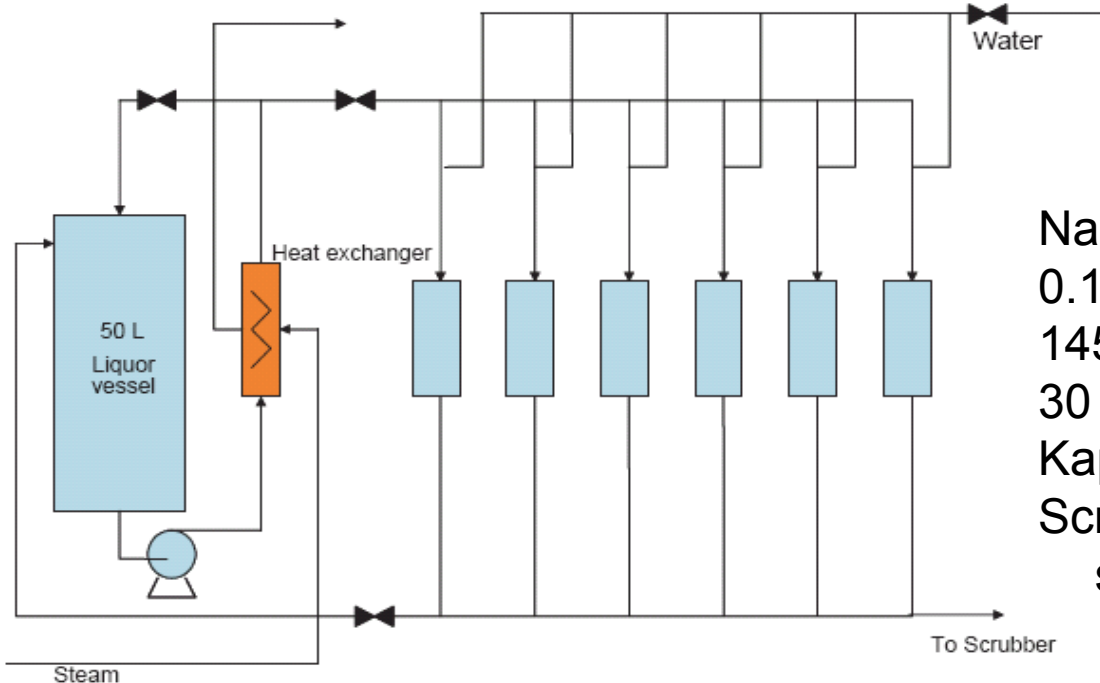Sub ε = 1 − αc into K-C model and rearrange

$$\left(Kc^2\right)^{1/3} = \left(\frac{1}{k\alpha^2 S_v^2}\right)^{1/3}\left(1-\alpha c\right)$$

Plot of $(Kc^2)^{1/3}$ vs c gives linear regression to estimate S_v and α

Bagasse preparation

- Heavily depithed
  - 40% of fine "pith" removed by sieving
  - 3% removed by washing

- Treatment to avoid degradation
  - Thoroughly washed
  - Dried to 85-90% solids
  - Refrigerated at 4 °C

