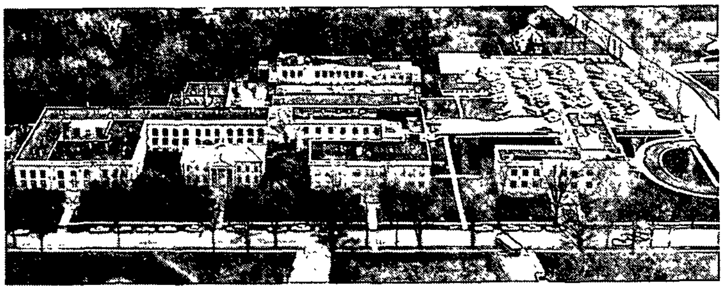

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CALCULATIONS OF AERODYNAMIC POROSITY, SPECIFIC SURFACE AREA, AND SPECIFIC VOLUME FROM GURLEY SECONDS MEASUREMENTS

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CALCULATION OF AERODYNAMIC POROSITY, SPECIFIC SURFACE AREA, AND SPECIFIC VOLUME FROM GURLEY SECONDS MEASUREMENTS

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ABSTRACT

Air permeability, measured as Gurley seconds, is correlated with the aerodynamic porosity, the aerodynamic fiber specific volume, and the aerodynamic fiber specific surface area for handsheets made from bleached northern softwood kraft pulp. Handsheets with basis weights of 60 and 200 g/sq m were formed from pulp beaten at five levels ranging from 0 to 5000 rev. in a PFI mill. Wet pressing was used to produce handsheets which varied in apparent density. Aerodynamic porosity, fiber specific volume, and fiber specific surface area were calculated from the Kozeny-Carman equation.

INTRODUCTION

Paper porosity is defined as the volume fraction of all the voids within a sheet of paper. In air permeability tests, however, only the voids which are active in the transportation of air through the sheet affect the test measurement. Therefore, a slightly lower porosity value, termed the aerodynamic porosity, is obtained by the air permeability apparatus.

The Gurley densometer and Bendtsen porosimeter are two standard instruments that measure the air permeability of paper and are commonly used for quality control purposes in industry. However, it is not known how measurements from these instruments are related to paper porosity.

Porosity is an important property of paper. It contributes significantly to the opacity and light weight of paper. For example, saturating papers used to make paper/resin laminates and paper used in car battery cells need to have a controlled porosity. In certain automated converting operations paper is picked up and transported by vacuum devices. Too high a permeability may cause two or more sheets to be picked up at once resulting in jamming of the operation.

In this paper we used the air permeability measurements from the Gurley densometer and Bendtsen porosimeter to determine the aerodynamic porosity, the aerodynamic specific volume, and the aerodynamic specific surface area of the fibers. The test instruments were also used to evaluate changes in these properties with respect to beating and wet pressing.

OBJECTIVE

The objective of this investigation is to relate air permeability measured in terms of Gurley seconds to the aerodynamic fiber specific volume, the aerodynamic fiber specific surface area, and the aerodynamic porosity of paper. How these quantities change with beating will also be determined.

LITERATURE REVIEW

The porosity of paper is easy to define but hard to accurately measure. It is defined as the void fraction of paper, and is related to apparent density and fiber specific volume by Eq. (1):

$$\text{Paper Porosity} = E = 1 - CV \qquad (1)$$

where C = apparent paper density (g/cc)
V = fiber specific volume (cc/g)

Paper porosity is hard to measure because of uncertainties in measuring C and V. Take for instance the apparent density of paper, C. The mass of a paper sample and its cross-sectional area can be accurately measured, but in order to obtain density one must know the thickness of the sample. Paper thickness can be measured by TAPPI caliper, IPC rubber platen caliper, and by stylus probes. Baum and Wink (1) analyzed these methods and found that each method gives a slightly different value depending on paper surface roughness and compressibility.

