Rheological measurements on pulps from South African gold mines

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SYNOPSIS

A method is described for the determination of the rheological parameters of a fast-settling slurry with conventional viscometric measuring equipment. The effect of concentration, temperature, and pH on these parameters is investigated. The results agree with those obtained by previous workers using different viscometers, but this method allows a more detailed characterization of all the properties. From a literature survey, two semi-empirical equations were found that allow the effect of concentration, temperature, or pH on the rheological parameters to be correlated.

SAMEVATTING

'n Metode word beskrywe wat die gebruiker in staat stel om die reologiese parameters van 'n vinnig uitsakkende flodder te bepaal met behulp van gewone viskometriese meetapparaat. Die invloed van konsentrasie, temperatuur en pH op hierdie parameters word ondersoek. Die resultate is in ooreenstemming met die verkry deur vorige werkers wat ander viskometers gebruik het. Hierdie metode laat egter 'n meer uitvoerige karakterisering van hierdie parameters toe. 'n Oorsig van die literatuur is gemaak en twee semi-empiriese korrelasies is gevind wat dit moontlik maak om die effek van of konsentrasie, of temperatuur, of pH op die reologiese parameters te korreleer.

INTRODUCTION

The development of the resin-in-pulp process for the extraction of uranium and of processes requiring heat transfer to slurries has revived interest in the rheology of mineral slurries. Measurement of the rheological properties of suspensions of this type is complicated by the facts that the slurries exhibit non-Newtonian behaviour, which must be correctly characterized, and the solids in the slurry settle. Consequently, valid data can be obtained only where the effects of settling can be allowed for.

The aim of the work reported in this paper was, from a review of the literature on the subject, to find a simple method of characterizing the rheological properties of slurries. A simple rotating-bob method that was not influenced significantly by settling was selected, and the effects of solids concentration, temperature, and pH were then determined on three typical gold-mine pulps.

LITERATURE SURVEY

The literature revealed a number of theoretical equations to express relative viscosity, and these were converted to a common basis by use of Taylor expansions to present the equations in the form

$$\eta_{rel}=a_0+a_1\phi+a_2\phi^2+a_3\phi^3+\ ..\quad (1)$$

As can be seen from Table I, which lists these equations, the value of a_1 is 2,5 in most of the equations. This results from the fact that they all follow on from Einstein's original equation. Thereafter, the values of the constants differ, depending on which simplifying assumptions were made when the equations were derived.

Two major conclusions were drawn from the literature survey: (1) there is an exponential relationship between the viscosity index and the concentration, and (2) there is a direct relationship between the size of the particles and the viscosity. The relationship between particle size and viscosity is not a simple one, and various workers[10, 12–14] obtained different and, in some instances, conflicting results. Levy[15] discusses this in detail.

Although there are a number of theoretical equations that predict the viscosity of a suspension of spherical particles, it is not possible to justify the use of one above another as each equation has an error associated with it. Also, these equations were derived for use in ideal situations (i.e., equal-sized spherical particles) and thus it is evident that more work is required on suspensions before predictions can be made of the effect of concentration, particle size, shear rate, etc., on the viscosity of a suspension of non-ideal particles (i.e., non-spherical, rough particles of different sizes).

EXPERIMENTAL WORK ON PULPS FROM GOLD MINES

Two types of viscometers have been used in work on slurries: the capillary and the rotational.

The use of a capillary viscometer similar to the 'consistometer' used by De Vaney and Shelton[12] was considered for this study but was rejected for the following reasons:

(i) the effect of swirl on the viscosity is unknown,
(ii) the pulp settles during measurements,
(iii) particles migrate to the centre of the tube, and
(iv) the tube becomes blocked.

Three rotational viscometers were then considered for this investigation: cone-and-plate, concentric-cylinder, and spindle-in-fluid viscometers.

Both Brookfield[16] and the Haake[17] cone-and-plate viscometers require only a small sample — 1,5 and 0,5 ml respectively — for analysis, but as difficulties were envisaged in obtaining a true representation of the pulp with such a small sample, this apparatus could not be used. Clarke's modifications[14] to the concentric-cylinder viscometer were not employed because of their suspected disturbance of the viscometric flow.

