Effects of freeness and consistency on the viscosity of hardwood and softwood pulp suspensions

William C. Chase, Alfred A. Donatelli, and John W. Walkinshaw*
Chemical Engineering Dept., University of Lowell, Lowell, Mass. 01854

ABSTRACT *Normal viscometers do not provide enough mixing to maintain uniform fiber distribution, which causes the measurements to approach the viscosity of the pure fluid. We constructed a viscometer on the concept of flow over a flat plate. With this viscometer, the viscosity is calculated from the shaft rotational velocity and the torque transferred to the stator plates. Viscosities of fiber suspensions for hardwoods and softwoods were determined. For both, viscosities increased linearly with consistency. The viscosity of hardwoods decreased linearly with freeness, while the viscosity of softwoods increased initially and then decreased with a decrease in freeness.*

KEYWORDS
Analysis
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Viscometers

The paper industry relies on the transport of fibers in aqueous media, but little is known about the fundamental property of viscosity as it relates to processed pulp, which is a suspension of fibers in water. The effects of freeness and consistency on viscosity can best be studied using a viscometer.

Consider a viscometer as composed of two parallel plates, each of a unit of area, with liquid between the plates. If one plate is moved along its plane, the viscosity is the tangential shearing force per unit area that will produce a velocity gradient between the two plates (*1*):

$$\eta = \tau/\gamma \tag{1}$$

where

τ = the tangential shearing force per unit area or shear stress, N/m^2

γ = the velocity gradient, or the rate of shear, s^{-1}

η = the coefficient of viscosity, N•s/m^2 or Pa•s.

Thus, the measurement of viscosity can be made by determining the rate of shear caused by a known shear stress.

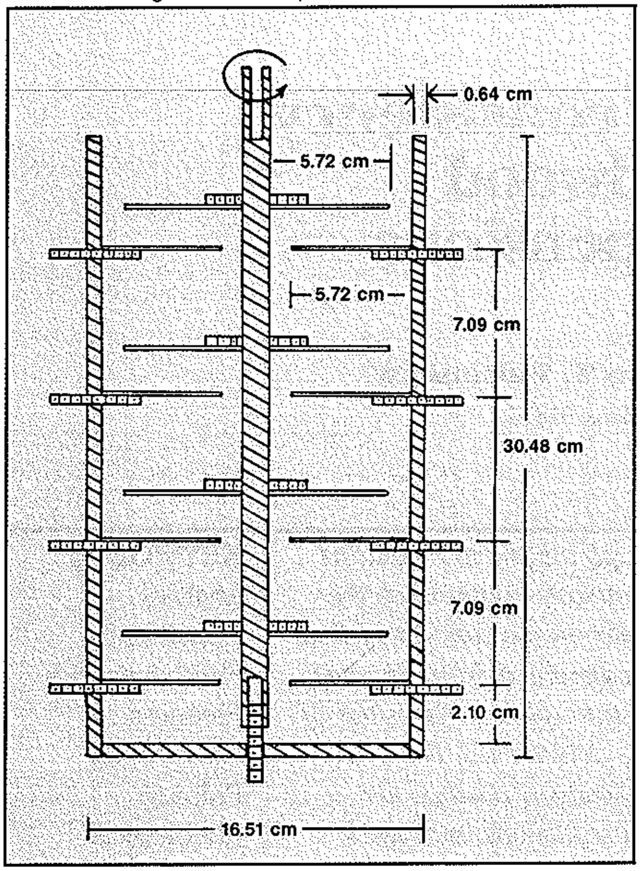
If the viscosity is a constant at various rates of shear, then the fluid is said to be Newtonian. Newtonian fluids are characterized by a loose molecular structure, or one that forms a weak structure with low cohesive forces, so that any application of stress causes flow in the fluid.