In water permeability tests, the fiber specific volume is calculated from the Kozeny-Carman equation. The derivation of the Kozeny-Carman equation is presented by several investigators (3, 4,5,6). Ingmanson and Andrews (7) explain the physical significance of V calculated by water permeability tests as follows:

> "Since the specific volume calculated from the Kozeny equation is defined in a hydrodynamic sense, it represents the volume denied to fluid flow per unit mass of dry cellulose. The volume which is denied to flow consists of cellulose and water associated with the cellulose."
>
> "Water is included in this so-called solid fraction because it is not free to move, at least in the range of compacting pressures used in the filtrations (zero to 100 cm H_2O)."

Therefore, in water permeability tests, V is commonly referred to as the hydrodynamic specific volume of the fibers and is related to the moisture content of fiber mats under fluid stress. Likewise, in cases where air is used as the permeating fluid, V will be referred to as the aerodynamic specific volume of the fibers.

If the steady flow of a Newtonian fluid through a fiber mat is laminar, isothermal, and incompressible, then Darcy's Law can be applied. Darcy's Law relates the flow rate of fluid to the pressure drop, Newtonian viscosity, bed thickness, and permeability.

Darcy's Law states:

$$Q = \frac{K \Delta P A}{u\ L} \qquad (2)$$

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where Q = volumetric flow rate (cc/sec)
K = permeability (sq cm)
ΔP = pressure drop (g/cm s^2)
A = cross sectional area (sq cm)
u = Newtonian viscosity (g/cm sec)
L = sample thickness (cm)

The permeability can be related to porosity by the Kozeny-Carman equation (3,4,5,6):

$$K = \frac{E^3}{k\,S_v^2\,(1-E)^2} \qquad (3)$$

where E = sample aerodynamic porosity
k = Kozeny factor
K = sample permeability
S_v = fiber surface area per unit volume of fiber (sq cm/cc)

Equation (1) can be substituted into Eq. (3) and rearranged to give:

$$(KC^2) = \left[\frac{1}{kV^2\,S_v^2}\right](1 - VC)^3 \qquad (4)$$

Then substituting $VS_v = S_w$, the fiber specific surface area (sq cm/g), Eq. (4) can be rewritten as

$$(KC^2)^{1/3} = \left[\frac{1}{kS_w^2}\right]^{1/3}(1 - VC) \qquad (5)$$

The Kozeny factor is an empirical term that lumps together all the uncertainties related to the fluid flow and structure of the porous media. Table 1 represents a summary of published Kozeny factor relationships. The Kozeny factors were determined from Eq. (5) by using synthetic fibers of known specific volume and specific surface area and measuring permeability and apparent density during water permeability experiments.

Table 1 Kozeny factors as a function of porosity.

Investigator	Function	Porosity Range
Fowler, et al. (8)	$k = 5.55$	0.4-0.8
Davis (9)	$k = \frac{4E^3\,[1+56(1-E)^3]}{(1-E)^{1/2}}$	0.7-0.994
Ingmanson, et al. (10)	$k = \frac{3.5E^3\,[1+57(1-E)^3]}{(1-E)^{1/2}}$	0.6-0.99
Carroll (11)	$k = 5.0+\mathrm{EXP}[14(E-0.8)]$	0.68-0.96
Chen (12)	$k = 4.7+\mathrm{EXP}[14(E-0.8)]$	0.4-0.99

From Eq. (5), plots of $(KC^2)^{1/3}$ vs. C will be a straight line, provided k, S_w, and $\overline{V}$ remain constant. The Kozeny factor, k, can be assumed to be 5.55 if the porosity of the sample is less than 0.8. Specific volume, V, and the fiber specific surface area, S_w, can be calculated from the values of slope and intercept.

The hydrodynamic fiber specific surface area, S_w, is the unbonded geometric outer surface area per gram of fiber as it exists in the sample. Ingmanson (7) showed that S_w increases as beating time of the fibers increases.

For wood pulp, the specific surface area can be calculated by a geometric method, a silvering technique, and filtration resistance. Ingmanson, et al. (13) showed that for unbeaten pulp, all three methods correspond to nearly the same value.