Work done with a Brookfield spindle-in-fluid viscometer[16, 18–20] in-

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TABLE I

RELATIONSHIPS FOR RELATIVE VISCOSITY AS $\pi_{rel}=a_0+a_1\phi+a_2\phi^2+a_3\phi^3+a_4\phi^4 \dots$

Author	Reference	Equation	Coefficients of expansion				
			a_0	a_1	a_2	a_3	a_4
Einstein	1	$\pi_{rel}=1+2,5\phi$	1	2,5	0	0	0
Gold	2	$\pi_{rel}=1+2,5\left(1+\frac{5}{16}\frac{a}{d}\right)\phi$	1	2,5	14,1	+	+
Burgers and Saito	3, 4	$\pi_{rel}=1+2,5\phi+12,6\phi^2+\dots$	1	2,5	12,6	+	+
De Bruijn	5	$\frac{1}{\pi_{rel}}=1-2,5\phi+1,55\phi$	1	2,5	4,7	0	0
De Bruijn	5	$\frac{1}{\pi_{rel}}=\frac{(1-\phi)}{(1+1,5\phi)}$	1	2,5	2,5	+	+
Vand	6	$\pi_{rel}=\exp(2,5\phi)$	1	2,5	3,125	2,604	1,627
Vand	6	$\pi_{rel}=\exp\left[\frac{2,5\phi}{1-\frac{39}{64}\phi}\right]$	1	2,5	4,65	+	+
Vand	6	$\pi_{rel}=1=2,5\phi+7,35\phi^2+\dots$	1	2,5	7,35	+	+
Vand, Roscoe, and Brinkman	6, 7, 8	$\pi_{rel}=(1-\phi)^{-2,5}$	1	2,5	4,375	6,562	9,023
Roscoe	7	$\pi_{rel}=(1-1,35\phi)^{-2,5}$	1	3,375	7,973	16,143	29,947
Mooney	9	$\pi_{rel}=\exp\left(\frac{2,5\phi}{1-K\phi}\right)$ for $K=1,35$	1	2,5	6,5	7,116	+
Mooney	9	$\pi_{rel}=\exp\left(\frac{2,5\phi}{1-K\phi}\right)$ for $K=1,91$	1	2,5	7,9	26,404	+
Shaheen	10	$\pi_{rel}=\exp\left(\frac{2,5\phi}{1-a\phi\, n}\right)$ for $n=0,5$	$1+2,5\phi+1,935a^2\phi^2+(3,906a+24,435a^3+11,166a^4)\phi^3+\dots$				
Frankel and Arcivos	11	$\pi_{rel}=\frac{9}{8}\left(\frac{(\phi/\phi_m)^{1/3}}{1-(\phi/\phi_m)^{1/3}}\right)$ for $\phi_m=0,74$	$1,156\phi^{13}+1,222\phi^{23}+1,35\phi+1,49\phi^{43}+\dots$				

dicated that this would be a satisfactory instrument. Preliminary experimentation, in which a laboratory magnetic stirrer was used to maintain the suspension, proved that the spindle-in-fluid viscometer could be used to obtain the required viscosity.

The apparatus used was a Brookfield synchro-lectric LVT model[16], but the guard supplied with the viscometer for use with Newtonian liquids was not used in these experiments. Three spindles were used to enable the viscometer to measure the viscosity of the pulps over the entire concentration range. Two of these spindles were commercially available (LV Model Cylindrical Spindles[16]), whereas the third had to be specially built. This was done by designing a Perspex sleeve that slipped onto one of the spindles, thereby creating a new one. The use of an O-ring allowed the sleeve to slip on and off but, once on, permitted no relative movement between the spindle and the sleeve even when the viscometer exerted its maximum torque. The spindles were calibrated as described by Rosen[19, 20] and Brookfield[16].

The temperature of the pulp was controlled by the pumping of water from a constant-temperature bath through a jacket surrounding the beaker containing the pulp. Beakers of two sizes were used — a 1-litre beaker for the largest spindle and a 600 ml beaker for the two smaller spindles.

EXPERIMENTAL TECHNIQUE

A beaker containing a homogeneous sample of pulp of known specific gravity was placed in a water-jacket. The viscometer was then placed in position and the spindle immersed to a pre-set depth, which was determined by a notch on the spindle. A special laboratory stand, available from the manufacturers[16], was used to ensure that the viscometer was level and remained in the same horizontal plane for the duration of the experimental run. The temperature regulator was set to the required temperature and the pulp allowed to reach steady state.

