Preferred citation: T.A. Arnevik and T. Helle. Some effects of fibre form on the pulp drainage resistance. In **Fibre-Water Interactions in Paper-Making**, *Trans. of the VIth Fund. Res. Symp. Oxford, 1977*, (Fundamental Research Committee, ed.), pp 315–353, FRC, Manchester, 2018.
DOI: 10.15376/frc.1977.1.315.

SOME EFFECTS OF FIBRE FORM ON THE PULP DRAINAGE RESISTANCE

T. A. ARNEVIK and T. HELLE, Laboratory of Pulp and Paper Technology, University of Trondheim, Norway

1—*Introduction*

TODAY, several important parameters in sheet forming on the paper machine are changing considerably.

The twin wire concept is about to become the standard for new installations. Here, the drainage zone is drastically reduced compared to the fourdrinier, with corresponding reduction in drainage time. Besides, there is a general increase in paper machine speed. The drainage elements are changed, reducing the degree of pulsed drainage.

Also the papermaking furnish is changing.

New fibre raw materials are introduced by a change from mature to juvenile trees on the one hand and the increasing use of tropical hardwoods on the other. This implies a significant change in the fibre compositions of the furnishes.

This tendency is enhanced by another technical trend, partly caused by scarce wood supplies, towards pulps of higher yields. The trend is significant both within the conventional chemical pulping processes, and for the development of new processes like the thermomechanical pulping methods.

The change in paper forming speed, and in the fibre composition may cause problems for the production process. It therefore seems useful to try to produce new information on the influence of fibre form on the pulp drainage characteristics.

List of symbols

A = cross section area
Q = filtrate volume
Δp = pressure drop
T = fibre bed thickness

Under the chairmanship of J. Mardon

S_0 = specific surface of solids (volume basis)
K^1 = permeability
K = specific permeability
$\bar{K}_s$ = average specific flow resistancy
k = Kozeny's factor (Kozeny's constant)
V = fluid permeation rate
μ = fluid viscosity
ρ = density of fluid phase
v = specific volume of the filter bed material
c = concentration of fibres in web (mass/vol)
C_0 = Concentration of fibres in uncompressed state
E = modulus of elasticity
M, M_1 = constants
N = constant
a = constant
b = constant
L = fibre length
D = fibre diameter
d = fibre lumen diameter
w = grammage
t = time to form a sheet of grammage w
G = drainage constant
s = concentration of pulp suspension
$\left.\begin{matrix}\alpha\\ n\end{matrix}\right\}$ = exponents of the eq.: $t = \frac{G}{s} w^{\alpha}(\Delta p)^n$
ε = exponent, defined by $\Delta p^{-\varepsilon} \approx (1-vc)^3$
K_1, K_2 = constants
m = factor giving the degree of turbulence
$m = 1$: Purely laminar flow
$m = 2$: Purely turbulent flow

2—*Fibre web forming as a filtration process*

FORMING of the paper sheet, on both the traditional Fourdrinier and the more recent twin-wire machines, is in its first stadium essentially a hydro-mechanical filtration process. During drainage on the Fourdrinier, a definite boundary exists between the fibre mat that has been deposited on the wire and the pulp suspension lying above it. While the concentration of this upper layer is usually that of the headbox, special drainage elements, such as table rolls and foils, may increase it slightly.[1] The filtration characteristics of sheet formation on twin wire machines is even more pronounced and approximates a constant pressure filtration process.

Because of the importance of the filtration process, or drainage as it is commonly termed, as a unit operation of the paper forming process, it has been studied extensively and a series of mathematical models have been proposed to describe it. Commonly, these models have been based on classical filtration theories which were developed for incompressible media. Because of this, various modifications have been required to account for the very special properties of the nonideal, fibrous material, which serves as the filter medium.

These studies, which have been performed on the drainage properties of fibre mats and related processes and on the drainage on the paper machine have been reviewed in a series of excellent papers.[1–6]

The mechanisms of fluid flow through porous media were first formulated mathematically by d'Arcy, who observed that the flow rate $\mathrm{d}Q/\mathrm{d}t$ was directly proportional to the cross-sectional area of the bed, A, and the applied pressure across the bed, Δp, and inversely proportional to the bed thickness, T, i.e.,

$$\mathrm{d}Q/\mathrm{d}t = K' \cdot \frac{A\,\Delta p}{T}. \qquad (1)$$

K', the proportional constant, is known as the permeability of the bed.

The basic equation describes the effects of both the flow properties of the liquid and the porosity characteristics of the medium. When it is modified to take account of the fact that liquid flow is inversely proportional to its viscosity μ, that the liquid can only flow through the void fraction $(1-vc)$ of the filtering medium and that the internal surfaces of the medium will exert a drag on the fluid flow, it takes the form

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = \frac{(1-vc)^3}{k(vc)^2 S_0^2}\frac{1}{\mu}\frac{A\,\Delta p}{T}. \qquad (2)$$

Here, v is the specific volume of the filter bed material, c is the concentration of fibres in web, and S_0 is the specific surface of solids. This more precise form of d'Arcy's equation is known as the Kozeny–Carman equation and the term 'k' is the Kozeny constant. The proportional constant 'K', where

$$K = \frac{(1-vc)^3}{k(vc)^2 S_0^2}. \qquad (3)$$

is the specific permeability.

The Kozeny–Carman equation is based on two specific assumptions:

1. The filtered web is incompressible, i.e. the porosity of the web is constant throughout its thickness.

2. The liquid flow is laminar.

Work has shown that neither of these two premises are strictly true for the papermaking operation. Ingmanson *et al.* examined the properties of fibre webs in a series of basic studies[7–9] and extended the Kozeny constant to include the compressibility of the web. As such, the constant is known as the Kozeny factor and is a function of the web porosity in addition to the other factors discussed above, i.e.,

$$k = \frac{3{\cdot}5(1-vc)^3}{(vc)^{1/2}}(1+57(vc)^3). \qquad (4)$$

Also, it has been shown that for the case of free pulps and for the pulp/mat suspension system in the first part of the drainage process, the assumption of laminar flow is frequently not valid. This means that not all of the applied pressure drop is used to overcome viscous friction as some is consumed in accelerating the liquid as a result of the turbulence. Ingmanson and Andrews[10] and Meadley[11] examined this and proposed the following formula to describe the pressure drop over the bed:

$$\frac{dp}{dT} = \left(\frac{\mu S_0{}^2(vc)^2 k}{(1-vc)^3}\right)V + \left(\frac{0{\cdot}1(vc)S_0 k^{1/2}\rho}{(1-vc)^3}\right)V^2. \qquad (5)$$

V is the fluid permeation velocity.

This equation, together with a continuum equation for the flow, a mass balance and an equation describing variation in pressure with level and velocity changes, allows the calculation of the change of the mat/suspension level interface as a function of time. When Meadley did this, he noted some deviation from direct observation.[11] Bergström has shown that the pressure drop in the fibre web experiences a time delay relative to the flow speed and this may account for the deviation.[12]

The crucial factor in paper web filtration is the filtration resistance characteristics of the web. In turn, this may be determined by the web components, the effect of pressure, web thickness, time dependencies, etc.

3—*Factors influencing the web drainage resistance*

EQUATIONS (*3*) and (*4*) show clearly that the drainage resistance is determined by

1. the surface area of the fibre material,
2. the volume occupied by the fibres and fines,
3. the apparent density of the web, which reflects the resistance of the web to compaction, which in turn is determined by fibre properties like length and cross-sectional dimensions, and stiffness.

However, most paper making furnishes are very difficult to define exactly in terms of their component fibre characteristics.

Fibre surface areas of wood pulps are normally calculated from permeability measurements. Ingmanson *et al.*[13] found that fine material had a considerably higher specific surface area than the fibres, whereas they found no difference in specific volume (degree of swelling) between the two fractions. The latter conclusion may be questioned, as studies using other techniques, have indicated a substantially larger degree of swelling for most fine materials.[14,15]

Most of the analytical studies of drainage have been done using synthetic model fibres, or unbeaten, classified wood pulps, which allow the surface to be readily determined. One may, however, question the physical reality of the calculations performed to determine the surface area of beaten pulp rich in fine material. The fine material, especially, has a gellike character, and it may hold as much as five times it own weight as 'bound water'.[15] Similarly, it is hard to determine exactly the real volume of beaten fibres.

In a recent study, Binotti and Nicholls[16] examined the correlation between fibre morphological factors and filtration resistance, and specific volume and specific surface, using fractions of unbeaten, bleached loblolly pine. They were particularly interested in the difference between the short, earlywood fibres, which predominate in juvenile wood, and the longer, latewood fibres, which are dominant in mature wood.

At a constant mat density, the short earlywood fibre fraction had a specific filtration resistance which was four times that of the long latewood fibres. The ratio between the specific surfaces of the two fibre types was 2:1.

The porosity of the web changes as the water drains through it, both as a function of web thickness T and time. The compressibility characteristics of the web therefore are very important, and consequently the fibre properties that influence the compressibility. An extensive survey on this relationship has been given by Han.[4]

A common way of expressing the concentration of a fibre web under static compression, is

$$c = c_0 + M(\Delta p)^N, \qquad (6)$$

where c_0 is the fibre concentration in the incompressed state and M and N are constants.

For thick pulp webs—from a papermaking point of view—pressure time from 5 to 20 minutes may be required to reach the equilibrium conditions. For thinner webs, the process is much faster, but, as the sheet forming time on a modern, twin wired paper machine may be less than 0·1 second, it is evident that the whole process may take place long before the point of constant concentration is reached. Consequently, a knowedge of the compaction process as a time function is more essential to the understanding of sheet forming than the static end points.

Considerable work has been performed to determine the values of M and N of the compression equation (*6*) for various types of fibres.[4, 9, 14, 18, 19] N is surprisingly constant, in the range 0·3–0·4 for almost all pulps, beaten and unbeaten.

Conversely, M increases with beating, but usually just by some few per cent.

Elias[20] studied the behaviour of single fibres under loading in webs. Quantified as the number of apparent fibre contacts per length unit, for a given load, he found that the number of contact points was decreased with increasing fibre length, diameter and modulus of elasticity.

Using synthetic model fibres, Jones[21] studied the influence of some fibre properties on the constants M and N of equation (*6*), and found

increasing fibre length reduces M and increases N;
increasing E-modulus reduces M;
the ratio between fibre length and diameter, L/D has a significant effect up to a certain critical value which varies with the fibre material. Below this critical value, increasing L/D ratio reduces M and increases N.

From a physical point of view, it seems likely that M and N are at least partially interrelated, e.g. a pulp of low M could be expected to have a higher value of N than a pulp of higher initial packing degree.