The Gurley densometer is the TAPPI standard air permeability test instrument. It has been a standard instrument for 37 years, yet a relationship between Gurley seconds and paper porosity has not been established. Using the Kozeny-Carman equation to calculate aerodynamic specific surface area and aerodynamic specific volume may provide this relation.

In summary, the review of the literature dealt with the area of fluid permeability through fiber mats. Many of the investigators were interested in modeling the flow of water through fiber mats in order to obtain a better understanding of drainage on a forming wire. Two key parameters are the fiber specific surface area, S_w, and the Kozeny factor, k. Common to all the investigations is the result that at porosities less than 0.8, the Kozeny factor is a constant and at porosities greater than 0.99, the Kozeny factor approaches infinity.

What is not well understood is whether or not the fiber specific surface area, S_w, remains constant during compaction of the fibers. By definition, S_w is a constant, and as long as the fiber structure is not changed during compaction S_w should remain a constant.

EXPERIMENTAL PROCEDURES

The raw material used for this investigation was a bleached northern softwood kraft dry lap pulp. Beating of the pulp was done in the PFI mill according to TAPPI Standard Method T 248 pm-74. However, one set of handsheets was formed directly from disintegrated dry lap pulp soaked overnight in deionized water.

All of the handsheets used in this study were formed in a British handsheet mold, TAPPI T 205 os-75. It was observed that the sheets with basis weight of 200 g/sq m had less fiber dispersion than the standard 60 g/sq m. Couching of the handsheets was done according to TAPPI Standard methods.

Wet pressing was used to produce handsheets which varied in apparent density. The TAPPI standard press and the Carver laboratory press were sufficient in producing handsheets with densities of 0.5 to 1.1 g/cc. Each handsheet was pressed individually for a period of 5 minutes.

After pressing, the handsheets were placed in drying rings. The sheets were then allowed to come to equilibrium (40 hours) in the 50% RH, 73°F testing laboratory. At this point, the sheets were ready for testing.

Handsheet testing was carried out in the 50% RH, 73°F testing laboratory. Each handsheet was cut into 4 samples of nearly 5 x 5 cm using paper cutters. Templates were used to assure squareness of the samples' corners.

To calculate the apparent density, the cross-sectional area, weight, and thickness of the samples were measured. An engineering scale was used to accurately measure the x-y plane dimensions of the samples. A Mettler analytical balance was used to weigh the samples, and the thickness of the samples was determined from IPC caliper tests. Thickness readings were taken from three locations within the samples.

The Gurley densometer and Bendtsen porosimeter were chosen to measure the flow rate of air through the samples. Of the four samples cut from each handsheet, one sample was tested by both test instruments, while the other three samples were tested just by the Gurley densometer. The room temperature was measured at the beginning of the testing period and checked at the end of testing.

In the Gurley densometer, the smooth side of the sample was placed facing the soft rubber gasket. The cross-sectional area exposed to flow is 1 sq inch. One test was run for each sample.

In the Bendtsen porosimeter, the smooth side of the sample was placed facing the rubber gasket. The cross-sectional area exposed to flow is 10 sq cm. Three measurements were taken on a single sample corresponding to the three pressure drop values associated with the test instrument.

IPC Filtration Resistance measurements were performed on beaten and unbeaten pulps. A slurry of 1×10^{-4} g/cc of deaerated pulp is prepared and continuously stirred in a large tank. A rotameter setting is chosen such that the time of the experiment is near 300 seconds. The stock is then pumped through the permeability cell where a pad of fibers forms on the septum. The pressure drop arose the pad is continuously recorded by a strip recorder which receives a low Hz filtered voltage signal from the pace pressure transducer. The experiment ends when the pressure drop across the pad equals 100 cm H_2O.

At the end of the experiment the fiber pad is removed from the septum and dried in an oven. The stock consistency is calculated by dividing the oven-dry pad weight by the volume of fluid filtered.