A Bingham plastic fluid is one that requires a specific stress to initiate flow. This stress is referred to as a "yield" stress and is the stress required to break down the internal structure within the fluid. Once flow has been initiated, the fluid behaves in a Newtonian manner and has a constant viscosity. To characterize a Bingham plastic, both the yield stress and the viscosity must be determined. Suspensions of solids such as paper pulps are typical of Bingham plastics. A second characteristic of a Bingham plastic solution is that the yield stress is reduced with dilution, and the fluid approaches Newtonian behavior as the suspended particles are separated by a distance at which they can no longer interact.

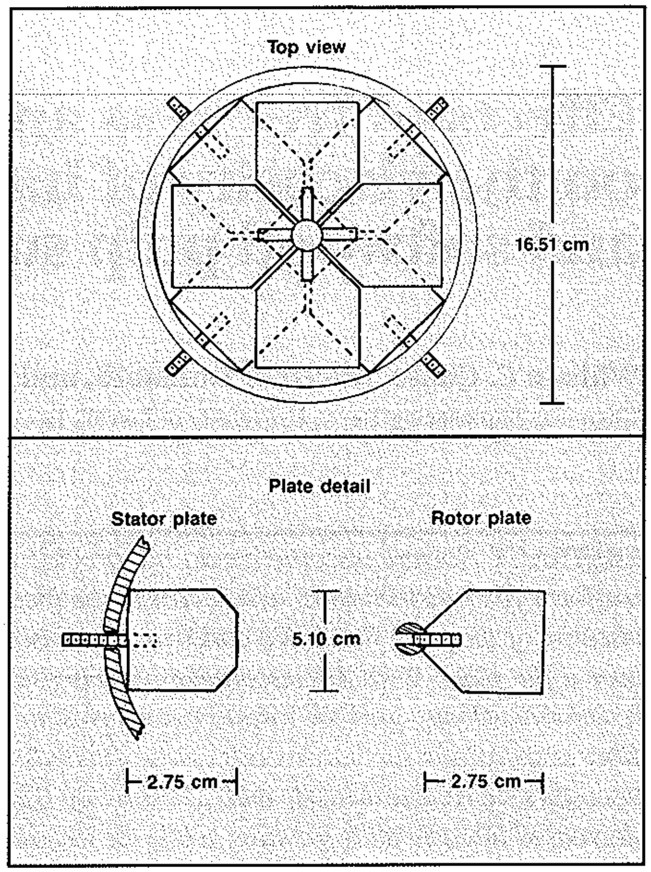
The work of Sharma (*2*) on dilute pulp suspensions indicated that the loss of internal structure occurred below a consistency of 0.15%. In other words, this is the point at which pulp suspensions have a negligible yield stress and can be characterized as

*Correspondence should be addressed to Walkinshaw. Chase's present address is 61 South St., West Winfield, N.Y. 13491.

1. The viscometer containment cylinder, showing the spacing of the fixed and rotating measurement plates



2. Viscometer and plate detail



Newtonian. Sharma's work was performed to study the structure within the suspension and its effect on flow within a pipe, and the results may not be related to the Bingham yield stress.

Brecht and Heller's work (*3*) was directed at the flow of low-consistency pulps in pipes. Their results indicated that as the consistency of the pulp was increased, greater shear forces were required to distort the fiber plug in contact with the wall and begin motion. For unbleached sulfite pulp (with a freeness of 822° Schopper-Riegler in copper pipe with an inside diameter of 20.0 cm), yield stresses were measurable above 0.5% consistency, but significant stresses required a consistency of more than 1.5%. Gullichsen and Harkonen (*4*) extended Brecht's work from 4% to 12% consistency with bleached pine kraft. They developed the following relationship between the disruptive shear stress and consistency:

$$T_d = (27/100)\, C^2 \tag{2}$$

where

T_d = shear stress, kN/m²

C = consistency, %.

This equation was obtained by using a rotational device that measured the torque required to initiate flow. It is unclear from their work if the disruptive shear stress is the same as the yield stress of a Bingham plastic fluid.