The experimental data were obtained by selecting a speed of rotation for the viscometer and noting the deflection of the pointer on the dial. Owing to the construction of this particular viscometer, the dial pointer oscillated before settling down. The readings taken were those at steady state, indicated by no change in the dial reading for three successive rotations. A minimum of three readings was taken at each rotational speed, the magnetic stirrer being used to resuspend the pulp after each reading. These readings were repeated for each selected speed of rotation. After the run had been completed, a new temperature was selected and, after equilibrium had been reached, the procedure was repeated. Normally, three to four temperatures in the range 8 to 30 °C were investigated for each concentration The effects of the magnetic stirrer and of the settling during experimentation were investigated and were found to be minimal[15].

For each experimental run the following data were recorded: the rotational speed, the corresponding dial reading, the temperature, and the spindle attached to the viscometer. The data were plotted as log (dial reading) versus log (rotational speed). The reciprocal of the slope of this graph was defined as the shear thinning index, *STI*. The shear rate, shear stress, and apparent viscosity were obtained from the following equations:

$$\text{Shear rate} = \dot{\gamma} = -\frac{\pi}{15} \times \text{r/min} \times STI \quad \ldots \quad (2)$$

$$\text{Shear stress} = \tau = \frac{dr \times sc/100}{2\eta\ (r)^2\ (el)} \quad \ldots \quad (3)$$

$$\text{Apparent viscosity} = \eta = \frac{dr \times sc/100}{2\pi(r)^2\ (el) \cdot \frac{\pi}{15} \times r/min \times STI} \quad . \quad (4)$$

where r/min = rotational speed,
STI = shear thinning index,
dr = dial reading,
sc = spring constant,
r = radius of spindle in cm, and
el = effective length of spindle in cm.

The derivation of these equations can be found in Rosen[19, 20] and the determination of the effective length in Levy[15].

RESULTS

Concentration

All three pulps investigated were found to be shear thinning over the entire concentration range investigated (viz, 0,17 to 0,43 volume fraction). Similar results were obtained by Marsden[21] and Beazley[22]. The latter also found that, above 0,46 volume fraction, the pulps became shear thickening. Clarke[14] found shear-thickening behaviour over the entire concentration range that he investigated, but these anomolous results could be due to changes that he made to his viscometer[15].

In an investigation of the effect of concentration on the viscosity index, the experimental data were fitted to a number of correlations.

Only two correlations were found to allow the effect of concentration, shear rate, and temperature on the viscosity index to be investigated. These were extensions of the equations of Shaheen[10] and Beazley[22].

Shaheen proposed an equation of the form

$$\eta_{rel} = \left(\exp\frac{A\phi}{1-a\phi^n}\right), \quad \ldots \quad (5)$$

where A has a constant numerical value and a and n are constants. Investigation proved that, although equation (5) was not extremely sensitive to changes in the value of A, a three-constant equation gave an overall smaller standard deviation (i.e., a better fit) than the two-constant equations and was thus used as a three-constant equation.

The correlation used by Beazley, which is an extension of Mooney's equation[9], was also tried. The equation is

$$\eta_{rel} = \exp\left(\frac{A\phi}{1-K\phi}\right). \quad \ldots \quad (6)$$

A description of how these equations were used to fit the data and tables of the results obtained can be found in Levy[15]. Either equation (5) or equation (6) can be used to fit the data. These apply over the entire range of relevant