RESULTS AND DISCUSSION

Relating aerodynamic porosity to handsheet permeability via the Kozeny-Carman equation requires that Darcy's Law must be applicable. The Bendtsen porosimeter was used to check whether the pressure drop was proportional to the flow rate of air. Three pressure drop settings were available: 75 mm H_2O, 150 mm H_2O, and 225 mm H_2O. For the 200 g/sq m handsheets, Darcy's Law was easily obeyed. In Fig. 1, the flow behaviors for two samples are illustrated.

The Reynolds number, Re, is the ratio of inertial forces over the viscous forces. According to Robertson and Mason (3), Darcy's Law should be valid if $Re < 2$; where $Re = \frac{\rho \langle V \rangle E}{u S_v (1-E)} = \frac{\rho (Vo)}{u S_w C}$.

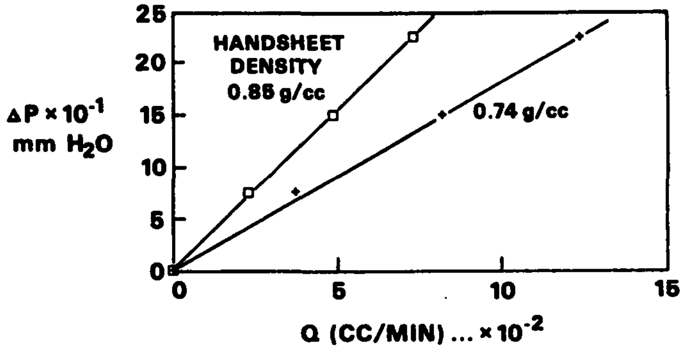

Fig. 1 Check for the applicability of Darcy's Law. CSF = 725 mL, basis weight = 200 g/sq m.

Table 2 Reynolds number for data plotted in Figure 1.

Apparent Density, g/cc	ΔP mm H_2O	Re
0.85	225	0.00146
0.85	150	0.000984
0.85	75	0.000447
0.74	225	0.00284
0.74	150	0.00188
0.74	75	0.000862
0.55	225	0.0106
0.55	150	0.00739
0.55	75	0.00397

ρ air = 0.001122 g/cc = air density
u air = 0.010968 g/cm min = air viscosity
S_w (aero) = 6031 sq cm/g

In all cases, the Reynolds numbers are several orders of magnitude below the value of 2.0. In our experiments, pressure drop (125 mm H_2O) and mean free path of air molecules were so small that the effect of air compressibility and slip flow can be neglected. Therefore, the flow can be described by Darcy's Law.

It became evident that both Gurley densometer and Bendtsen porosimeter are limited in the range of flow rates that can be accurately measured. For the Gurley densometer, TAPPI T 460 om-83 states this range is 0.0556 to 20 cc/sec. In this investigation, the 200 g/sq m handsheets made from pulp with CSF 725 mL through 345 mL accommodated the limited flow rate range well. However, the 60 g/sq m handsheets were not able to accommodate the flow rate limits very well. In this investigation, the only 60 g/sq m handsheets which could be evaluated were made from pulp with CSF equal to 345 mL. Tests with 60 g/sq m handsheets made from pulp with CSF equal to 725 mL exceeded the maximum flow rate limit.

Since the Reynolds numbers were all well within the laminar flow region and the validity of Darcy's Law was established, the permeability could then be related to apparent density according to Eq. (5). Figures 2 through 4 are plots of $(KC^2)^{1/3}$ vs. apparent density. The data were found to be linear at constant freeness. This provides indirect justification for assuming kS_w^2 and V to remain constant as wet pressing pressure is increased.

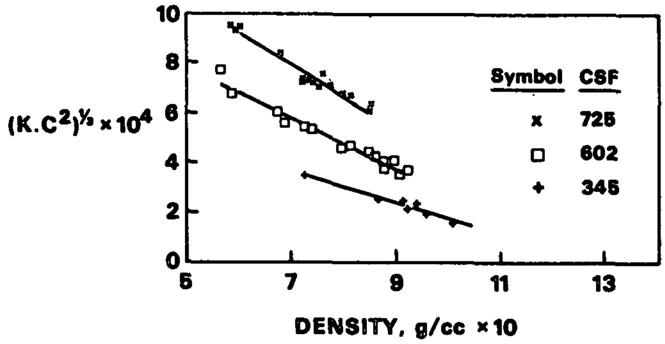

Fig. 2 Permeability as a function of apparent density for basis weight = 200 g/sq m.

