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THE EFFECT OF BEATING DEGREE ON PHYSICAL CHARACTERISTICS OF WOOD PULP FIBRES

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The purpose of our investigation was to study the influence of the degree of beating on the physical characteristics of unbleached and bleached kraft pulp fibres. For various degrees of beating, the specific volume as well as specific surface based on both volume and mass of fibres were determined. To characterize pulp fibres at different degrees of beating, the weighted and arithmetic average lengths of fibres were measured.

Introduction

Beating process can be carried out under two different sets of conditions. If predominantly bruising conditions prevail, the beating serves to make the fibres more flexible and give them a fibrillated surface in order to enlarge the contact areas

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between the fibres in the final paper and to increase its strength. In order to result in increased surface areas, the mechanical treatment must be performed in a manner which facilitates swelling of the fibres and inhibition of the liquid. On the other hand, if predominantly cutting conditions dominate, another effect of beating is the fragmentation of long fibres, which is sometimes considered to improve the sheet formation and the uniformity of the paper but usually impairs some of its strength properties. The shortening of the long-fibered fraction on prolonged beating affects the strength properties of the paper adversely but may be desired to improve the uniformity of paper formation in the case of extremely long-fibered and resilient pulp. Some loose fibre debris is also formed on beating, which contributes little to the paper strength and impairs the drainage properties. It has to be reminded that the strength of a paper is not derived purely from frictional forces in an entanglement of fibres and fibrils, but the main interfibre cohesion arises from hydrogen bonds developed between hydroxyl groups of the carbohydrates in adjacent fibres [1]. Increased beating of fibres enhances the staining power of pigments incorporated in the sheet.

The aim of our investigation was to determine the effect of beating degree on the specific volume and specific surface of wood pulp fibres.

Theoretical

The volumetric liquid flow rate through pulp bed is given by Darcy's law [2] in the form

$$V = B\frac{A\Delta p}{\mu h} \tag{1}$$

which holds in streamline flow regime. The permeability of the pulp bed can be expressed [3] as

$$B = R^2\frac{\varepsilon}{K} \tag{2}$$

where the hydraulic mean radius of the pores is given as

$$R = \frac{\varepsilon}{(1-\varepsilon)a_v} \tag{3}$$

The specific surface, a_v, is defined as the external area per unit volume of pulp fibres. On substituting Eq. (3) into Eq. (2), the relationship for the permeability of the pulp can be obtained as

$$B = \frac{\varepsilon^3}{(1-\varepsilon)^2 a_v^2 K} \tag{4}$$

where the factor, K, is called the Kozeny constant [2] and is dependent only upon the shape of the pores and the ratio of the tortuous length that liquid traverses in passing through the bed to the actual thickness of the bed. It was found that the Kozeny constant has an average value of 5.55 for randomly packed fibrous beds and shows no apparent variation with porosity, ε, over a range of 0.45 to 0.86 (Ref. [4]).

According to Ingmanson [4] the porosity, ε, can be expressed in terms of the consistency of fibres in pulp bed, C, and the effective specific volume of the swollen fibres, v. Thus,

$$\varepsilon = 1 - vC \tag{5}$$

It must nevertheless be stressed that cellulose fibres swell in water, and since the dimensional swelling of the fibrous mass is not known, the void fraction cannot be obtained directly from the mass concentration of solids in the bed. In addition, the effective specific volume involves the volume of the fibres in the water-swollen state including the volume of the liquid immobilized on their surface. The specific swollen volume can be characterized as a volume denied to flow by the material in the bed per unit mass of fibres. If the permeability and specific surface of fibres are known, the average porosity of pulp fibre bed can be determined from Eq. (4).

After substituting Eq. (5) into Eq. (4) and subsequent rearranging, we obtain Kozeny–Carman equation [2] in the linearized form as follows

$$(BC^2)^{1/3} = (v^2 a_v^2 K)^{-1/3} - (v^2 a_v^2 K)^{-1/3} vC \tag{6}$$

The Kozeny–Carman equation (6) is based on the assumption of an analogy between flow in tubes and flow through a porous medium. A criterion for the validity of the Kozeny–Carman equation is that Reynolds number is less than 10 (Ref. [3]). The effective specific volume, v, and the specific surface of the fibres, a_v, can be determined by a treatment of permeability data obtained at various values of bed consistency. Detailed description of this method is given in the paper [4].