Soda AQ pulping

NaOH: 13.8% Na_2O (on oven dry fibre)
0.1% anthraquinone (on oven dry fibre)
145°C
30 min
Kappa number of 20
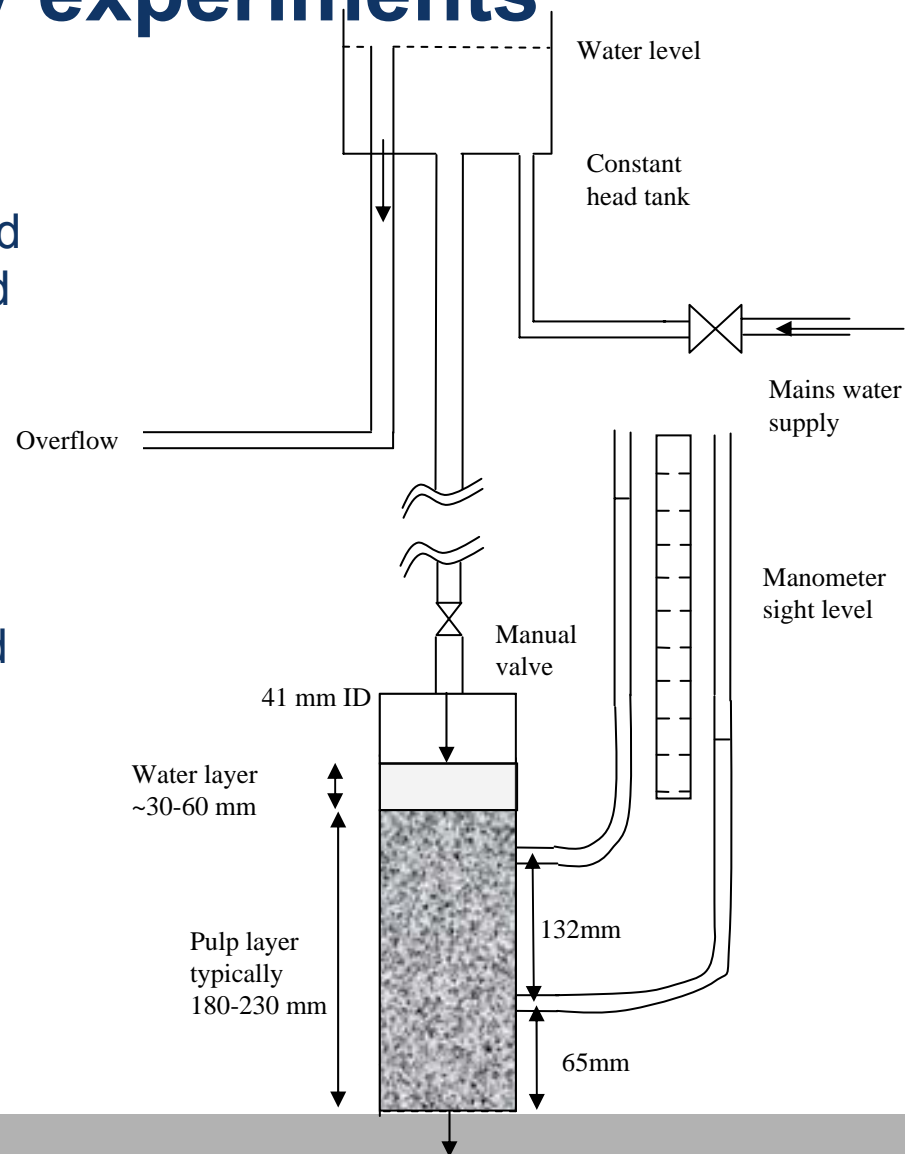Screened with 200 µm vibrating slotted
  screen

[3] Nguyen, K.L. and Dang, V.Q., The fractal nature of kraft pulping kinetics applied to thin
  Eucalyptus nitens chips. Carbohydrate Polymers, 2006. **64**(1): pp. 104-111.

Permeability experiments methodology

- 40 samples of bagasse pulp produced in cells

- 10 samples selected at random

- Measure permeability over a range of concentration

- Permeability tests repeated in triplicate to determine S_v and α

- Bagasse pulp compared to *Eucalyptus globulus* pulp

Permeability experiments

- Concentration varied by adding slurry and compressing with compressed air whilst maintaining saturation

- Hydraulic load negligible compared to large mechanical load applied

Water level

Constant head tank

Mains water supply

Overflow

Manometer sight level

Manual valve

41 mm ID

Water layer ~30-60 mm

Pulp layer typically 180-230 mm

132mm

65mm

Results

Sample number	Specific surface area, S_v (cm^{-1})	Swelling factor, α (cm^3/g)
Average 'milled' bagasse pulp	1741	3.393
Average 'diffuser' bagasse pulp	1962	3.334
Eucalypt pulp	2480	3.383

S_v , α comparable with eucalypt

Data for eucalypt consistent with previous researchers

Previous workers

Pulp source	Investigator	Other details	Specific surface area, S_v (cm^{-1})	Swelling factor, α (cm^3/g)
Soda AQ Australian bagasse	This study	Not dried	1490-2170	3.20-3.54
Sulfite wood pulp	[2]	Previously dried	~4100	2.80-3.08
		Not dried	~2300	4.4-4.5
Kraft wood pulp	[2]	Not dried	~2300	3.66-4.27
Wood pulp	[3]		4200	1.65
Sulphate wood pulp	[4]		2000-3000	4.8