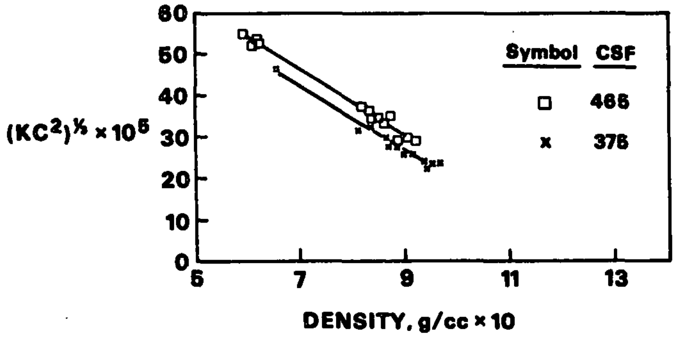

Fig. 3 Permeability as a function of apparent density for basis weight = 200 g/sq m.

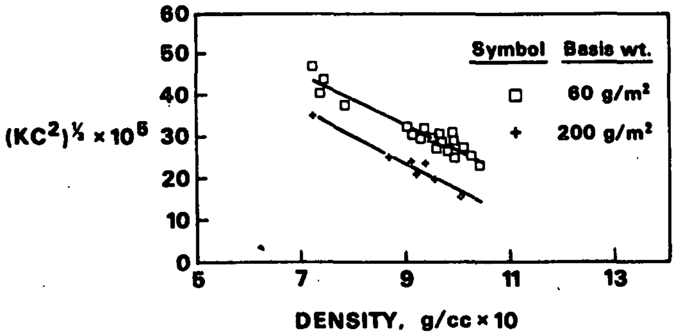

Fig. 4 Permeability as a function of apparent density for CSF = 345.

Figures 2-4 provide indirect justification that the term kS_w in Eq. (5) is a constant at constant freeness. All of the samples had porosities less than 0.8, thus the Kozeny factor, k, can be assumed to be a constant. Since k is a constant, then S_w must also be a constant at constant freeness. This result is in agreement with the definition of S_w as it was derived in the Kozeny-Carman equation (3,4,5,6). In other words, S_w is considered to be a fiber property which remains constant under the wet pressing conditions used here. Only when extreme wet pressing and/or drying conditions are used such that the fiber structure is significantly altered, one would expect S_w to change.

It is known that wet pressing enhances fiber bonding, and as a result, sheet density and strength properties like breaking length increase, while light scattering coefficient (considered to be a measure of unbonded area) decreases. Intuitively, one would expect the aerodynamic surface area to decrease due to wet pressing. But this does not seem to be the case. Wet pressing is expected to consolidate the sheet, alter the pore size distribution, and lower the porosity but should not have significant effect on S_w as long as fiber structure is preserved.

Chen (12) showed from his measurements of water permeabilities of polyester fiber mats that at lower porosities ($E<0.8$), S_w cannot be assumed to be constant. As the fiber mat is compacted, hydrodynamic surface area seemed to be decreasing. Accordingly, his plots of $(KC^2)^{1/3}$ vs. C were not linear. On the other hand, Fig. 2-4 indicate that these plots are indeed linear for the air permeability measurements. One can therefore conclude that the aerodynamic surface area remains constant for the wet pressing conditions examined here.

Table 3 presents the regression analysis data obtained for Fig. 2-4 along with the results from filtration resistance experiments. Values of V and S_w were calculated from the slopes and intercepts obtained from linear regression results.

Table 3 Results from $(KC^2)^{1/3}$ vs. C and filtration resistance regressions.