The assumed interrelation between M and N has been confirmed in several studies. Empirically, Han[3] found the relationship

$$\log M = aN + b, \qquad (7)$$

where a is negative.

Jones[21] found that up to the critical value for L/D, the relationship $M \sim (1/E)^{0\cdot 24}$ holds. E is the modulus of elasticity of the fibre material.

In view of this, it may seem surprising that beating only has a minor influence on M, as it is well known that beating reduces the stiffness of the fibres. One reason for this may be that the specific volume of the fibres increases in proportion with the swelling caused by the beating process. High consistency refining increases M more than low consistency refining.[4]

It is known that the E-modulus of the fibres is reduced with bleaching and increased with increased pulp yield. The resulting effects on M are in accordance with Jones' relationship $M \sim (1/E)^{0\cdot 24}$.

In a further study, Binotto and Nicholls,[22] examined the relationship between fibre morphological factors and wet mat compressibility of loblolly pine bleached sulphate pulp, and found M to be proportional to $(1/I_F)^{1/3}$, where I_F is the moment of inertia for flattened cross sections. N was constant for all pulps, and the fibre wall thickness was found to be a predominant morphological factor for the compressibilities.

Most of the studies on pulp web compression have been performed as static tests. The compression is, however, strongly time dependent but there is a lack of information concerning the variation of the time constant of the compression process with different pulp and fibre types. Some old data reported by Seborg[23] suggest that the time constant increases significantly with beating.

Wood pulps consist of particles of various forms, ranging from thick cylindrical latewood fibres and thin-walled springwood fibres which tend to collapse to ribbonlike forms when beaten, to fine cell wall debris etc. of varying form, thickness and stiffness.

The effect of the cross-sectional form of the fibre on its stiffness and consequently its packing characteristics in the web can be judged by simple calculations. Allan *et al.*[24, 25] reviewed the relationship between the cross-sectional form and the moment of inertia for different fibre types.

Several methods have been developed for measuring the stiffness or flexibility of single fibres directly[21, 26–28] and indirectly.[27–32] The influence of the cross-sectional form and mechanical treatment on the tendency to collapse have been investigated.[33, 34]

The results of these studies of single fibre flexibility may briefly be summarised thus:

Thin walled fibres are more flexible than thick walled (springwood *vs.* latewood);
Fibre flexibility increases with decreasing pulping yield;
Sulphite fibres are more flexible than sulphate fibres, compared at constant fibre dimensions and pulping yield;
Mechanical treatment, such as beating, will substantially increase the flexibility. Even a very light mechanical treatment (disintegration) increases the flexibility significantly.

These changes in fibre flexibility are the result of changes in cross-sectional form due to collapse which effects the moment of inertia and changes in the structure and cohesion of the fibre wall.

Labreque[35] has experimentally studied the effect of various fibre cross-sectional forms on the flow resistance of fibre webs, using nylon fibres having elliptical cross-sections, of aspect ratio in the range 1:5. Aspect ratio is the ratio of the major to the minor axis of the cross-sectional ellipse. The Kozeny factor was increased by roughly 50 per cent when the aspect ratio increased from 1 to 5 at a given porosity level.

In a theoretical work, Masliyah[36] found an even stronger effect of the aspect ratio on the Kozeny factor.

Examination of fibre cross-sections visible in a cut edge of a paper sheet made from beaten chemical pulp, shows that most fibres have rather high aspect ratio. Additionally, the skinlike fine material removed from the outer layers of the fibres during beating do have very high aspect ratio during sheet forming. It therefore seems very important to include ribbonlike flat fibres in model studies of paper pulp drainage.

4—*Empirical equations for drainage time*

A PAPERMAKING furnish is a complex mixture of fibres and fibre debris and other particulate matter of varying form, flexibility, size, swelling degree etc., and the nature of the paper web will change continuously, with respect to composition, density etc. throughout the forming period.

When developing mathematical models of such systems scientists have normally had to introduce severe degrees of simplification, as has already been pointed out: model staple fibres of known dimensions, usually no fines, and no beating, frequently thick webs of constant compaction and slow, constant rate drainage.

While much valuable information has been obtained from these analytical studies, people working closer to the paper making practice often find it difficult to take advantage of the results in their own work.

In integrated paper mills, the paper maker will have to use the mill's pulp, in nonintegrated mills the pulp will be chosen to give an end product to specified properties. For a specific paper machine, his input variables include such factors as beating, consistency, drainage suction and drainage and retention aids. These factors have to be optimised with respect to economy and quality.

With this background, it is natural that there has been a separate trend of study, which starts from a position close to technical practice, and attempts to evaluate the influence of the practical variables that the paper maker has at hand.

Analytically, it is more difficult to define the parameters of these studies than those of carefully controlled filtration experiments, but practical application of the results seems more immediate.

When Wahlström and O'Blenes[37] examined sheet formation at constant drainage pressure, they varied the grammages and stock consistencies of a series of different furnishes over the range used on commercial machines, and found the drainage time to follow this relationship for grammages over 30 g/m²:

$$t = \frac{G}{s} w^{\alpha}(\Delta p)^{n}, \qquad (8)$$

where t = time to form a sheet of basis weight w,
G = drainage constant of the furnish in question,
s = concentration of the pulp suspension,
Δp = applied constant pressure,
α and n = exponents.

Lindberg[38] studied the drainage using pulsating drainage suction, and summarised his findings in the form

$$u = u_0 \left(\frac{w}{w_0}\right)^{-\alpha} \left[\frac{\Delta p}{\Delta p_0}\right]^{\beta} (1+f)^{\gamma}. \qquad (9)$$

(For definitions, see [38]).

Drainage at table rolls of a paper machine was examined by Brauns and Tellvik.[39] They concluded that the drainage speed on each roll can be written as

$$u = \frac{2r}{F^2} U^{\alpha}. \qquad (10)$$

(For definitions, see [39]).

When the equations (*8*), (*9*) and (*10*) are rearranged and modified, the experimental results of these studies can be compared. Thus, Wahlström's *et al.* and Lindbergs's work has the following similarities:

Wahlström		Lindberg
α	=	$\alpha+1$
n	=	β
$\frac{1}{G\alpha}$	=	$u_0 w_0^{\alpha} \Delta p_0^{-\beta}$

Compared in this way, the results of Wahlström *et al.* and Lindberg correspond well, especially for chemical pulp. The basis weight exponent (Wahlström's α, Lindberg's $\alpha+1$) is found to be strongly influenced by the beating degree of the pulp. Most of the values obtained were in the range 2·0–3·0, but some lay outside this.

Also, the drainage pressure exponents (Wahlström's n, Lindberg's β) generally agree well in the two studies. In most cases, the exponent was found to be in the range −0·35–0·50. For newsprint furnish, however, the value was higher, and here Lindberg found a considerably larger pressure exponent than Wahlström did (−0·72 against −0·52) which may have been the result of the difference in the application of pressure. Brauns and Tellvik,[39] who studied the drainage on a table roll found an even greater difference in the influence of the drainage pressure between chemical and news furnish, than Lindberg did.

5—*Factors affecting the influence of drainage pressure and sheet grammage on drainage time*

IN the work that formed the basis for this paper,[17] the authors studied the factors determining actual sheet drainage times, using a principle similar to the one applied by Wahlström and O'Blenes.[37] They also wished to examine some of the discrepancies noted in the previous studies,[37–39] with regard to factors determining the influence of drainage pressure and basis weight on drainage time.

Consequently, they found it useful to critically examine the literature and develop a series of hypotheses from the models already proposed to describe the effect of the pressure exponent n, and the grammage exponent α, in Wahlström and O'Blenes's equation (*8*)

$$t = \frac{G}{s} w^{\alpha}(\Delta p)^{n}.$$

In the following, a discussion will be given, concluding in the hypotheses developed.

5.1—*The character of the flow during sheet drainage*

Most model studies on sheet drainage have assumed the water flow through the fibre web to be purely viscous. However, as pointed out by Ingmanson and Andrews[10] and Meadley[11] the basic assumption of d'Arcy's equation, of laminar flow, is not valid for paper sheet forming at high speeds. These high flow speeds imply a degree of turbulence, which means that only a part of the total pressure drop is applied to the viscous part of the flow (Δp_v). The maximal drainage flow at commercial sheet forming is calculated by Ingmanson and Andrews[10] to give a Reynolds number of about 100, at which the Δp_v is some 20 per cent of the total pressure drop.

Thus it is feasible that Δp_v should not be assumed to be identical to the applied pressure drop in hand sheet formers, especially if dilute suspension and relatively high drainage pressure are used.

Wahlström *et al.*[37] discussed this point and concluded that they did not observe any transition point between laminar and turbulent flow in their study.

The assumption of some degree of turbulent flow may, however, explain some of their findings (grammage exponent (α) values of less than 2 for free pulps at low consistencies).

5.2—*Factors influencing the drainage time's pressure dependence*

From the previous discussion, it is clear that the drainage rate, and consequently the drainage time for a given grammage is dependent on, among other factors, the applied pressure difference and the compaction of the web. The latter, in its turn, is a function of the pressure difference. A qualitative impression of the influence of applies pressure on drainage time, may be gained by tentatively assuming pure laminar flow (i.e., d'Arcy's equation (*1*) is valid), 100 per cent retention, and that the Kozency factor is constant.