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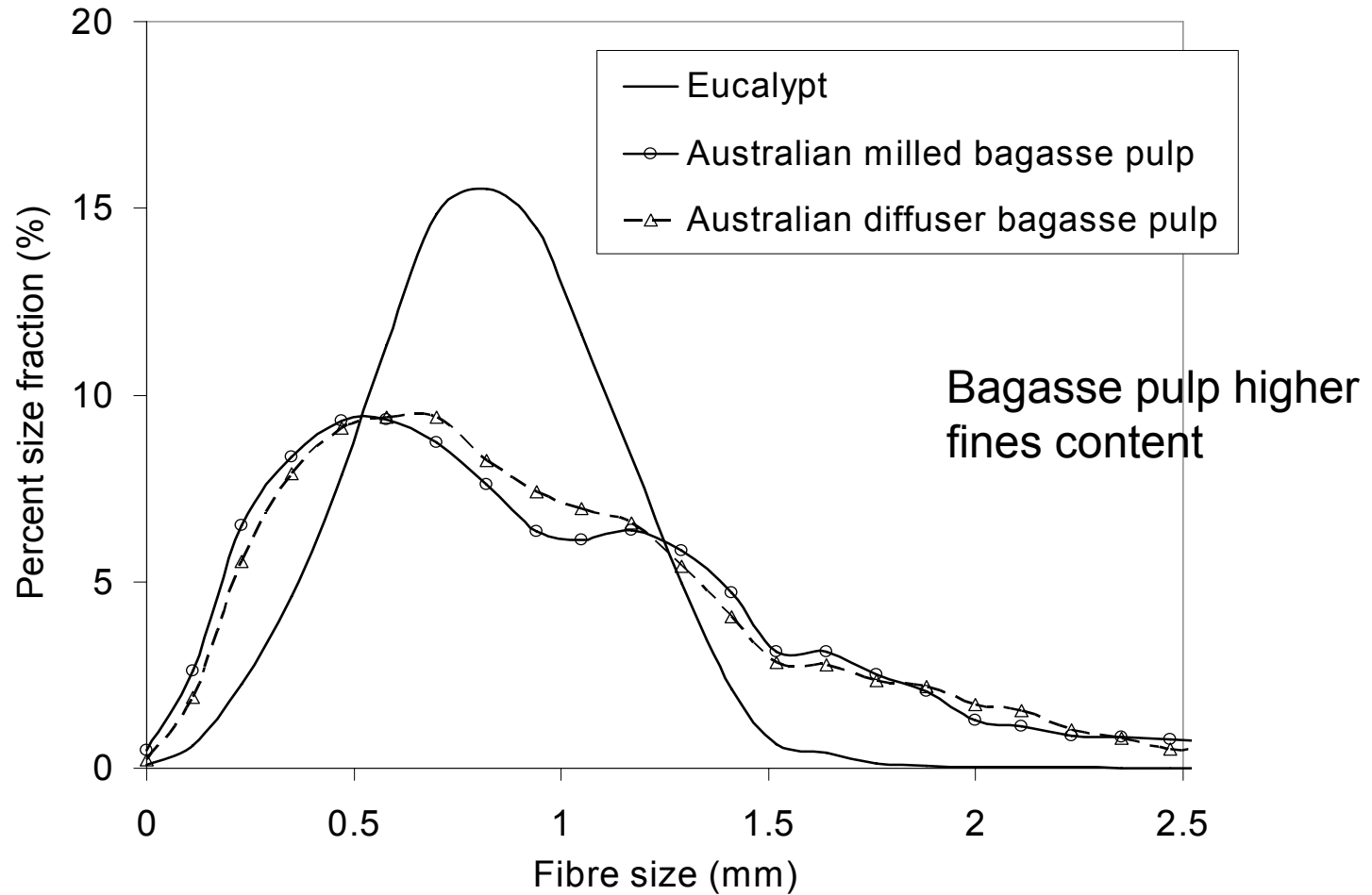
Comparison with El-Sharkawy & co-workers [5]

- Used form

$$K = k' \frac{\varepsilon}{(1-\varepsilon)^2}$$

- Converted our data into their constant
- k' = 2.36×10^{-9} cm^2 for an Indian bagasse pulp
- k' = $2\text{-}4 \times 10^{-8}$ cm^2 in this study

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Fibre length distribution

Conclusion

- Bagasse pulp can be produced in the laboratory with permeability properties favourable to eucalypt pulp

- Reasonable prospects for strength generation

- No difference in pulp permeability whether the bagasse comes from a milling train or a diffuser

Further work

- Physical property testing of pulp required

- What is the fundamental reason for the high permeability? (e.g. fibre length distribution, fibre stiffness, cell wall thickness)