CSF	Wet Press Temp. (°C)	Basis Weight (g/sq m)	V (cc/g)	S_w (sq cm/g)	R^2
From Air Permeability Measurements					
725	25	200	0.7603	6031	0.955
602	25	200	0.7920	9092	0.966
465	25	200	0.7822	12920	0.989
375	25	200	0.8019	14280	0.986
345	25	200	0.7919	18100	0.973
345	25	60	0.6980	16194	0.921

From Water Permeability Measurements

CSF	V (cc/g)	S_w (sq cm/g)	R^2
725	2.165	6990	0.999
602	2.452	12170	0.988
345	2.616	20520	0.996

FIBER SPECIFIC VOLUME

The fiber specific volume calculated by air permeability instruments represents the volume denied to air flow per unit mass of the paper sample. This volume consists of fiber, water, and air and may be termed the aerodynamic fiber specific volume.

For the 200 g/sq m handsheets wet pressed at 25°C, the aerodynamic fiber specific volume increased slightly with small amounts of beating, then leveled off to about 0.79 cc/g as shown in Fig. 5. Beating increases the amount of cellulose available to interact with the moisture in the air by externally fibrillating the fiber wall and creating fines. Upon drying, if the fibrils are able to bond to adjacent fibers and remain exposed to the flow of air, then the aerodynamic fiber specific volume should increase slightly.

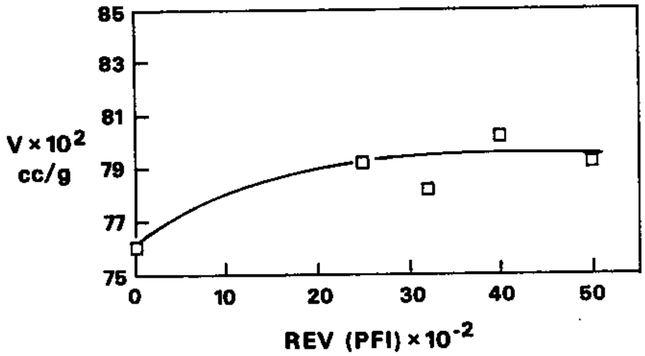

Fig. 5 Aerodynamic fiber specific volume as a function of beating.

The hydrodynamic fiber specific volume calculated from filtration resistance also increases with beating. Figure 6 appears to be similar in shape to Fig. 5. The hydrodynamic fiber specific surface area increases with small amounts of beating, then levels off (Table 3).

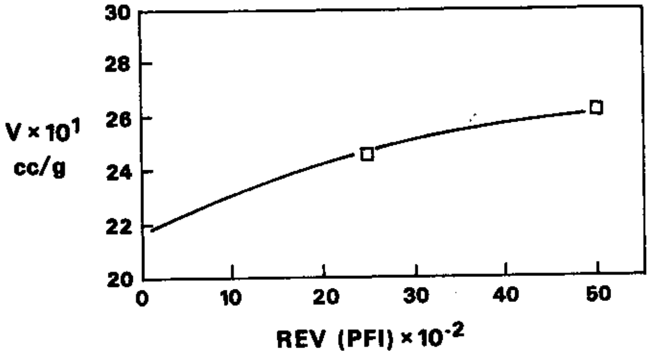

Fig. 6 Hydrodynamic fiber specific volume as a function of beating.

FIBER SPECIFIC SURFACE AREA

Using Darcy's Law, Hosseiny and Yan (15), derived a theoretical relationship between CSF and fiber specific surface area. According to the authors, a plot of specific surface area vs. ln(CSF) will be a straight line. In this investigation, it was found that fiber specific surface areas for both the hydrodynamic and aerodynamic experiments obeyed the semilog relation quite well. Figure 7 illustrates the linear relationship and Table 4 gives the regression analysis data.