For the concentration of the fibre web, an average value (modification of equation (*6*)) suggested by Higgins and de Yong[19] is used,

$$c = M_1 \left(\frac{2-3N}{4-3N}\right)^N (\Delta p)^N, \quad . \quad . \quad . \quad . \quad (11)$$

which disregards the time dependence of the compaction. This also means that one assumes a constant average value for the specific drainage resistance. Kozeny Carman's equation (*2*) was

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = \frac{(1-vc)^3}{k(vc)^2 S_0{}^2} \cdot \frac{1}{\mu} \frac{A\,\Delta p}{T}.$$

Assuming $(1-vc)^3 \approx 1$,

$$Q = \frac{w}{s}; \qquad \mathrm{d}Q = \frac{1}{s}\,\mathrm{d}w,$$

$$T = \frac{w}{A\cdot c},$$

the equations can be combined:

$$\frac{\mathrm{d}w}{\mathrm{d}t} = \frac{s\,\Delta p A\cdot c}{k\cdot w\mu S_0{}^2 v^2 c^2} = \frac{A\cdot s}{k\cdot\mu S_0{}^2 v^2 M_1 \left(\frac{2-3N}{4-3N}\right)^N} \cdot \frac{\Delta p}{w\cdot\Delta p^N}$$

$$K_1 = \frac{A\cdot s}{k\cdot\mu\cdot S_0{}^2 v^2 M_1 \left(\frac{2-3N}{4-3N}\right)^N}$$

$$\frac{\mathrm{d}w}{\mathrm{d}t} = K_1 \frac{\Delta p^{(1-N)}}{w}.$$

Integrating from $t = 0$, $w = 0$, to $t = t$, $w = w$,

$$t = \frac{1}{2K_1} \Delta p^{(N-1)} w^2. \quad . \quad . \quad . \quad . \quad (12)$$

To include that the porosity varies in the direction opposite to the drainage pressure,

$$(1-vc) \neq 1 \qquad \text{and} \qquad \frac{d(1-vc)}{d(\Delta p)} < 0.$$

By definition,

$$(1-vc)^3 \approx \Delta p^{-\varepsilon}.$$

ε is a positive function of the compressibility constant, N, $\varepsilon = f(N)$.

$$K_1 = K_2 \cdot \Delta p^{-\varepsilon}$$

and

$$t = \frac{1}{2K_2} \Delta p^{N+\varepsilon-1} \cdot w^2 = \frac{1}{2K_2} \Delta p^n \cdot w^2. \qquad (13)$$

For physical reasons, n has to be negative. Based on the listed crude estimations, the conclusion is

$$\frac{d|n|}{dN} < 0.$$

Further, for *laminar flow,*

$$\frac{d(\log t)}{d(\log \Delta p)} = n \qquad (14)$$

will depend on the compressibility of the mat in such a way that increased compressibility reduces the pressure dependence of the drainage time.

At partial turbulent flow, the total pressure drop may be written in the form

$$\Delta p = F_1 \frac{dQ}{dt} + F_2 \left(\frac{dQ}{dt}\right)^2, \qquad (15)$$

where F_1 and F_2 are factors giving the relative effect of laminar, and turbulent flow respectively, on the total pressure drop.

This may be simplified to[40]

$$\Delta p = F_3 \left(\frac{dQ}{dt}\right)^m \qquad (16)$$

where $1 \leqslant m \leqslant 2$.

$m = 1$: purely laminar flow

$m = 2$: purely turbulent flow

and hence,

$$\frac{dQ}{dt} = \left(\frac{\Delta p}{F_3}\right)^{1/m}. \qquad (17)$$

The assumption that the pressure dependence of F_3 has the same form as that of K_2 equation (*13*) implies that, at partially turbulent flow, the drainage time's pressure dependence is reduced compared to the situation of pure laminar flow through the same fibre web.

According to Ingmanson and Andrews[10] turbulent flow may be the dominant flow condition in high speed commercial paper sheet forming.

As the average drainage flow is inversely related to sheet basis weight, the relative degree of turbulent flow will evidently be reduced at increasing grammages.

Based on the foregoing calculations, and this statement, it may be concluded that for sheet forming where there is some degree of turbulence initially the pressure dependence of the drainage time will increase with increasing grammage of the sheet, and approach a limit determined by the compression characteristics (N) of the pulp.

As the statements in this discussion are based upon severe simplifications, the conclusions must be regarded as being qualitative only. They may be summarised in the following form.

Hypotheses:

$$\frac{\delta(\log t)}{\delta(\log \Delta p)} = f(N, m), \qquad (18)$$

$$\frac{\delta|\delta(\log t)/\delta(\log \Delta p)|}{\delta N} < 0, \qquad (19)$$

$$\frac{\delta|\delta(\log t)/\delta(\log \Delta p)|}{\delta m} < 0. \qquad (20)$$

In cases with some degree of turbulence:

Hypotheses:

$$\frac{\delta|\delta(\log t)|/\delta(\log \Delta p)}{\delta w} > 0, \qquad (21)$$

$$\frac{\delta(\log t)}{\delta(\log \Delta p)}\underset{w\to\infty}{\to} f(N). \qquad (22)$$

5.3—*Factors determining the influence of the grammage on the drainage time*

During the discussion of the influence of drainage pressure on drainage time, a constant flow resistance was assumed to exist throughout the whole web. However, this is not the case in reality, as the degree of web compression will increase continuously from the boundary between the fibre suspension and the fibre web, down to the wire. This compression will be time dependent, and the eventual turbulent flow component will be reduced with increasing web thickness.

A better assumption is that the average specific drainage resistance is changed during the web build-up.

Again a slightly modified form of d'Arcy's equation provides a suitable starting point:

$$\frac{dQ}{dt} = \frac{A \cdot \Delta p}{\mu w \bar{R}_s} = \frac{dw}{s\,dt},$$

where $\bar{R}_s$ = average specific flow resistance.[7, 8] Assuming that the relationship between the average specific flow resistance and the deposited fibre web's grammage follows an equation of the form $\bar{R}_s = K_4 w^\lambda$, the change in grammage with time is

$$\frac{dw}{dt} = \frac{A \cdot s \cdot \Delta p}{\mu \cdot K_4 \cdot w^\lambda \cdot w}.$$

Rearranging, and using the relationship $dQ = (1/s)\,dw$,

$$w^{\lambda+1}\,dQ = K_5 \cdot dt.$$

Solving for $t = 0$, $w = 0$, to $t = t$, $w = w$ and $\lambda \neq -2$,

$$t = \frac{1}{(\lambda+2)K_5} \cdot w^{\lambda+2}. \qquad (23)$$

Thus, based on the listed assumptions,

$$\frac{\delta(\log t)}{\delta(\log w)} = \lambda + 2. \qquad (24)$$

Here, $\lambda < 0$ means that the marginal increment in total drainage resistance decreases with each unit increase in grammage whereas $\lambda > 0$ means that the marginal increment in drainage resistance increases with increasing grammage.

As outlined in the discussion on the influence of drainage pressure on drainage time, the degree of turbulence will be lower at increasing grammages. As the flow rate increases at increasing drainage pressure, the degree of turbulence will increase.

Hypothesis:

$$\frac{\delta[\delta(\log t)/\delta(\log w)]}{\delta(\Delta p)} < 0. \qquad (25)$$

(This equation is also a consequence of equation (*21*))

$$\frac{\delta[\delta(\log t)/\delta(\log w)]}{\delta m} > 0. \qquad (26)$$

This hypothesis is only suggested for high drainage rates where there is a substantial turbulence component. As pointed out by Wahlström *et al.*,[37] and shown in equation (*13*), the consequences of the ideal case of d'Arcy's law to apply fully (low consistencies, no time dependence of the compaction,

$\lambda = 0$, i.e. $d(\log t)/d(\log w) = 2$), the drainage time increases with the second power of the grammage.

Now, consequences of the time dependence characteristics of the fibre web compression should be considered.

Several studies[12, 23, 40] have shown that the fibre mat compaction does not occur instantaneously. Equation (*6*) therefore just describes the equilibrium status, whereas an expression for the actual process should include a time dependent element.

Time dependence probably is caused by factors such as

1. Structural rearrangements in the fibre web,
2. Plastic changes of the fibres,
3. Hydraulic pressure over the mat, as compression implies that water is expressed. The fibre web will try to resist this.

Beating is very likely to increase the effect of all three factors, as it increases the flexibility and degree of swelling of the fibres, and makes them more amenable to structural and plastic changes. Also the fine material produced will increase the flow resistance.

Seborg's[23] studies strongly support this assumption.

Wilder[41] examined the long fibre fraction of an unbeaten sulphate summerwood pulp. Using a combination of theoretical and empirical calculations he found that the specific drainage resistance increased by 26 per cent at a total load of 98·1 Pa, and by 62 per cent at a total load of 981 Pa, when the loading time was increased from 0·001 to 600 s. An increase in loading time from 0·001 to 10 s, increased the resistance by 18 and 40 per cent respectively. These are very significant changes. And the pulp used by Wilder was a very free one.

The time dependence of the compression process implies that the specific drainage resistance increases with the loading time, and hence that the total flow resistance at continued filtration increases at a faster rate than the corresponding increase in basic weight. The increased compaction also results in an improved fine material retention, which in turn increases the drainage time further.

The mechanism discussed here means that the deposition of each additional unit increment of fibres on the bed causes a larger increase in the total drainage resistance than the previous weight unit did. Using equation (*24*),

Hypothesis:

$$\lambda > 0.$$

$$\frac{\delta(\log t)}{\delta(\log w)} > 2. \qquad (27)$$

According to Wilder's[41] conclusion that the relative change in drainage resistance with time increases with increasing applied pressure difference, it may be concluded that in terms of the time dependence, the effect of increasing basis weight is to increase the average specific flow resistance.

Hypothesis:

$$\frac{\delta[\delta(\log t)/\delta(\log w)]}{\delta\,(\Delta p)} > 0. \qquad (28)$$

This also implies that the effect of pressure decreases at increasing basis weight.

Hypothesis:

$$\frac{\delta|\delta(\log t)/\delta(\Delta\, p)|}{\delta w} < 0. \qquad (29)$$

Now, the hypotheses in equations (*21*) and (*25*) are contradictory to the hypotheses in equations (*28*) and (*29*).

Equations (*21*) and (*25*) are based on the assumption of partial turbulent flow in fibre webs, whereas equations (*28*) and (*29*) are the consequences of the time dependence of the fibre web compaction.

Thus, there are two competing effects, and the net result will depend on the properties of the pulp in question.

Generally, however, the turbulent flow can be assumed to take place primarily in webs from free pulps, whereas the time dependence of the compaction is of greater importance with pulps of lower freeness.

5.4—*The influence of fibre cross-sectional form on the effect of the drainage pressure*

Labreque[35] in his study on the importance of the aspect ratio (AR) of the fibres suggests an empirical equation for Kozeny's factor for fibre beds:

$$\begin{aligned} k = &-12{\cdot}29+42{\cdot}9(1-vc)-24{\cdot}5(1-vc)^2+[1{\cdot}90-10{\cdot}9(1-vc) \\ &+9{\cdot}6(1-vc)^2]\cdot(\mathrm{AR})-[0{\cdot}18-1{\cdot}61(1-vc)+1{\cdot}45(1-vc)^2](\mathrm{AR})^2; \qquad (30) \end{aligned}$$

$$0{\cdot}6 \leqslant (1-vc) \leqslant 0{\cdot}8; \qquad \mathrm{AR} \leqslant 4{\cdot}7.$$

By partial derivation of this, one gets some impression of how the cross-sectional form of the fibres and the porosity of the web influence the drainage resistance of the web.

Fig. 1 shows the derived values of equation (*30*) as functions of the porosity $(1-vc)$, for various AR values.

For fibre webs made from fibres of AR > 2, the flow resistance will increase at increasing aspect ratio, compared at constant porosity. The effect increases with increasing mat density.