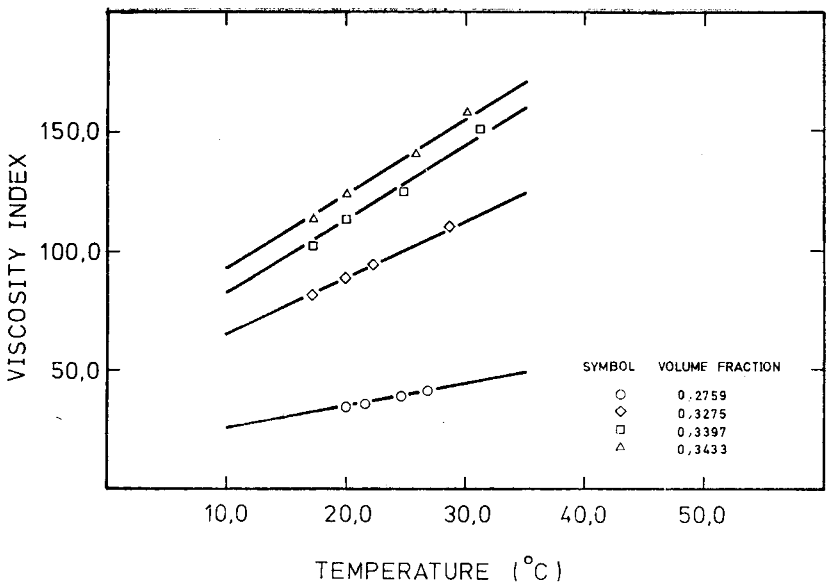

Fig. 1—The dependence of viscosity on temperature

concentration, temperature, and shear rate. The exponential nature of the effect of concentration on the apparent viscosity was in agreement with the results of many previous workers[9, 10–14, 21, 23, 24].

Temperature

The effect of temperature on the viscous parameters K and n of all three pulps was investigated. During the investigation, it was found that there was a linear relationship between the viscosity index and the temperature of the pulp. As can be seen in Fig. 1, the slope of the curves increases monotonically with increasing concentration, and the use of this relationship is thus possible in the prediction of the viscosity at any temperature.

In the calculation of the effect of temperature on the rheological properties of a non-Newtonian liquid, it was necessary to decide on two parameters: (1) a common basis on which the variables could be compared, i.e., shear rate or shear stress, and (2) which variables to compare, i.e., the power-law variables K and n or the viscosity index η_{rel}. The literature survey revealed that no work had been done on the effect of temperature on the rheological properties of a slurry, and thus, as no precedent existed, it was decided to report the effect of temperature on all three variables (K, n, and the viscosity index) at a common shear rate and the effect of temperature on the viscosity index at both a common shear rate and shear stress. These are shown in Figs. 2 to 5. These graphs were plotted for pulp B but were typical of all three pulps. The co-ordinates of the graph were chosen to give the best linear relationship between the variable investigated and the temperature. As can be seen from the graphs, the temperature range is rather limited and no firm prediction can therefore be made about the effect of temperature on the rheological properties of the pulps. The results, however, do seem to indicate that there is a change in the effect of temperature on the parameter investigated. Above a certain concentration, the apparent viscosity increases with temperature, instead of decreasing. A tentative explanation of this can be found in Levy[15]. Marsden[21] also found this 'reversal' of the rheological properties of concentrated alkaline slurries at high temperatures. It is suggested that further work should be done on this problem using a larger temperature range than was used in this project.

Significance of pH

The three pulps all exhibit similar exponential curves of viscosity index versus concentration. Within experimental error, the alkaline and the neutral pulp both lie on the same curve, whereas the curve of the acid pulp lies well below these. The difference in the curves is thought to be due to the presence of an ionic cloud surrounding the individual particles. The pH value of the pulp will influence the size of this cloud, and thus the ease with which particles can move past one another. Presumably, the ionic cloud is unaffected by going from basic to neutral but is reduced in acid. The size of this cloud will have a large effect on the value of the viscosity.