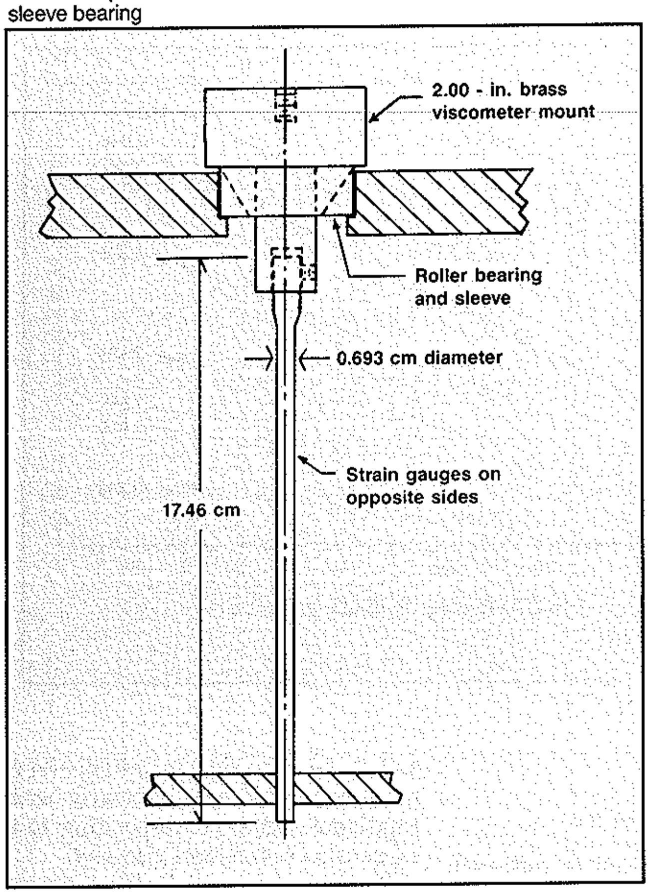
Our purpose was to examine the effects that pulp consistency, freeness, and wood type (hardwood or softwood) have on the viscosity and yield stress of a fiber suspension. During the early stages of the project, traditional viscometers were used on pulp suspensions of 1.5% consistency. The rotational viscometers, such as the cup and bob, cone and plate, or spindle types, showed an apparent viscosity approaching that of water. This measurement occurred as fiber flocs formed in the central regions of the viscometer. Essentially, only water was interacting with the rotational elements of the viscometer. Here, we will present a viscometer that maintains fiber suspension and the interaction with the viscometer's active elements.

Viscometer construction

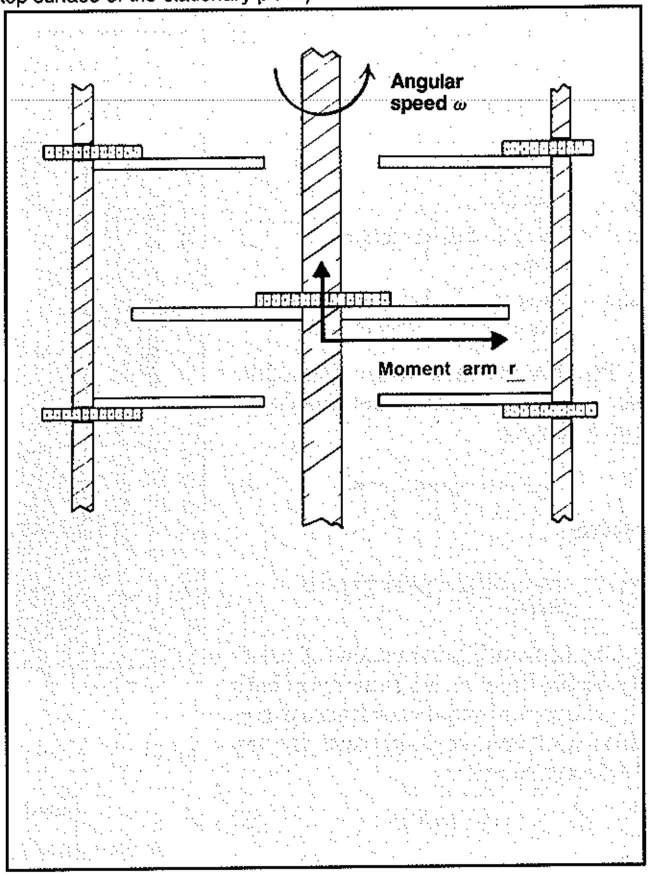
The viscometer was designed to have one set of driven plates mounted on a rotating shaft that transferred torque through the fiber suspension to a set of stationary measurement plates mounted inside the containment cylinder. The shape of the plate was chosen so that the leading edge would cause continuous fiber dispersion and yet allow for the development of a model.