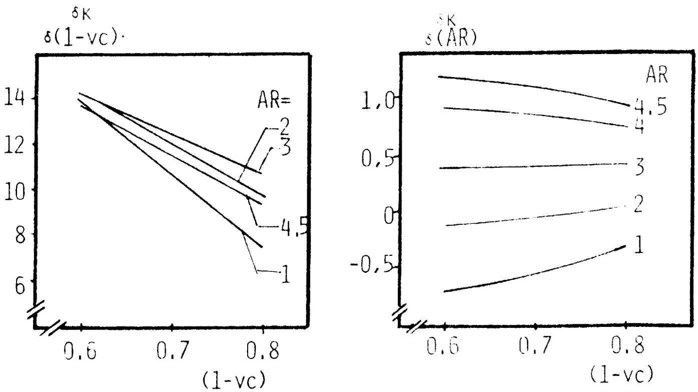


Fig. 1—$\delta K/\delta(1-vc)$ and $\delta K/\delta(AR)$ as functions of the fibre mat void fraction (porosity). The functions are developed by derivation of Labreque's equation

According to Labreque,[35] fibres of high aspect ratio will pack more densely at a given applied compaction load, than will cylindrical fibres.

Compared at constant N (equation (*6*)), a given increase in drainage pressure will increase the drainage resistance of a mat of flat fibres significantly more than of a mat of cylindrical fibres, i.e. at given compressibility, flat fibres will give lower value for the influence of drainage pressure on drainage time (assuming laminar flow).

Hypothesis:

$$\left|\frac{\delta \log t}{\delta \log (\Delta p)}\right|_{\text{flat fibres}} < \left|\frac{\delta \log t}{\delta \log (\Delta p)}\right|_{\text{cylindrical fibres}} \quad . \quad . \quad (31)$$

The time-dependent compression is caused partially by the drainage resistance within the fibre web. The specific drainage resistance depends very much on fibre cross-sectional form,[22, 35] and as seen from Fig. 1.

Seborg[23] reported a significantly slower compaction rate for beaten than for unbeaten pulp. One major change of the fibre form by beating is the collapse and flattening of the fibres.

Therefore, the rate of the change of the web compression can be expected to decrease with increased aspect ratio, on a constant porosity basis.

Hypothesis:

$$\left|\frac{dc}{dt}\right|_{\text{flat fibres}} < \left|\frac{dc}{dt}\right|_{\text{cylindrical fibres}} \quad . \quad . \quad . \quad . \quad (32)$$

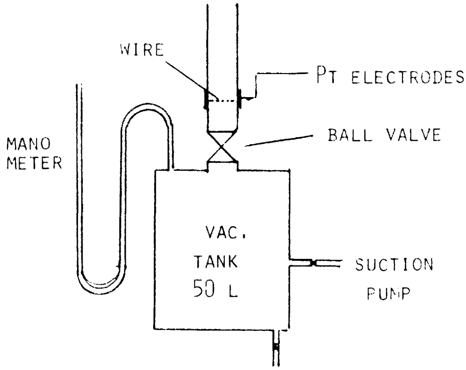


Fig. 2—Schematic of the drainage apparatus

6—*Experimental study*

6.1—*Apparatus*

IT WAS the intention of this project to determine actual sheet drainage times using a constant pressure drainage apparatus, as this was considered to be the most relevant principle from a practical paper-making aspect.

The authors chose to work as closely as possible to the realistic levels of grammage, drainage pressure and suspension consistency used on commercial machines.

The drainage apparatus used is shown in Fig. 2. It is similar to those used by Wahlström and O'Blenes,[37] and Meadley,[11] which were based on previous work by Mardon *et al.*[2] A plexiglass tube with an inner diameter of 60 mm was installed above a vacuum tank of 50 litre volume. A removable paper making wire, fixed on a circular frame, was fitted at the base of this tube. The wire was a standard bronze wire, 3-shed, 26 × 19 mesh/cm. An Ohio ball valve of the same internal cross-section as the tube was placed under the wire. The drainage time was measured with an electric clock that was activated by a switch on the valve. Two Pt electrodes were installed on the inner surface of the plexiglass tube, at a point 5 mm above the wire and connected to an external power cell. Thus when the liquid level fell below the electrodes, the circuit was broken, and the clock stopped. This system has been used successfully for many years at the research laboratory of SCA, Sundsvall, Sweden.[42]

At the beginning of each run, the section of the plexiglass tube between the valve and the wire was filled with water, while the volume beneath the valve was under vacuum. Thus, when the valve was opened, the water under the wire dropped into the vacuum tank, and the water/air interface created on the under side of the wire. Wahlström *et al.* used a system with a continuous water phase under the wire, and the characteristics of the two systems are discussed in their paper.

As an introduction to the work being reported in this paper, the dynamics of the drainage apparatus were studied, using the type of level register principle used by Wahlström *et al.*[37]

6.2—*Experimental procedure*

The pulp suspension was prepared using distilled water, to which was added 0·05 g/l NaCl to obtain the desired conductivity. The temperature of this suspension was held thermostatically at 23° C.

Most of work was performed using consistencies in the range 0·05–0·2 per cent, which is on the low side compared with technical practice. Grammages were in the range 80–200 g/m², which is fairly high.

Applied drainage pressure was varied between 2·5 and 50 kPa.

Six replicates were normally run for each set of experimental conditions. The grammage was determined by drying and weighing the sheet from every second run.

The percentage fibre retention was not measured. The grammages reported are those actually retained on the wire.

Drainage times were normally in the range of 0·3–50 s., mostly 0·5–5 s.

The reproducibility of the tests was checked by calculating the coefficient of variation for each experimental point. For most experiments it was found to be less than 5 per cent. For some tests on highly beaten pulps, the coefficient of variation was found to be 10–15 per cent.

6.3—*Experimental results*

The first series of experiments were performed on synthetic model fibres, in order to have a simple system for the first investigation on the validity of the hypotheses.

The next series of experiments then was performed on various classified wood pulps of very varying fibre characteristics, to study the applicability of the findings from the first series.

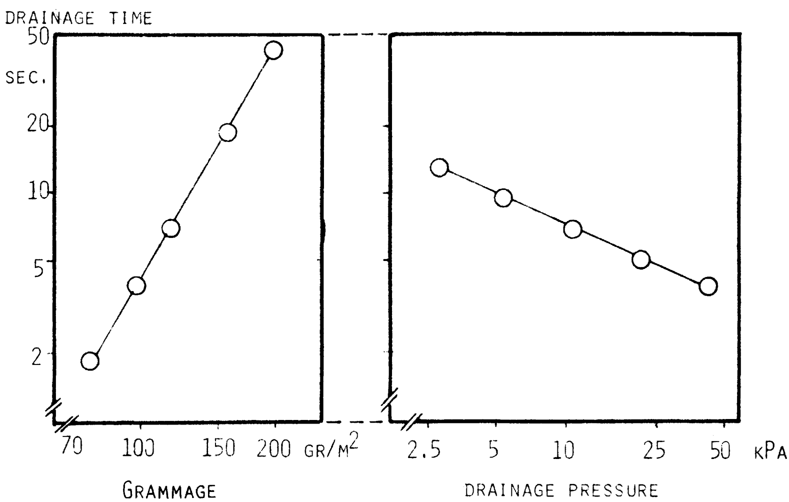


Fig. 3—Typical set of drainage time readings. Sulphate pulp 12 000 rev. PFI-mill, 0·5 g/l

The last series of experiments then was performed on whole, beaten pulps.

Typical results of the drainage tests are presented in Fig. 3, where the drainage time is plotted against the grammage and the drainage pressure on a log-log scale.

There is a good linear relationship in both instances, which proves that the results follow Wahlström and O'Blenes' equation

$$t = \frac{G}{s} w^{\alpha}(\Delta p)^{n}.$$

The slope of the lines give α and n from data sets like those of Fig. 3. The values of α and n were normally obtained by regression analysis based on accumulated data sets.

The inverse relationship between drainage time and suspension consistency was generally confirmed, but was not extensively investigated.

6.4.1—*Results for model fibres*

Model staple fibres prepared from rayon monofilaments of various denier were used in this part of the study. In the experimental runs using the model fibres, the low concentration of 0·5 g/l was normally used.

Dimensional data of the model fibres used are listed in Table 1. A typical set of drainage times from a series using medium grammage and drainage pressure is also included.

In a study of the sheet drainage characteristics of cylindrical and flat fibres, sheets were made, using fibre lengths 6·5–7 mm, 1·5 denier, from the pure

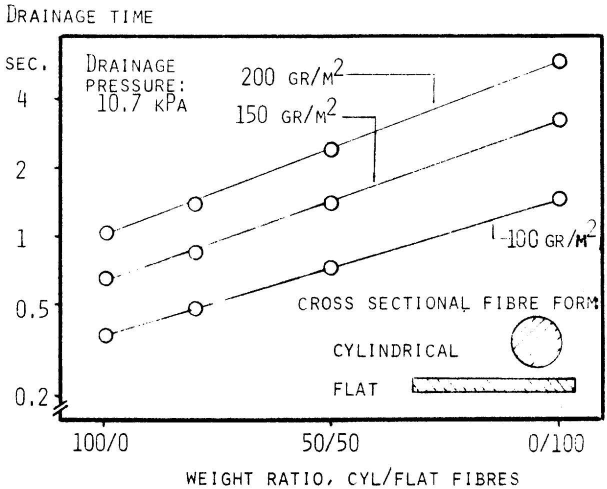


Fig. 4—Drainage times for mixtures of cylindrical/flat fibres, 1·5 denier. Fibre length 6·5–7·0 mm

TABLE 1—DIMENSIONAL DATA OF MODEL STAPLE RAYON FIBRES, USED FOR DRAINAGE STUDIES

Fibre form	*Denier*	*Cross-sectional dimensions* $mm \times 10^{-3}$	*Fibre length mm*	*Length/diameter ratio*	*Relative cross-sectional moment of inertia Flat fibre = 1*	*Drainage time, s. cons. 0·5 g/l 150 g/m²* $\Delta p = 10{\cdot}7$ *kPa*
Cylindrical	1·5	$D = 11{\cdot}8$	1·85	159	12	0·76
Cylindrical	1·5	$D = 11{\cdot}8$	2·5	216	12	0·72
Cylindrical	1·5	$D = 11{\cdot}8$	3·2	278	12	0·71
Cylindrical	1·5	$D = 11{\cdot}8$	6·9	590	12	0·66
Cylindrical	3·0	$D = 16{\cdot}7$	3·2	190	47	0·53
Cylindrical	4·5	$D = 20{\cdot}5$	3·5	171	106	0·50
Cylindrical	8	$D = 27{\cdot}3$	3·2	118	334	0·45
Cylindrical	8	$D = 27{\cdot}3$	7·0	225	334	0·47
Flat (rectangular	1·5	3×36·3	2·8	2 140	1	3·79
cross-section)	1·5	3×36·3	3·4	1 132	1	3·06
	1·5	3×36·3	3·15	939	1	3·15