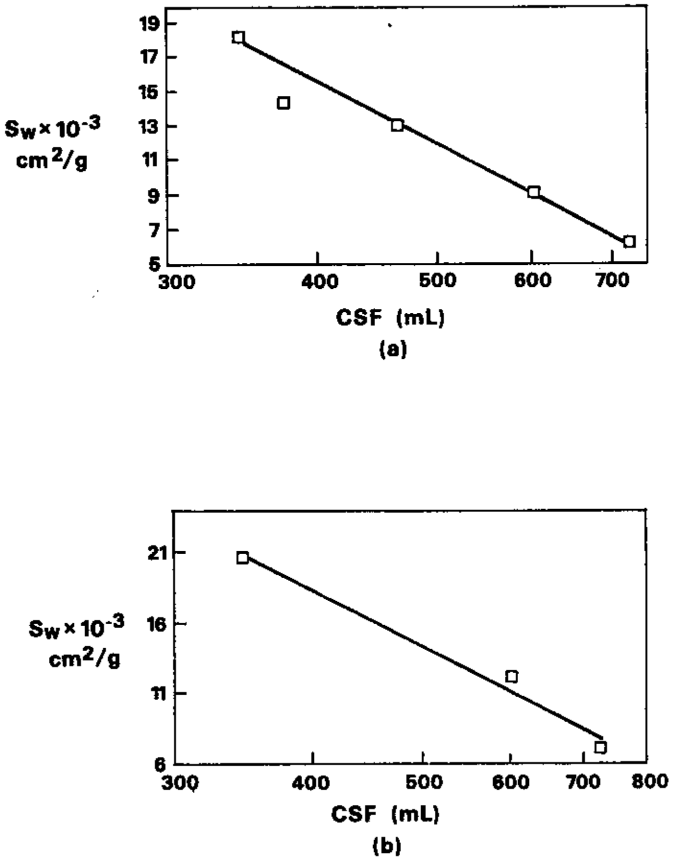

Fig. 7 Semilog relationship between fiber specific surface area and CSF.
(a) Aerodynamic specific surface area.
(b) Hydrodynamic specific surface area. One data point in Fig. (a) was neglected due to contamination of pulp.

Table 4 Semilog regression analysis data.

Basis Weight (g/sq m)	Wet Press Temp. (°C)	S_w = a - b*ln (CSF)	R^2
	Aerodynamic Experiments		
200	25	a = 112,200 b = 16.13	0.999
	Filtration Resistance		
		a = 122,900 b = 17.48	0.979

In filtration resistance experiments and in CSF measurements, the resistance of water flowing through fiber mats was measured. It therefore seems reasonable that the relationship between hydrodynamic fiber specific surface area and CSF is valid. However, in aerodynamic experiments where air flowed through handsheet samples, the relationship unexpectedly was also valid.

The hydrodynamic fiber specific surface area calculated from filtration resistance is the water swollen surface area of the fibers and should represent the maximum specific surface area for a pulp of given freeness. During drying, wood fibers shrink and external fibrils can collapse back onto parent or bond to adjacent fibers. Consequently, one expects the aerodynamic fiber specific surface area to be less than the corresponding hydrodynamic fiber specific surface area. Figure 8 illustrates the differences between hydrodynamic and aerodynamic fiber specific surface area for pulps and handsheets of similar freeness.

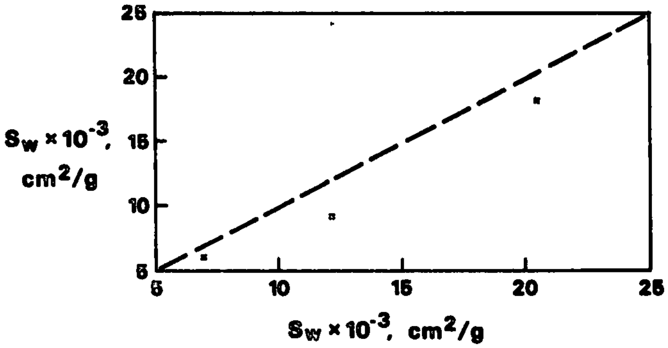

Fig. 8 Comparison of aerodynamic specific surface area to hydrodynamic specific surface area.

The differences in corresponding aerodynamic and hydrodynamic surface areas are most likely due to fiber shrinkage effects. The aerodynamic properties of the handsheets thus become dependent not only on beating but also on pressing and drying techniques.