Each of the plates was cut from 1.6-mm-thick aluminum stock with a surface area of approximately 25 cm². The aluminum stock was kept thin to minimize fiber stapling on the edges. Each plate was riveted to a short length of No. 5-40 TPI threaded rod. This arrangement allowed each plate to be mounted to either the drive shaft or the cylinder wall. All plates were checked for parallelism prior to being tightened. The mounting locations

3. The torque measurement device and its attachment to the roller and sleeve bearing



4. A set of rotating and stationary plates within the viscometer (z = top surface of the stationary plate.)



and plate spacings are detailed in **Figs. 1 and 2.**

The shaft drive for the viscometer consisted of a dc motor (permanent magnet field) with its speed controlled by the voltage supplied to the armature. A fixed-ratio gear box was assembled for reducing the speed of the shaft drive and to drive a tachometer used to measure the actual shaft speed.

To allow for the torque measurement, the containment cylinder was mounted on a thrust bearing that supported the weight of the cylinder and its contents while allowing for free rotational movement. Below the bearing assembly was a 17.5-cm length of aluminum rod attached in such a way as to be free to rotate with the cylinder at one end and fixed at the other end (**Fig. 3**). The torque, or the rotational force exerted on the rod, was measured by two strain gauges mounted on opposite sides of the rod at a 45° angle to the axis of the rod. The mounting of the strain gauges and the connections to the Wheatstone bridge circuit allowed for only the rotational forces to affect the balance of the bridge; the effects of the axial load and bending moment were minimized.

The output of the tachometer for the speed measurement and the output from the torque measurement bridge were both connected to an x-y oscilloscope. The oscilloscope gave both qualitative and quantitative information on the relationship of speed to torque. The tachometer circuit was calibrated by both mechanical measurement devices and by stroboscope methods. To calibrate the torque transducer, a string was wrapped around the 2-in.-diameter top of the thrust bearing, then over a pulley to a dead weight hanger. The torque axis on the oscilloscope was then calibrated with dead weight loads attached to the 1-in. moment arm of the thrust bearing hub.

Theory

Consider a set of rotating and stationary plates within the viscometer as shown in **Fig. 4**. The moving plates are rotated at an angular speed ω. The torque is equal to the product of the moment arm and the shear force at the surface of the stationary plates. Since both the shear force and moment arm are variables, the following equation is used to evaluate the torque:

$$T = \int_A (-\tau_{z\theta})|_{z=0} \cdot dA \cdot r \qquad (3)$$

where

T = torque

$(-\tau_{z\theta})|_{z=0}$ = shear stress at the plate surface

dA = differential surface area element

r = the moment arm.