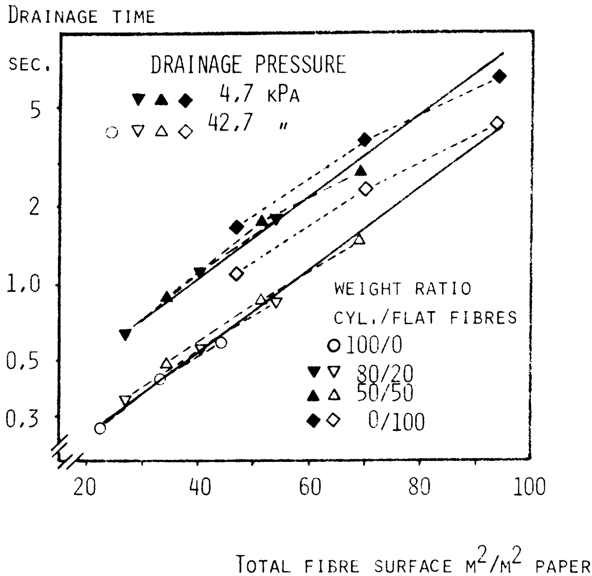


Fig. 5—Drainage time for mixtures of cylindrical and flat rayon model fibres 1·5 den. *vs.* total fibre surface in the sheet. Grammages 100, 150 and 200 gr/m^2

components, and from mixtures. In Fig. 4 log drainage time has been plotted against weight percentage of flat fibres in the furnish. Straight line relationships appear, one for each grammage.

As the flat fibres have a larger specific surface than the cylindrical ones, a plot of drainage time *versus* total fibre surface, as square metre fibre surface per square metre of paper also yields series of straight lines, which are independent of grammage or fibre composition, Fig. 5. However, there is one exception, which is the sheets made from flat fibres only.

The points for the two extreme drainage pressure levels are plotted. The results of three intermediate pressure levels fell in between.

The deviation of the flat fibres from the other furnishes appears to increase with increasing pressure.

It can be seen in Fig. 5 that the relative difference between drainage time for the flat fibres at the two stated drainage time levels is less than for the other fibre compositions. The effect of varying drainage pressure evidently gives different drainage time response by the various fibre types.

The drainage pressure exponent n from equation (*8*) was calculated from

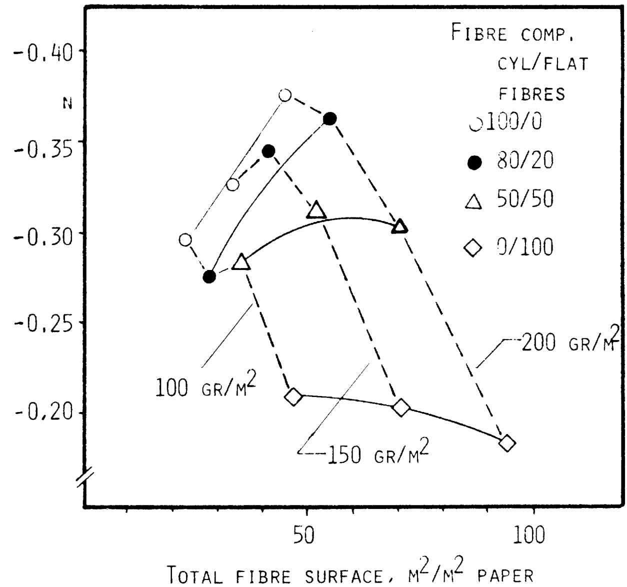


Fig. 6—The drainage pressure exponent ***n*** for various fibre compositions and grammages. Model rayon fibres

the drainage times for the various fibre compositions, and is presented in Fig. 6. It varies widely both as a function of the grammage and the fibre form.

As an explanation of this, it would appear that the fibres and grammages used cover a wide region relative to that of the viscous and turbulent flow and degree of web compaction.

For purely cylindrical fibres, the values of n increase with increasing grammage. These fibres presumably have low mat compaction, and low specific surface area, and one may therefore suspect a substantial degree of turbulent flow. The degree of which is reduced at increased grammage, giving higher n values, in accordance to the postulate in equation (*21*).

For the flat fibres, n has a low value, with a slight downward trend, as a function of the grammage. The low level can be explained by high web compaction of the flat fibres,[35] which according to equation (*32*) will give low n values. The high drainage resistance will reduce the tubulent flow component very much. The grammage influence on n therefore will be determined by the time effect of the web compaction, which according to equation (*29*) reduces n with increasing grammage.

The mixtures of cylindrical and flat fibres fall in between the extremes of the two pure types of fibres, as could be expected.

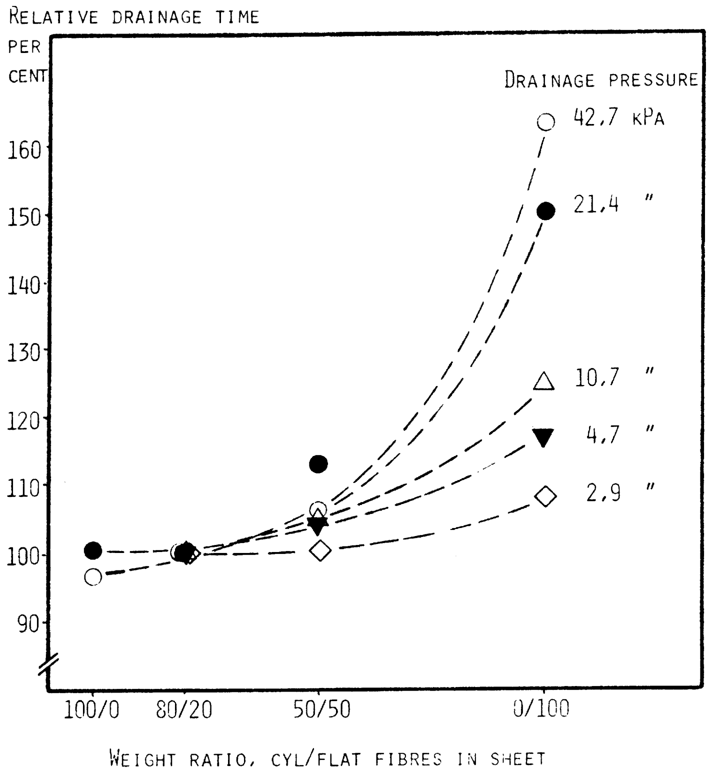


Fig. 7—The effect on the relative drainage time of the fibre composition and the drainage pressure. Basis: drainage time for sheet with 80/20 cyl./flat fibres. Comparison made at constant fibre surface area, 50 m^2/m^2 paper

It is interesting to notice that the flat fibres form a mat of low permeability. The value of n at 200 g/m^2 is $-0{\cdot}183$, which means that the drainage pressure will have to be increased to almost its sixth power in order to double the drainage speed if drainage pressure only is to be varied. This point illustrates the problems of making such papers as glassine.

However, as there is no linear relationship between the percentage of flat fibres in the furnish and n, we may improve the effect of drainage pressure on the paper-making by adding some percentage of relatively stiff fibres.

This point becomes amplified further, when the actual drainage times are compared relative to a constant total fibre surface area basis. This has been done in Fig. 7. Two trends are evident. Firstly, large increases in drainage

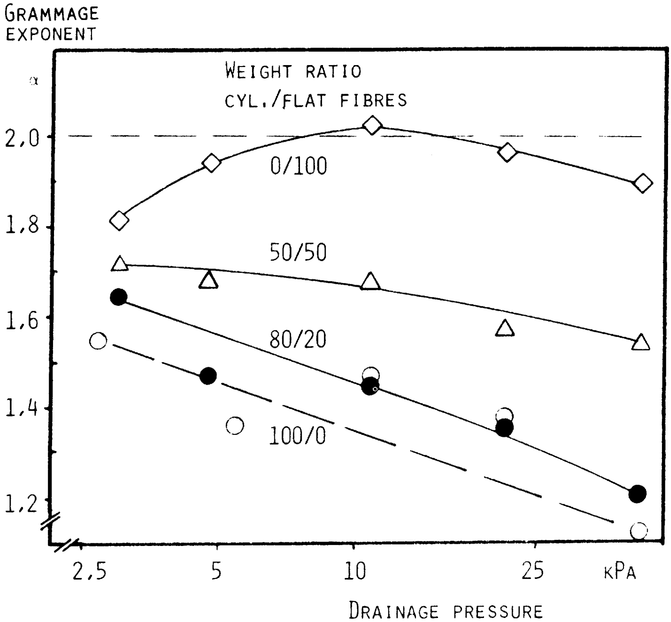


Fig. 8—The influence of drainage pressure on the grammage exponent α of equation (*8*). Mixtures of cylindrical and flat model fibres, 1·5 denier

time occur primarily with paper made purely from flat fibres. Secondly, the effect increases most rapidly at increased drainage pressure. Thus, from the point of view of drainage pressure efficiency, it is evidently a significant advantage to include some stiff fibres in the furnish.

This finding is confirmed by the behaviour of practical furnishes containing mechanical pulps, which contain a mixture of stiff whole fibres and fibre fractions, and very flexible flat fibre wall fragments. The material drains fairly slowly at low pressure, as in freeness testers, but at the higher drainage pressures present on paper machines the stiffer material will resist web compaction and thus will efficiently maintain drainage. Well beaten chemical pulp is more homogeneous with regard to the flexibility of its components. Consequently the high drainage pressure on the paper machine, relative to that in the freeness tester, will not increase the drainage speed as much as it does for mechanical pulp.

In Fig. 8 the grammage exponents α of the drainage time equation (*8*) are plotted against log drainage pressure for the various model fibre compositions.

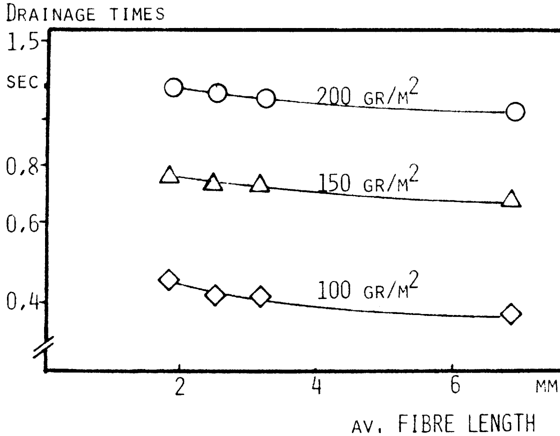


Fig. 9—The influence of the fibre length on drainage time. Model cylindrical rayon fibres, 1·5 den.