For unbeaten fibers, the aerodynamic fiber specific surface area approaches the hydrodynamic fiber specific surface area. The unbeaten hydrodynamic fiber specific surface area was 6,990 sq cm/g. Upon beating, the aerodynamic fiber specific surface area becomes significantly lower than the corresponding hydrodynamic value, as illustrated in Fig. 8.

AERODYNAMIC POROSITY

The Gurley densometer measures air permeability in terms of Gurley seconds, T, which is defined as the time in seconds for 100 cc of air to flow through one square inch of paper sample. Gurley seconds is often plotted as a function of apparent density of the paper sample. These plots are nonlinear and give only qualitative information about paper properties. Figure 9 (a) illustrates the nonlinear relationship between Gurley seconds and density, Fig. 9 (b) illustrates the nonlinear relationship between Gurley seconds and aerodynamic porosity.

CONCLUSION

The flow of air through handsheets can be described by Darcy's Law, provided basis weight is about 200 g/sq m. Handsheet density was varied by changing wet pressing pressures. Aerodynamic fiber specific volume, specific surface area, and porosity can be calculated by application of the Kozeny-Carman equation.

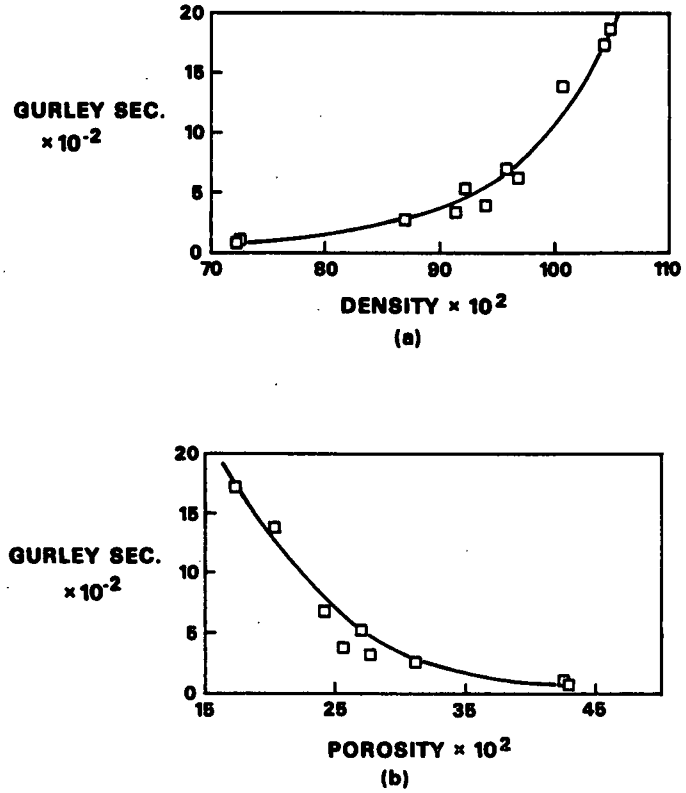

Fig. 9 Gurley seconds as a function of (a) apparent density, (b) aerodynamic porosity for CSF = 345 mL, basis weight = 200 g/sq m.

By keeping the porosity of the sample below 0.8, the Kozeny factor becomes a constant. At high porosity the Kozeny factor is a complicated function of porosity. In the interest of simplification, the porosity of the samples was kept below 0.6, and the Kozeny factor was assumed to be a constant 5.55.

The aerodynamic fiber specific volume was found to increase nonlinearly with beating. The hydrodynamic fiber specific volume obtained from filtration resistance also increased nonlinearly with beating but was much more gradual. As expected, the aerodynamic fiber specific surface area increased with beating and was always lower than the corresponding hydrodynamic surface area. The aerodynamic fiber specific surface area was found to correlate well with CSF measurements. A semilog plot of aerodynamic fiber specific surface area and CSF gave a straight line as illustrated in Fig. 7.

In conclusion, the aerodynamic porosity of paper can be accurately related to the Gurley densometer test method, TAPPI Standard T 460 om-83, provided that the Kozeny factor is a constant. The aerodynamic porosity varies nonlinearly with air permeability measured as Gurley seconds but varies linearly with handsheet density.

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