In cylindrical coordinates,

$$dA = r dr\, d\theta$$

so that Eq. 3 can be written as

$$T = \int\int (-\tau_{z\theta})|_{z=0}\, r^2\, dr\, d\theta \qquad (4)$$

The stress tensor τ for a Bingham plastic fluid is given by the following constitutive equation (*5*):

$$\tau = - \left\{ \mu_\phi + \frac{\tau_0}{\left|\sqrt{1/2\,(\Delta:\Delta)}\right|} \right\} \Delta \qquad (5)$$

where

τ = yield stress

μ_ϕ = viscosity

Δ = the rate of deformation tensor

$\Delta:\Delta$ = the second invariant of the rate of deformation tensor.

The shear stress at the surface of the stationary plates can be obtained from Eq. 5, giving

$$\tau_{z\phi}/_{z=0} = -\{\mu_0 \gamma|_{z=0} + \tau_0\} \qquad (6)$$

where

$\gamma|_{z=0}$ = the velocity gradient at the surface.

The tangential component of velocity for the fluid, v_ϕ, is a function of both the radial and axial coordinate directions and can be expressed by the following relation:

$$v_\theta = r\omega f(z) \qquad (7)$$

where $f(z)$ is a function of the distance between the moving and stationary plates. Thus, the velocity gradient at the surface of the stationary plates is found by

$$\gamma|_{z=0} = rwf'(z)|_{z=0} = rwC \qquad (8)$$

where $C = f'(z)|_{z=0}$ is constant for the viscometer. Combining Eqs. 6 and 8 with Eq. 4 gives the following expression for torque:

$$T = \int\int \tau_0 r^2\, dr\, d\theta + \int\int \mu_0 C\omega\, r^3 dr\, d\theta \qquad (9A)$$

$$T = \tau_0 K_1 + C\mu_0 \omega K_2 \qquad (9B)$$

where

$K_1 = \int\int r^2\, dr\, d\theta$

$K_2 = \int\int r^3\, dr\, d\theta$

Equation 9B can be used to characterize Bingham plastic fluids by measuring torque as a function of rotational speed. The parameters K_1 and K_2 are related to the design of the stationary plates, while C is dependent on the flow characteristics within the apparatus. For the hardwood pulp solutions, four levels of rotating and stationary plates were used in the viscometer so that

$$K_1 = 2.14 \times 10^{-3}\ m^3$$

and

$$K_2 = 1.10 \times 10^{-4}\ m^4$$

On the other hand, for the softwood pulp solutions, three levels of rotating and stationary plates were used so that

$$K_1 = 1.60 \times 10^{-3}\ m^3$$

and

$$K_2 = 8.23 \times 10^{-5}\ m^4$$

The parameter C was evaluated by performing a calibration experiment for the viscometer using water, such that