Again there is a wide variation which is dependent on drainage pressure and fibre composition.

Ideally, assuming low consistency and d'Arcy's law to hold, α should be 2, as shown in equation (*13*) and mentioned by Wahlström *et al.*[37] However, in the current work, only one value reaches that level, whereas all the others were lower. Wahlström *et al.*, too, report some α-values lower than 2, and discuss possible reasons for this, without reaching any definite conclusion.

The results of the present study again are explained as a consequence of the varying degree of turbulence during drainage, and the time dependent compression.

There will be an increasing degree of turbulence with increasing proportions of cylindrical fibres because of the less compacted fibre web, and the lower specific fibre surface. The reduction in α with increasing pressure supports the hypothesis in equation (*25*), and the different positions of the curves, equation (*26*).

The curve for purely flat fibres initially rises, then turns downward. The initial rise is believed to be caused by time dependent compression, as postulated in equation (*28*). The trend downward is thought to be caused by an increasing component of turbulent flow at very high drainage pressure, in accordance with equation (*25*).

In Fig. 9 the drainage time (log scale) is plotted *vs.* the fibre length for various rayon model fibres of denier 1·5. There is a slight increase for shorter fibres.

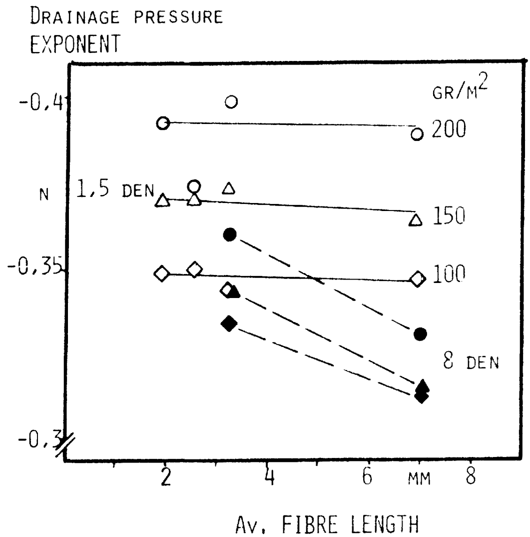


Fig. 10—The influence of the fibre length on drainage pressure exponent *n* in equation (*8*)

Fig. 10 shows that the variation of the fibre length of denier 1·5, in the range 2–7 mm, has no significant effect on the drainage pressure exponent *n* of equation (*8*). For denier 8, a reduction of the fibre length from 7 to 3·2 mm increases the drainage pressure exponent.

The fibre length effect for the thick 8 denier fibres probably is caused by the fibre's *L*/*D* ratio having fallen below the critical value, as explained by Jones.(15) The critical *L*/*D* ratio for glass fibres, according to Jones, is 500, and 75–100 for nylon fibres. The exact value for rayon is not known. From Table 1 we see an *L*/*D* value of 118 for the short 8 denier fibres.

As this is the only fibre length used that seems to be below the critical *L*/*D* value, the latter is likely to be somewhere in the region 120–160 for the rayon fibres used in this study.

The results are in full accordance with the results found when studying the model fibres, assuming fibre *WL* to be collapsed already in unbeaten state. Beating, however, has reduced the influence of the fibre form in the unbeaten state significantly.

Variation of the lengths of the flat fibres in the area 2·8–6·5 mm had a small but significant effect on the drainage time (increased at reduced fibre length), and a small effect on the drainage pressure exponent *n*.

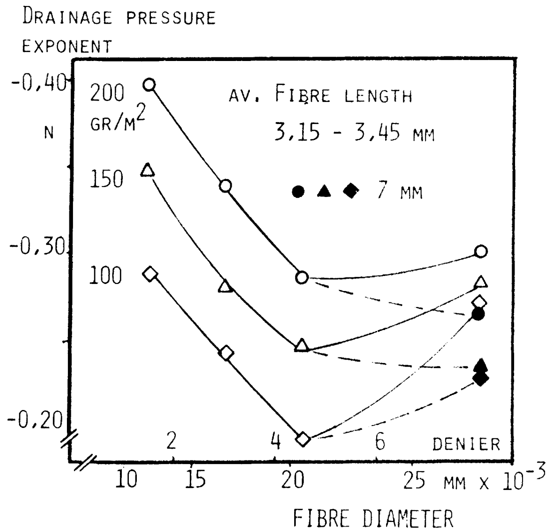


Fig. 11—The influence of the fibre denier on the drainage pressure exponent *n*. Model cyl. rayon fibre

Fig. 11 shows the drainage pressure exponent, *n*, for sheets made from cylindrical fibres of constant fibre length (3·15–3·45 mm) but varying denier. The thicker the fibres, or the lower the basis weight, the lower the specific

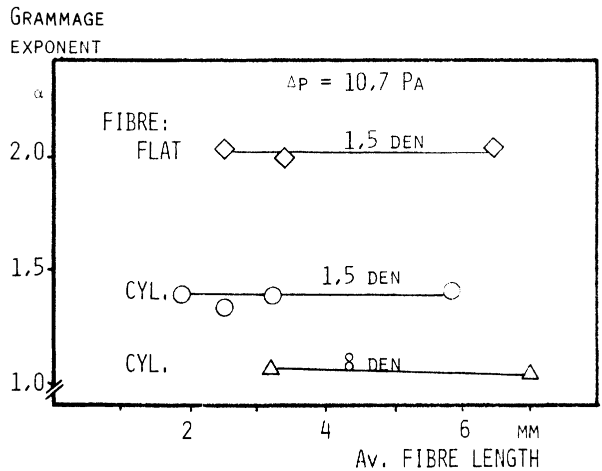


Fig. 12—The influence of the fibre length on the grammage exponent α

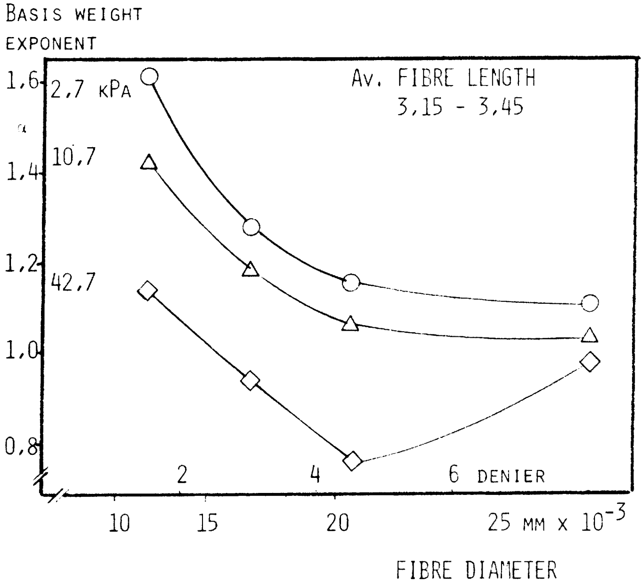


Fig. 13—The influence of the fibre denier on the basis weight exponent α. Model cyl. rayon fibre

fibre surface area, the larger the mat voids, and consequently the larger the turbulent component of the flow. This seems very likely, and the slopes up to a denier of 4·5, and the grammage effect are then in accordance with equations (*20*) and (*21*).

The n-values for 8 denier fibres do not fall into this picture. These 3·2 mm fibres are, as pointed out, probably below the critical L/D ratio. Values for 7 mm fibre length are therefore also plotted (dotted lines), and using these, the 8 denier fibres fall better into the general picture.

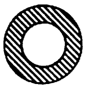
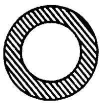
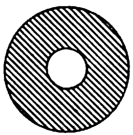
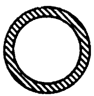
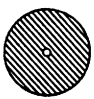
Fig. 12 reveals that the fibre length within the range tested has no effect on the grammage exponent α. The critical L/D ratio thus does not affect the grammage influence on the drainage time.

In Fig. 13 the fibre length is kept constant at 3·15–3·54 mm, whereas the denier is varied. α drops with increasing fibre denier or increasing drainage pressure, which probably is caused by an increasing degree of turbulence, and is explained by the mechanisms leading to equations (*25*) and (*26*).

6.4.2—*Results using classified wood fibres*

Wood fibres, which are the important ones for practical paper-making, have a wide variation of lengths, widths, surface areas, cross-sectional forms

TABLE 2—DIMENSIONAL CHARACTERISTICS OF SOME TROPICAL FIBRES

Cross-section form (Drawn from original wood)	Name	'Denier' g/9000 m pulp fibres	Fibre length weighted aver. mm L	Measured on wood		Fibre length/width ratio		Calculated fibre surface area m² per 100 g of fibres
				Fibre diam. arith. aver. mm × 10^{-3} D	Lumen diam. arith. aver. mm × 10^{-3} d	Original L/O	Collapsed L/(D−d)	
	Dangula	1·0	1·17	18·1	5·0	65	89	51
	Evodia	0·86	1·08	19·5	12·4	55	152	64
	Itagnan	1·01	1·94	26·0	19·0	75	277	73
	Katmon	3·94	2·83	34·9	14·1	81	136	25
	White Lanan	0·58	1·16	20·7	16·1	56	253	101
	Pangnan	0·69	0·93	14·1	3·0	66	84	58
	Tamaynan	1·87	2·02	22·0	3·3	92	108	33

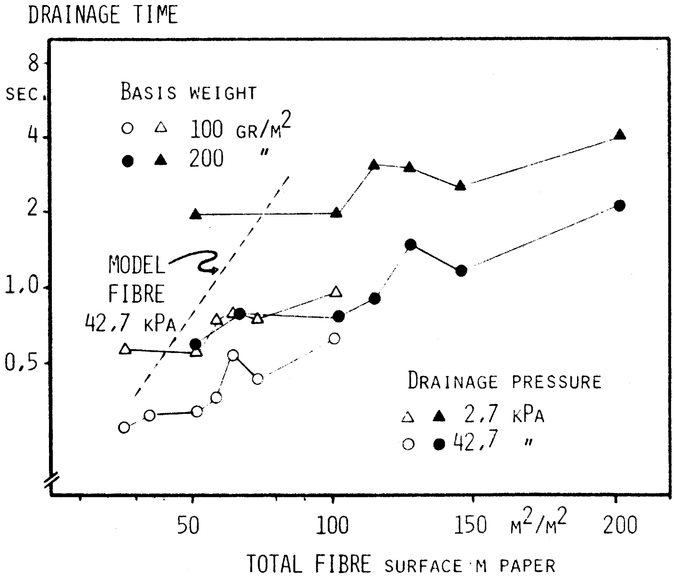


Fig. 14—Drainage time *vs*. calculated total fibre surface in the sheet. Classified hardwood fibres

and stiffnesses, even within the same pulp batch. The important factors are also considerably influenced by technical operations in pulp and paper making, such as pulping method, yield and beating.