Experimental

A single apparatus was constructed to carry out permeation runs. The permeation cell was made of brass cylinder 60 mm high, 21 mm inner diameter, and closed at the bottom by a permeable septum. The fibre bed occupied the volume between the septum and a permeable piston which could be slid into the top of the cylinder. The piston was used to compress pulp bed to desired consistency. Both the septum and piston covered with a 55-mesh screen were made permeable by 42 holes of 1.5 mm diameter. The pressure drop across the septum and piston was found to be negligible in comparison with the pressure drops used across the pulp beds in all the runs.

The experimental work was carried out with an unbleached kraft pulp or a bleached kraft pulp. Both sorts of unbeaten pulp were refined in a laboratory conical beater at a standardized temperature of 23 °C. During the beating period, samples of beaten pulp were removed at various intervals. The beaten pulp was tested for freeness by means of the Schopper–Riegler tester [5]. The freeness of pulp was designed to give a measure of the rate at which a dilute suspension of pulp may be drained. The results obtained by freeness test were used to assess the degree of beating. Using the Kajaani FS-100 fibre length analyzer [6], the mean length of the fibres was also determined. To calculate the mean fibre length, samples containing more than 5,000 fibres were measured.

Pulp beds were formed from a dilute fibre suspension of a given sort of pulp in distilled water. To start the permeability experiment, distilled water free of air bubbles and maintained at a temperature of 23 °C was distributed uniformly through the septum into the pulp bed, i.e. from bottom to the top of the bed. The volumetric flow rate of water was measured gravimetrically at various values of increasing bed consistency. With decreasing thickness of the pulp bed the pressure drop was increased to kept approximately constant value of the volumetric flow rate of water.

Results and Discussion

An example of one set of permeability data obtained for unbeaten bleached kraft pulp is shown graphically in Fig. 1. If the left-hand member of Eq. (6) is plotted against bed consistency, C, a straight line results if Kozeny constant, K, specific volume, v, and specific surface, a_v, do not vary with porosity over the range in question. An obvious difficulty with Eq. (6) is that experimental errors are obscured by the fact that fibre concentration, C, occurs in both X and Y axis. In spite of that permeability data as a function of pad consistency showed good agreement to the Kozeny–Carman equation (6). Bed consistency lower than approximately 60 kg m^{-3} were not studied since the frictions pressure drops necessary to give measurable amounts of flow tended to compress the bed and give nonuniform porosities. It should be emphasized that the Reynolds number in our measurement did not exceed 0.3. This value is thus well below the critical value of 10 (Ref. [3]), and the Kozeny–Carman equation (6) could be applied since the flow of liquid was laminar. The slope and intercept of this straight line were used to evaluate the specific volu-

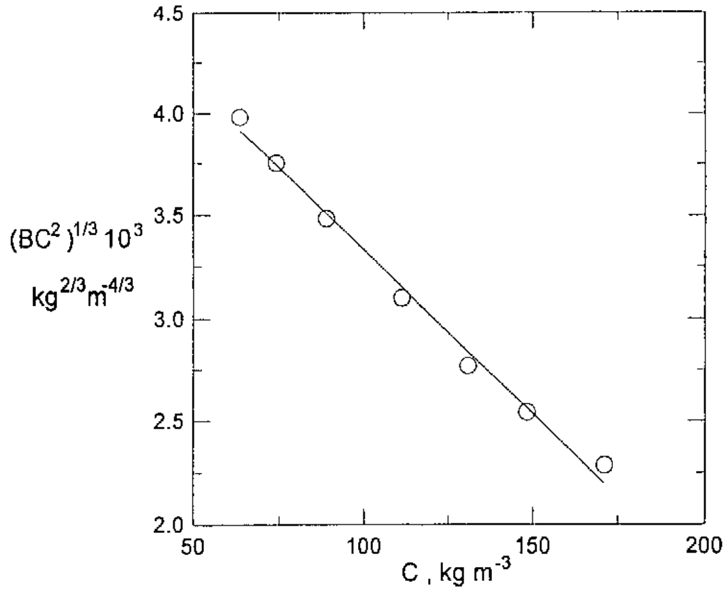

Fig. 1 Linearized Kozeny–Carman plot (Eq. (6)) for unbeaten bleached kraft pulp. The solid line is a linear regression fit