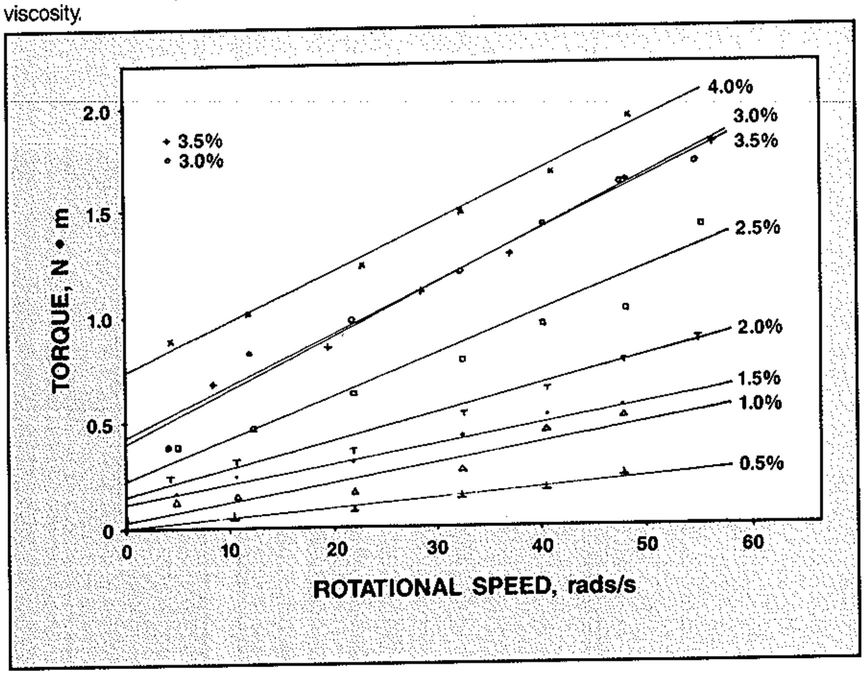
$$C = 2.45 \times 10^{-4}\ m^{-1}.$$

Results and discussion

The pulps were a mixed northern hardwood and softwood dry lap pulps. The hardwood pulp was mostly birch, aspen, and maple, with average fiber lengths in the range of 1.0-1.3 mm. The softwood pulp was primarily spruce, with an average fiber length of 2.5-3.0 mm. The mechanical refining was done in the Valley Beater at 2.0% consistency with predispersion in a Cowles Dissolver for 2 min at 5% consistency.

The hardwood and softwood pulp suspensions behaved as Bingham plastic fluids, as predicted by Eq. 9B and as shown in **Fig. 5**. A yield stress had to be exceeded to initiate flow, then torque increased linearly with rotational speed, corresponding to a suspension of constant viscosity.

5. The relationship of rotational speed to torque for hardwood pulps at 260 mL CSF at various consistencies. Torque increased linearly with rotational speed, like a suspension of constant viscosity.



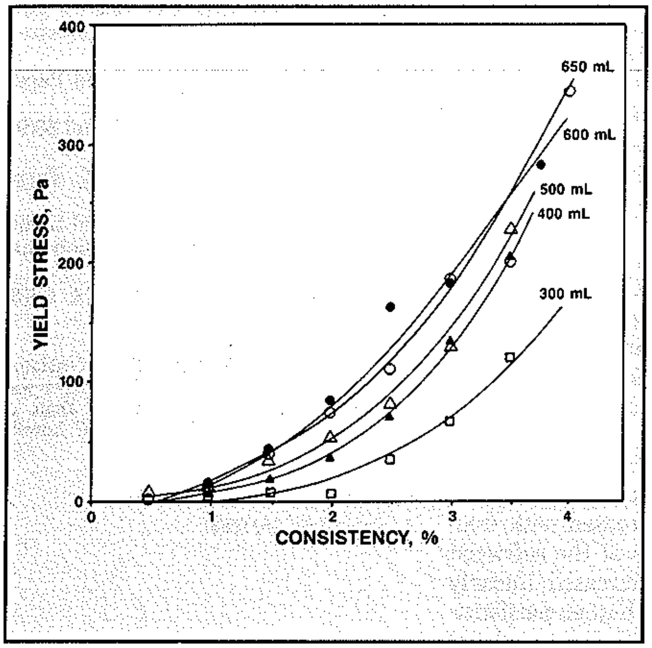
The Bingham model parameters of yield stress and viscosity were determined as a function of consistency and freeness for the hardwood and softwood pulp suspensions. For both types, yield stresses increased rapidly, and viscosities increased linearly with consistency, as would be expected. An increase in the consistency would increase the possibility of particle binding and interaction, which would result in an increase in the yield stress and viscosity.

For the hardwood fiber pulp suspensions, the yield stresses shown in Fig. 6 generally increased with freeness at a specific consistency. The suspensions approached Newtonian behavior at consistencies of 0.5-1.0%, at which the yield stresses were small.