It is difficult to isolate any special wood fibre dimensional factor, and study it separately.

To study the effect of wood pulp fibre dimensions on paper sheet drainage, sulphate pulps were made in the laboratory from some selected tropical hardwoods. The species were chosen to cover a wide range of cross-sectional forms and areas, as well as fibre lengths.

The fibre material is described in detail elsewhere.[43] To reduce the effect of fines, only the +50 mesh fractions are used. Some data are presented in Table 2, where sketches of the cross-sectional forms (drawn from wood cross-sections) are presented. The pulping yield was ca. 50 per cent. The pulps were not dried before drainage tests.

Fig. 14 shows some drainage times *vs*. calculated total fibre surface area. The surface area has been calculated using the average fibre diameter of Table 2, and this gives, especially for beaten pulps, very debatable results.

Fig. 14 reveals the same general trends as were seen using model fibres.

The points are more scattered, as might be expected because of the less well-defined fibre material.

The dotted line of Fig. 14 gives the regression line for the model rayon fibres of Fig. 5. There is a significant difference in slope.

Table 3 shows the change in drainage time caused by beating, for various fibre types, basis weights and drainage pressures. Beating: 8000 revs in PFI mill.

TABLE 3—THE CHANGE IN DRAINAGE TIMES CAUSED BY BEATING, FOR FIBRES OF VARIOUS FORMS

+50 mesh fraction of classified pulp.
The numbers give the ratio of the drainage times for beaten and unbeaten pulp.

		Wood species. Fibre specs. in Table 2					
Δp kPa	w gr/m²	*Dangula*	*Evodia*	*Itagnan*	*Katmon*	*White Lanan*	*Pangnan*
2·7	100	2·38	1·83	1·95	2·51	1·61	2·92
	200	2·96	2·18	2·15	3·89	1·89	3·85
42·7	100	1·72	1·46	1·72	2·00	1·55	2·06
	200	2·61	2·03	2·23	3·29	1·91	3·37
Drainage time sec. 100 g/m² beaten pulp 42·7 kPa		0·55	0·79	0·74	0·56	0·96	0·74

The fibres that originally were thick-walled and presumably stiff change considerably more with regard to drainage time than do thin-walled fibres.

Fig. 15 presents the influence on n of the basis weight of beaten pulps.

The lower four fibre types seem to approach a common value, in the well-known[38, 38] range of about $-0{\cdot}35$, whereas the upper two differ from this trend. These two very likely have fibre dimensions below the critical L/D ratio. Assuming the beating to have made the fibres prone to collapse during drainage, the values for the L/D ratio show that the two upper fibre types, even when collapsed, have L/D ratios below 100, whereas the other ones have L/D ratios well above.

The trends of the other curves may be explained by the cross-sectional form of the fibres, and the consequences of these on the type of flow, time dependent compaction, and the rate of compaction (equation (*32*)). K is a very coarse fibre whereas E is a thin-walled, and will have a very high aspect ratio when collapsed.

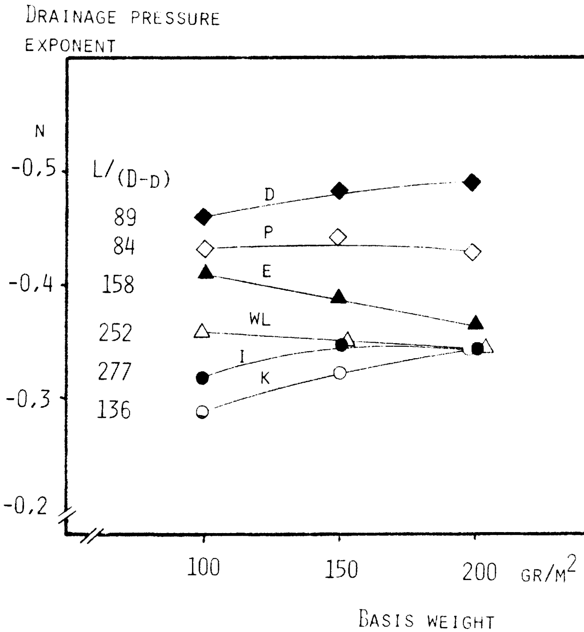


Fig. 15—Drainage pressure exponent *vs.* grammage, for various beaten hardwood fibres. Fibre dimensions: Table 2

For unbeaten pulps, there were no clear trends, probably because most fibre types—presumably not collapsed—were in the critical L/D-ratio range (compare Table 2).

For model fibres, the critical L/D ratio did not affect the influence of the basis weight on the drainage time (Fig. 12).

Fig. 16 leads to the same conclusion for the classified wood fibres. The figure shows the influence of the drainage pressure on α for some typical fibre forms, unbeaten and beaten.

The α-values for most beaten pulps are close to 2, indicating the flow to be mainly laminar. At higher pressure levels, the α-values for the coarser fibres drop below 2, probably because of some degree of turbulence (equation (*25*)).

There is a close relationship between the grammage exponent α and the drainage time for relatively heavy sheets (150 g/m^2), as illustrated in Fig. 17. Experimental points are presented here for all the model and classified wood pulp fibres, beaten and unbeaten. The grammage dependence of the drainage time is closely related to the drainage resistance of the web. Fig. 17 therefore

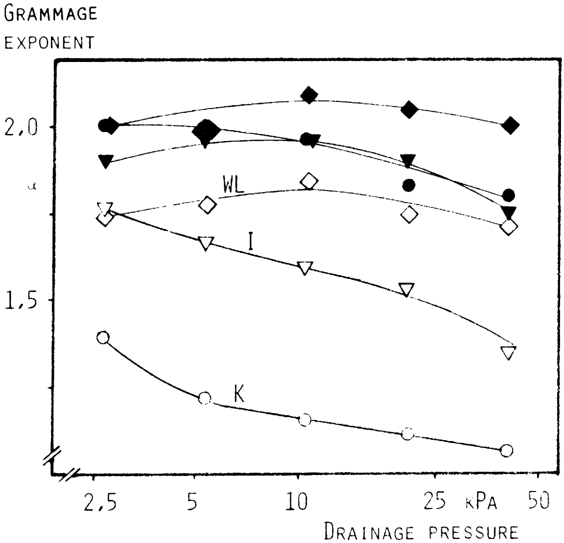


Fig. 16—Grammage exponent α for various hardwood fibres, unbeaten and beaten open symbols: unbeaten fibre dimensions: Table 2

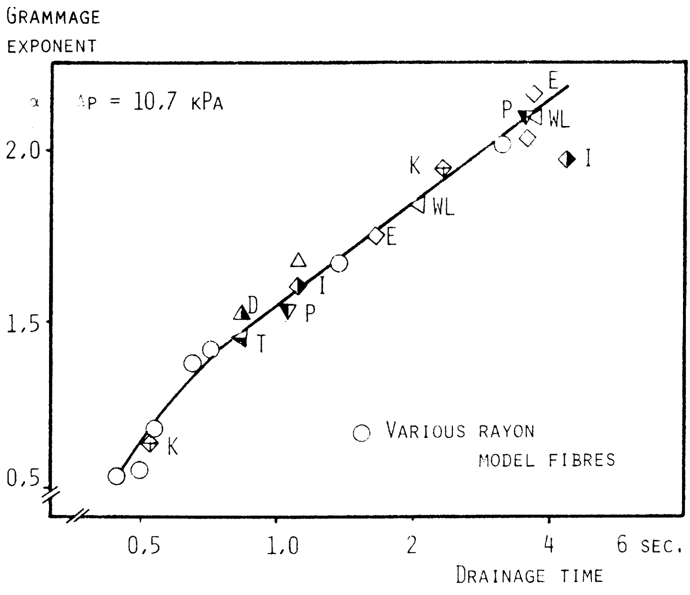


Fig. 17—The grammage exponent *vs*. drainage time for 150 g/m² sheet. Various fibre types, beaten and unbeaten. Drain, pressure: 10·7 kPa

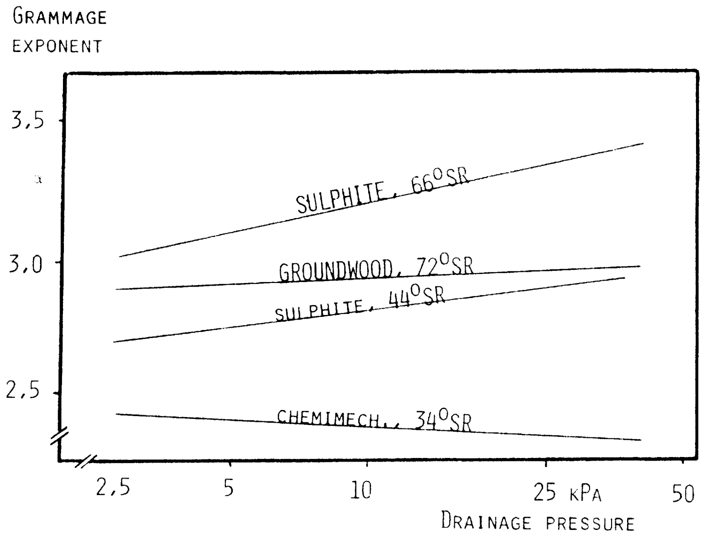


Fig. 18—Grammage exponent for various refined whole pulps

is a clear indication that the time dependence of the fibre web compression is essential for the influence of the grammage on the drainage time.

6.4.3—*Results using beaten whole pulps*

The fine material formed by beating and refining of the pulp has a decisive influence on the drainage resistance. It is difficult to define with regard to particle dimensions and properties. For these and other reasons it is frequently removed during analytical studies of the drainage process. The practical relevance of such studies is reduced because of this.

A few beaten pulps with the fine material present were analysed. Figs. 18 and 19 present some results.

The α-readings of Fig. 18 all are well above 2, indicating laminar drainage flow, and considerable influence of the time-dependent mat compaction (equations (*27*), (*28*)). The only exception is the relatively free chemimechanical pulp, which presumably compacts rapidly (equation (*32*)). The pulp contains stiff fibres, which give a fairly open structure, and consequently one may expect some turbulent flow at higher drainage pressures.