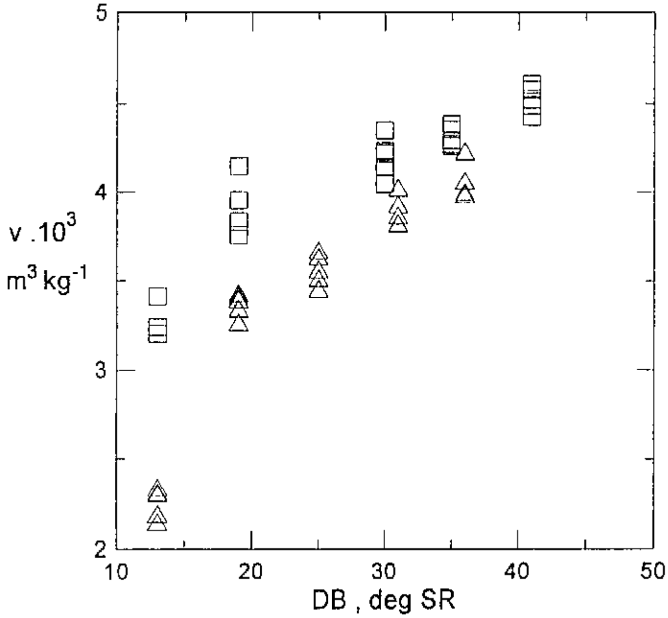

Fig. 2 Specific volume of pulp fibres plotted as a function of the degree of beating. △ unbleached kraft pulp, □ bleached kraft pulp

me, v, and specific surface, a_v (see Eq. (6)).

The dependence of the specific volume of pulp fibres on the degree of beating is illustrated in Fig. 2. The low values of the effective specific volume obtained for unbeaten unbleached pulp are in accordance with results reported by Ingmanson [4], who found for unbeaten pulp (beating degree of 12 deg SR) $v = 2.21\times10^{-3}$ $m^3\,kg^{-1}$. It must be noted that, in our case, the unbleached kraft pulp was never dried. However, the samples of suspensions of bleached kraft pulp were prepared from dried bleached pulp which was at first refined by means of Hollander beater and then refined once again to the desired degree in a conical beater. For pulp beaten to 38 deg SR, Ingmanson [4] found the specific volume of 3.40×10^{-3} $m^3\,kg^{-1}$.

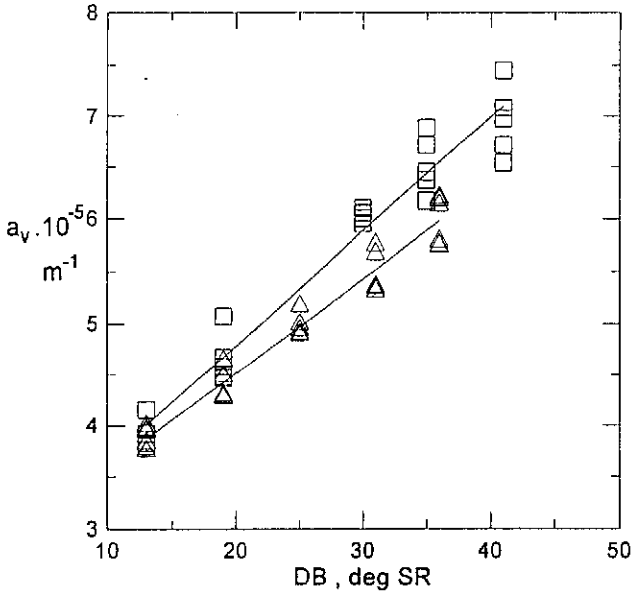

Fig. 3 Specific surface of fibres (volume basis) plotted as a function of the degree of beating. The solid lines are linear regression fits of the data. Δ unbleached kraft pulp, □ bleached kraft pulp