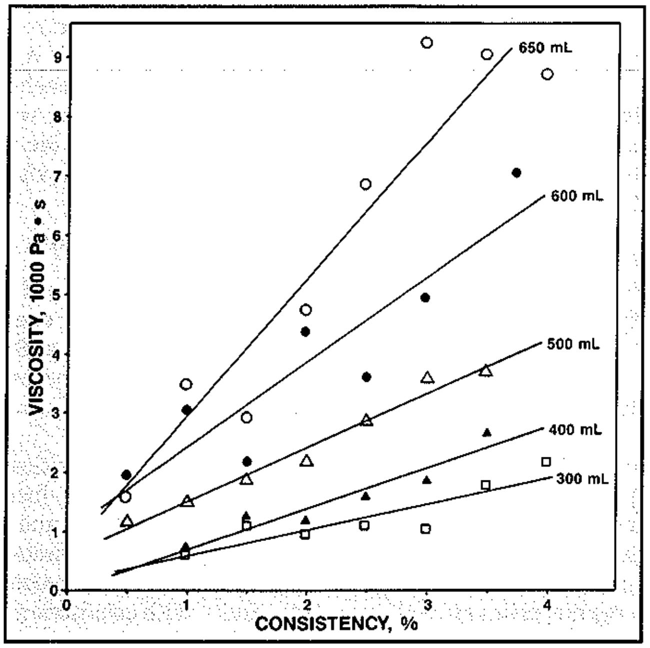
The viscosities of the hardwood pulp suspensions shown in Fig. 7 increased with freeness at a specific consistency. Also, the viscosities increased more rapidly with consistency as the freeness increased. In addition, solutions having a freeness of 300-400 mL CSF had viscosities close to that of water for consistencies less than 3%.

These results for hardwood are not unexpected. Hardwood, being composed of a short, thick-walled fiber,

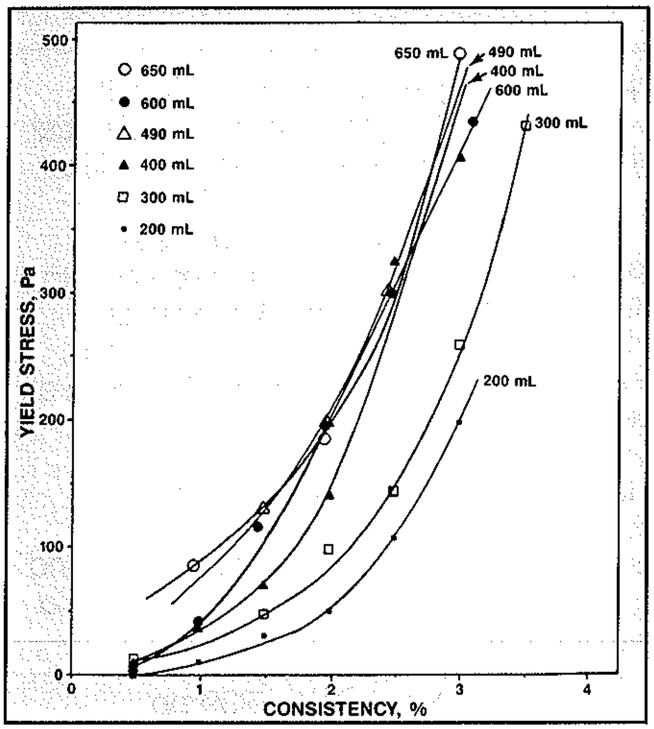
6. Yield stresses of pulp suspensions of hardwood fiber