The n-values of Fig. 19 decrease with increasing grammage, in accordance with the assumption of predominantly laminar flow (equation (*29*)). Again the free chemimechanical pulp differs strongly from the others, confirming

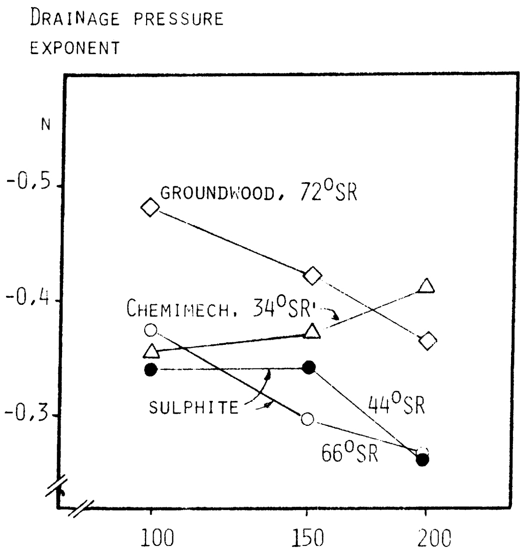


Fig. 19—Drainage pressure exponent *n* for various refined whole pulps

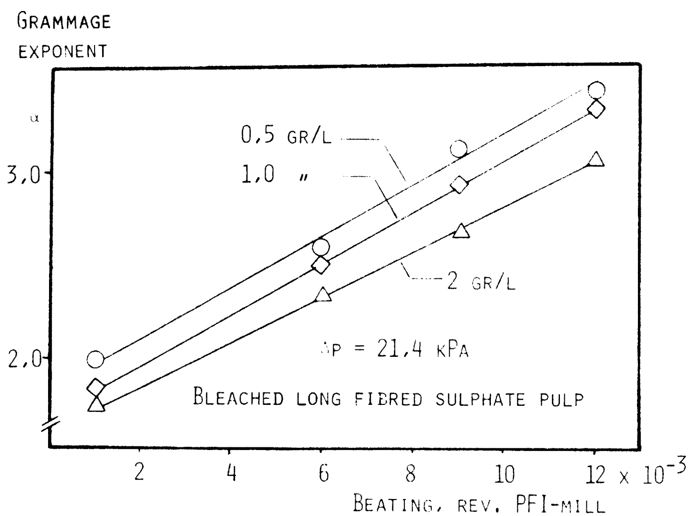


Fig. 20—Grammage exponent for various beating and concentration levels

the assumption of some turbulent flow (equation (*21*)). The higher *n*-values for mechanical and chemimechanical pulps are in accordance with the hypothesis of equation (*32*).

At this point, one might comment on the greatly varying *n*-values obtained by Wahlström and O'Blenes,[37] Lindberg,[38] and Brauns and Tellvik.[39] The variation in *n* reported for mechanical pulps may well be explained by the difference in applied pressure and grammage.

For a long-fibred chemical pulp, the α-value was found to increase linearly with increasing beating time in a PFI-mill, as shown in Fig. 20. α increases also inversely with the pulp concentration as pointed out by Wahlström *et al.*[37] This is probably partly caused by the longer drainage time, and the consequently more severe time dependent compression at lower concentrations.

In this study, the retention of fine material was not controlled. This retention is likely to vary with grammage and drainage pressure, and will therefore limit the significance of the conclusions.

Conclusions

THE results of the experiments using model fibres support the validity of the hypotheses developed in the theoretical part of the study. The fibre cross-sectional form and dimensions were shown to significantly influence the effects on the drainage time of the drainage pressure and the grammage in ways that could be explained by the listed hypotheses.

Also, several of the drainage characteristics of unbeaten and beaten classified sulphate hardwood pulps could be explained by the hypotheses. However, beating of the pulps tends to reduce the influence of the original fibre dimensions significantly. It is assumed that this is caused by swelling and increased flexibility of the fibres. The influence of the original fibre form on the fibre mat compaction and flow resistance is thus reduced considerably.

The experiments using beaten, whole pulps, also generally support the hypotheses. The difference in drainage behaviour between chemical and high-yield mechanical and chemimechanical pulp is in accordance with the hypotheses.

There seems to be a need for more information concerning the time characteristics of the pulp web compression for various fibre types, both with regard to fibre and pulping characteristics.

References

1. J. D. Parker, *The Sheet Forming Process*, STAP No. 9, *Tappi*, Atlanta, Ga. (1972)

2. J. Mardon, A. B. Truman, B. J. Howe and C. K. Meadley, *Papper och Trä*, 1961, **43**, 457, 499, 575, 586, 681, 697
3. S. T. Han, *The Status of the Sheet Forming Process—A Critical Review I.P.C.*, Appleton, Wisc., 1965
4. S. T. Han, *Pulp Pap. Can.*, 1969, **70**, T134
5. H. Meyer, *Tappi*, 1971, **54**, 1426
6. R. M. R. Branion, 'Drainage on the Paper Machine—A Review', presented at Techn. Sect. CPPA, Montreal, Febr. 1977
7. W. L. Ingmanson, *Tappi*, 1952, **35**, 439
8. W. L. Ingmanson, R. P. Whitney, *Tappi*, 1954, **37**, 525
9. W. L. Ingmanson, B. D. Andrews and R. C. Johnson, *Tappi*, 1959, **42**, 842
10. W. L. Ingmanson, B. D. Andrews, *Tappi*, 1963, **46**, 150
11. C. K. Meadley, *Consolidation of the Paper Web*, Techn. Sect. BPBMA, London 1966, 216
12. J. Bergström, Paper presented at 'Internordisk riseringssymposium', Stockholm 1964
13. W. L. Ingmanson, B. D. Andrews, *Tappi*, 1959, **42**, 29
14. B. Abrahamson, J. E. Stone, A. M. Scallan, *Svensk Papperstidn.*, 1968, **71**, 687
15. T. A. Arnevik, Unpublished results
16. A. P. Binotti, G. A. Nicholls, I.P.C. Technical Paper Series No. 39, Appleton, Wisc. Sept. 1976
17. T. A. Arnevik, Dr. ing. Thesis, Univ. of Trondheim 1974
18. P. E. Wrist, *Pulp Pap. Can.*, 1964, **65**, T284
19. H. G. Higgins, J. de Yong, in *Consolidation of the Paper Web*, Techn. Sect., BPBMA, London, 1966, 242
20. T. C. Elias, *Tappi*, 1967, **50**, 125
21. R. L. Jones, *Tappi*, 1963, **46**, 20
22. A. P. Binotti, G. A. Nicholls, I.P.C. Technical Paper Series No. 38, I.P.C., Appleton, Wisc. Sept. 1976
23. C. O. Seborg, F. A. Simmonds and P. K. Baird, *Paper Trade J.*, 1939, Tappi sect. 83
24. G. G. Allan, L. A. Smith, *Cell. Chem. Techn.*, 1968, **2**, 89
25. G. G. Allan, M. L. Miller and A. N. Neogi, *Cell. Chem. Techn.*, 1970, **4**, 567
26. A. P. Schniewind, G. Ifju and D. L. Brink, *Consolidation of the Paper Web*, Techn. Sect., BPBMA, London, 1966, 538
27. L. G. Samuelson, *Svensk Papperstidn.*, 1963, **66**, 541
28. P. Haugen, J. H. Young, 'The Physics and Chemistry of Wood Pulp Fibres', STAP No 8, Ed. D. Page, N. Y., 1970, 242
29. N. Thalen, D. Wahren, *Svensk Papperstidn.*, 1964, **67**, 259
30. J. Bergmann, N. Takamura, *Svensk Papperstidn.*, 1965, **68**, 703
31. U. Frölander, N. Hartler, *Svensk Papperstidn.*, 1970, **73**, 21
32. O. L. Forgacs, S. G. Mason, *Tappi*, 1958, **41**, 695
33. D. H. Page, *Tappi*, 1967, **50**, 449

34. J. E. Luce, in 'The Physics and Chemistry of Wood Pulp Fibres', STAP No. 8, Ed. D. Page, N.Y. 1970, 278
35. R. P. Labreque, *Tappi*, 1968, **51**, 8
36. J. H. Masliyah, PhD Thesis, U.B.C. Vancouver, 1970 (referred in [6])
37. B. Wahlström, G. O'Blenes, *Pulp Pap. Can.*, 1962, **63**, T405
38. L. Lindberg, *Svensk Papperstidn.* 1970, **73**, 451
39. A. Tellvik, O. Brauns, *Svensk Papperstidn.*, 1960, **63**, 803
40. H. Meyer, G. R. Brown, *Tappi*, 1973, **56**, 144
41. H. D. Wilder, *Tappi*, 1960, **53**, 715
42. Central Laboratorium SCA, Sundsvall, Sweden, Description of Drainage Tester
43. P. Bawagan, Dr. ing. Thesis, Univ. of Trondheim, 1972

Transcription of Discussion

Discussion

Mr J. L. De Yong Dr Helle, you based your theoretical work on the Kozeny–Carman model of a fibre pad. This is essentially a solid block of material with tortuous capillaries and the hydrodynamics are based on tubular flow. We have considered a completely different model, the drag model, which indicates the pad as an open structure transversed by cylinders and the drag on cylinders gives rise to the drainage resistence. And this gave us some very precise correlations between experiment and theory. It would be interesting to look at your raw data using our model. Maybe we could do this some time.

Helle I agree with you that the Kozeny–Carman theory is not entirely applicable in this case. But I would submit that our theoretical considerations are not too heavily based on this model.

Mr P. B. Wahlström We did some work along these lines in 1961 in order to find a method of predicting the behaviour of drainage on forming tables, using a constant pressure filtration method. We derived the equation referred to by Helle *et al.*, but were unable to give a good explanation of the variations of the exponents α and n, which you have done very well in this paper. We found that this method of measuring drainage is very useful as long as you deal with drainage under constant pressure without pulsations such as wet suction boxes and twin-wire formers. We are moving into these areas, where this type of work can be very useful to determine the drainage capacity needed for a given application.

Helle In fact we haven't looked at pulsations but we have investigated the effect of shake on drainage and we find a tremendous effect.

Dr H. G. Higgins I am gratified to see that someone at last has used the equation that we introduced in the Third Symposium. But I would like to point out that it assumes a linear pressure drop across the pad. This is a

Under the chairmanship of J. Mardon

restriction on its general applicability. We tried to go further but the mathematics became too involved. Our apparatus was later fitted with manometers so that we could measure the pressure drop at different points across the pad, and we have a great deal of unprocessed data, but the theory becomes extremely difficult when you try to allow for a non-linear distribution of pressure across the pad.

Helle I agree with you that it is an extremely difficult area but I can assure you we have familiarised ourselves with your earlier work.