Figure 3 portrays the influence of the degree of beating on the specific surface of pulp fibres. For both sorts of pulp, the data result in a linear relationship between the specific surface and the degree of beating. Hence, the dependence between the specific surface, a_v in m^{-1}, and degree of beating, DB in deg SR, was expressed in the following equations

$$a_v = 9.15\times10^3 DB + 2.68\times10^5 \tag{7}$$

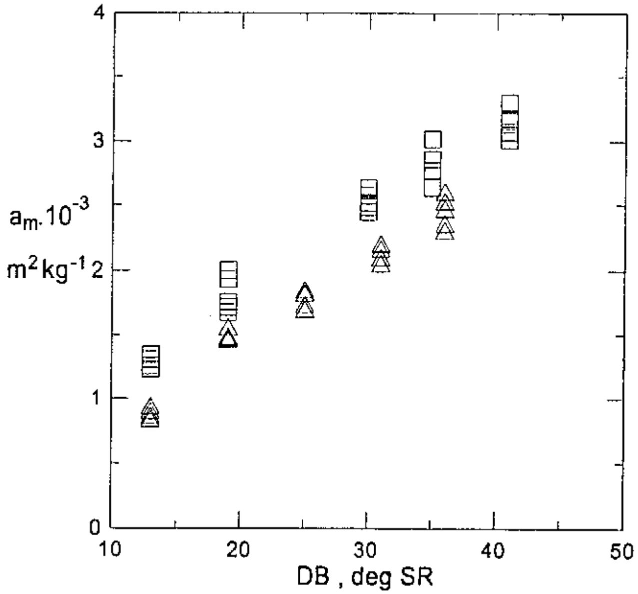

Fig. 4 Specific surface of fibres (mass basis) plotted as a function of the degree of beating. △ unbleached kraft pulp, □ bleached kraft pulp

Tab. I Weighted and arithmetic average fibre lengths

Unbleached kraft pulp			Bleached kraft pulp		
DB, deg SR	l_w, mm	l_a, mm	*DB*, deg SR	l_w, mm	l_a, mm
13	2.41	1.32	13	2.38	1.29
19	2.35	1.24	19	2.29	1.11
25	2.29	1.17	30	1.97	0.97
31	2.24	0.98	35	1.87	0.94
36	2.12	1.07	41	1.69	0.83

for unbleached kraft pulp, and

$$a_v = 1.11\times10^4 DB + 2.57\times10^5 \qquad (8)$$

for bleached kraft pulp with a correlation coefficient, in both cases, equal to 0.98. Equations (7) and (8) were derived for the degree of beating ranging from 13 to 36 deg SR and from 13 to 41 deg SR, respectively. Since the values of regression coefficients, which were evaluated by the least square method, represent an estimate

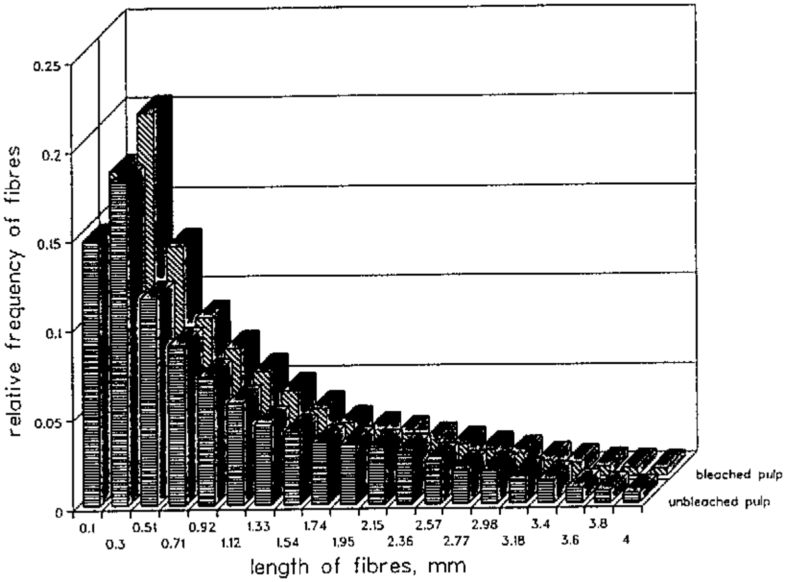

Fig. 5 Fibre length distribution for unbleached pulp (beating degree of 36 deg SR) and bleached kraft pulp (beating degree of 35 deg SR)

of the real values, the 95% confidence limits were also calculated. They are $(8.35\times10^3;\ 9.96\times10^3)$ for coefficient and $(2.35\times10^5;\ 3.01\times10^5)$ for constant of Eq. (7), and $(9.98\times10^3;\ 1.21\times10^4)$ for coefficient and $(2.04\times10^5;\ 3.10\times10^5)$ for constant of Eq. (8).