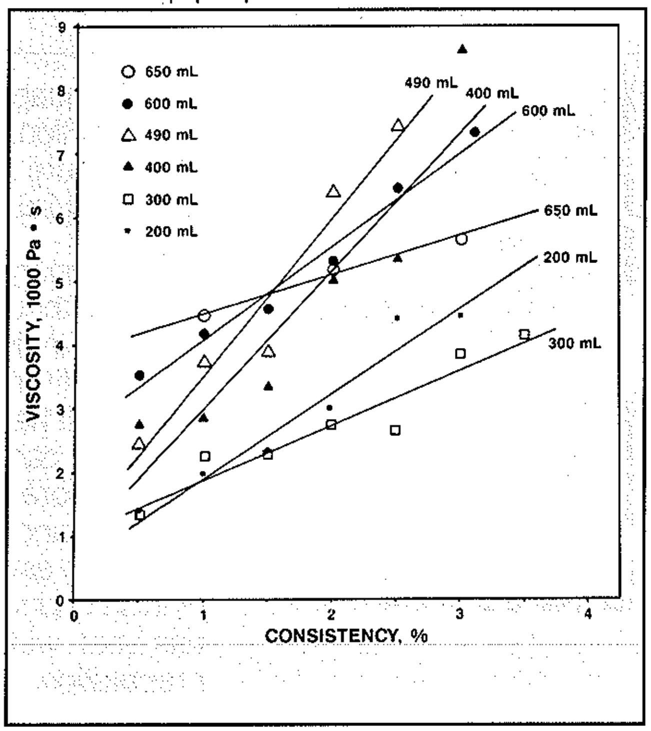
7. Viscosities of pulp suspensions of hardwood fiber



8. Yield stresses of pulp suspensions of softwood fiber



9. Viscosities of pulp suspensions of softwood fiber



would be subjected to more of a cutting action in the beater than one of fibrillation. Thus, beating time, as indicated by freeness, would reduce the fiber length and produce fines. Initially, the hardwood fiber had the ability to bind more water. However, additional beating of the fibers reduced their capacity to hold water, so that the slurry viscosity was reduced, eventually approaching the viscosity of water.

Yield stresses for the softwood fiber pulp suspensions are shown in Fig. 8. At a specific consistency, yield stresses increased with freeness through the range of 200-490 mL CSF. A further increase in freeness did not change the yield stresses substantially. As noted with the hardwood pulp suspensions, Newtonian behavior was approached at lower consistencies—about 0.5%, where the yield stresses were small.

The viscosities of the softwood pulp suspensions, as shown in Fig. 9, did not behave in a systematic manner with respect to freeness, especially at higher consistency. Viscosities tended to increase more rapidly with consistency as the freeness increased from 200-490 mL CSF. However, for the higher values of freeness—particularly at a freeness of 650 mL CSF—viscosities did not increase as quickly with consistency. This difference resulted in pulp suspensions with a freeness of 400 mL and 490 mL having higher viscosities than suspensions with a freeness of 600 mL and 650 mL for consistencies greater than 2%.

The results for softwoods can be explained if the viscosity of the suspension is related to the water binding power (or the degree of hydration) of the fiber as affected by the beating process (*6*). As beating started, the smooth primary wall was lost, and surface layers of the secondary wall started to open external fibrillation. While these changes were occurring, the hydration of the fiber increased, leading to increases in the viscosity. However, as beating continued, the fiber structure weakened, and the viscosity fell. With further beating, a point was reached where the production of fines, with a high degree of hydration, increased to produce a slight rise in viscosity.

Conclusions

The hardwood and softwood pulp suspensions examined exhibited the behavior of a Bingham plastic fluid. The yield stresses for both types of slurries increased rapidly with consistency.

The viscosities of the hardwood pulp suspensions increased linearly with consistency and decreased with freeness. The viscosities of the softwood pulp suspensions increased linearly with consistency. At higher consistencies, viscosities initially increased and then decreased with a decrease in freeness.□

Literature cited

1. McKennell, R., The measurement and control of viscosity and related flow properties, Ferranti Ltd., Moston, Manchester, England, 1960.
2. Sharma, S. K., Indian Pulp and Paper 23(5): 313(Nov. 1968).
3. Brecht, W. and Heller, H., Tappi 33(9): 14A(1950).
4. Gullichsen, J. and Harkonen, E., Tappi 64(6): 69(1981).
5. Bird, R. B., Steward, W. E., and Lightfoot, E. N., Transport Phenomena, Wiley, N.Y., 1960.
6. Kibblewhite, R. P., APPITA 26(3) 196(Nov. 1972).

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