In Fig. 4, the effect of the degree of beating on the specific surface, a_m, defined as an external surface area presented to flow by the fibrous material in the bed per unit mass of fibres is illustrated. The specific surface, a_m, was evaluated as the product of the specific surface, a_v, and the specific volume, v. It should be noted that, for pulp beaten to given degree, our experience indicates that the differences between the individual values of v, a_v, and a_m, might reasonably be caused by sampling variation.

Because a beaten pulp contains considerably more fines and fibre fragments than does an unbeaten pulp, the increase in the specific volume and specific surface might be attributed to the action of fibrils which may immobilize a portion of the liquid and thus contribute to the specific volume.

The values of weighted and arithmetic means of fibre length confirmed greater amount of fibre fragments in beaten bleached pulp in comparison with beaten unbleached pulp, as seen in Table I. As follows from Table I, beating process had a little impact on the average weighted fibre length of unbleached pulp in comparison with bleached pulp. Weighted fibre length takes into account both the number of fibres and their measured lengths and is an approximation to the weight of the given fraction. On the other hand, the numerical average fibre length is a meaningless quality, since the pulp consists of whole tracheids and shorter elements down to submicroscopic lengths, with the numerical proportion of the shorter elements becoming greater as their length decreases. The shortest fibres contribute very little to the total measured length, but numerically they are just as important and influence the final result of an arithmetic average just as much as do the longest fibres. Figure 5 portrays the fibre length distribution obtained for unbleached and bleached kraft pulps.

Stenuf and Anumoln [7] also investigated the influence of the beating degree on the specific volume and specific surface for bleached softwood kraft pulp. The degree of beating, however, was expressed in terms of Canadian Standard Freeness (in ml). In spite of this fact, the results reported by the authors [7] agree with those obtained in our work. In the range of 711 and 134 ml, the effective specific volume, v, increased from 2.240×10^{-3} to 5.449×10^{-3} $m^3\,kg^{-1}$ and the specific surface, a_m, raised from 1670 to 3825 $m^2\,kg^{-1}$ with increasing degree of beating.

Conclusion

As mentioned, the focus of this work was to investigate the effect of the beating degree on the physical characteristics of unbleached and bleached kraft pulp fibres. Both the specific volume of fibres and their specific surface based on volume or mass increased with increasing degree of beating. At all levels of degree of beating, greater values of specific volume and specific surface were obtained for bleached kraft pulp fibres in comparison with unbleached kraft pulp fibres.

Pulp fibre pad represents a packed bed of randomly oriented solid porous particles. There are several important differences between a bed of granular media and a bed of fibrous media. With spherical particles (granular media), the particles are always geometrically similar regardless of size, and with reasonable care the packing will also be similar. In the case of long cylindrical particles (fibrous media), the particles are not necessarily geometrically similar, since the length-to-diameter ratio may vary. It is also doubtful that geometrically similar packing is obtained when different size fibres are used. Another difference between the two systems is the fact that the beds of fibrous media have a much wider pore size distribution. Fibrous systems are compressible, and the porosity of a given bed can be varied depending upon the compacting load.

Symbols

A	cross-sectional area of pulp bed, m^2
a_m	specific surface of fibrous material, mass basis, $m^2\,kg^{-1}$

a_v	specific surface of fibrous material, volume basis, m^{-1}
B	permeability coefficient, m^2
C	consistency (i.e. concentration of oven-dried pulp given as mass of fibres per unit volume of uniform bed), kg m^{-3}
DB	degree of beating, deg SR
h	thickness of pulp bed, m
K	Kozeny constant
l_a	arithmetic average length of fibres, mm
l_w	weighted average length of fibres, mm
Δp	pressure drop, Pa
R	hydraulic mean radius of pores defined by Eq. (3), m
V	volumetric flow rate of liquid through a pulp bed, m^3 s^{-1}
v	effective specific volume of fibrous material, m^3 kg^{-1}

Greek letters

ε	average porosity of pulp bed
μ	viscosity of liquid, Pa s

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