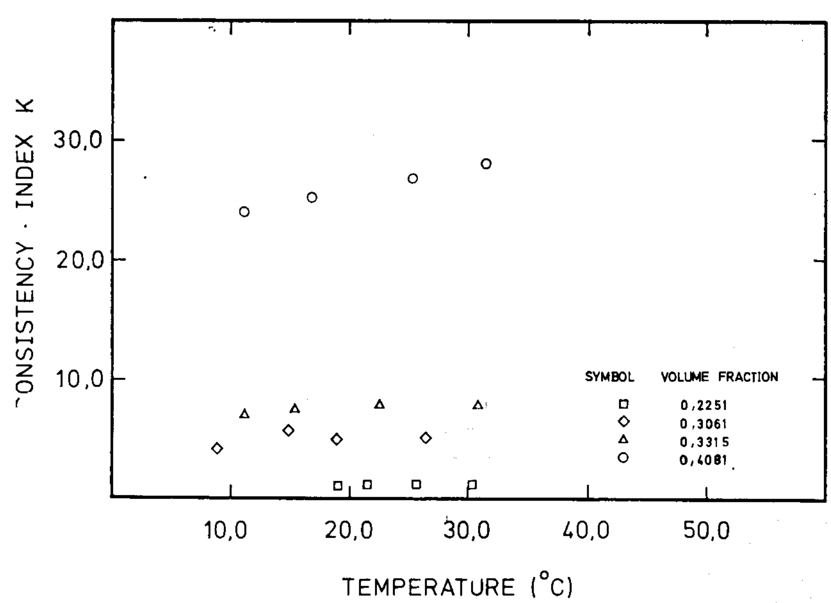

Fig. 2—The dependence of the consistency index on temperature

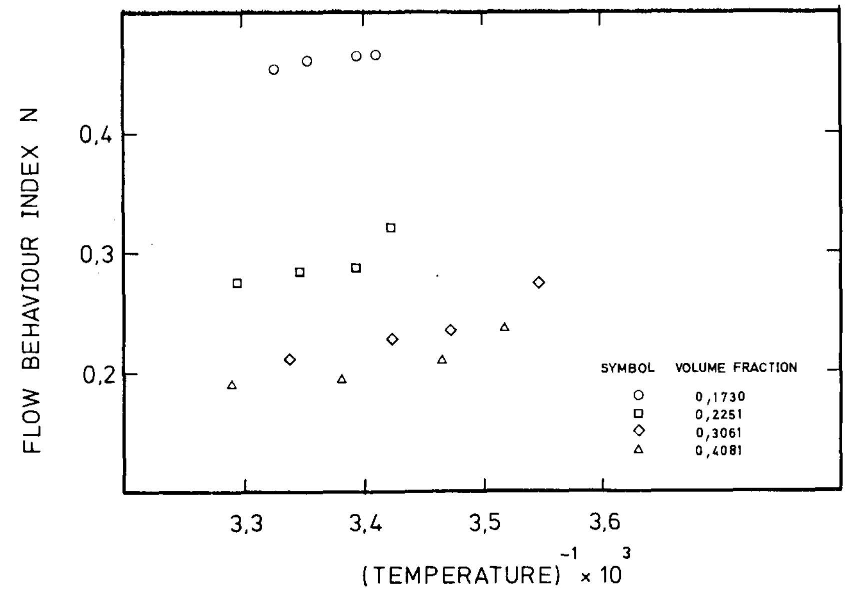

Fig. 3—The dependence of the flow behaviour index on temperature

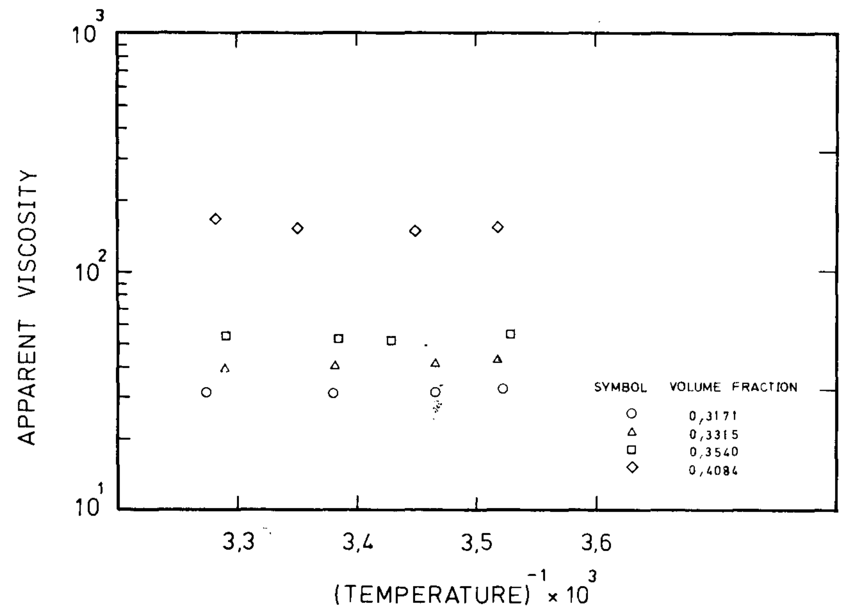

Fig. 4—The effect of temperature on apparent viscosity at a common shear rate

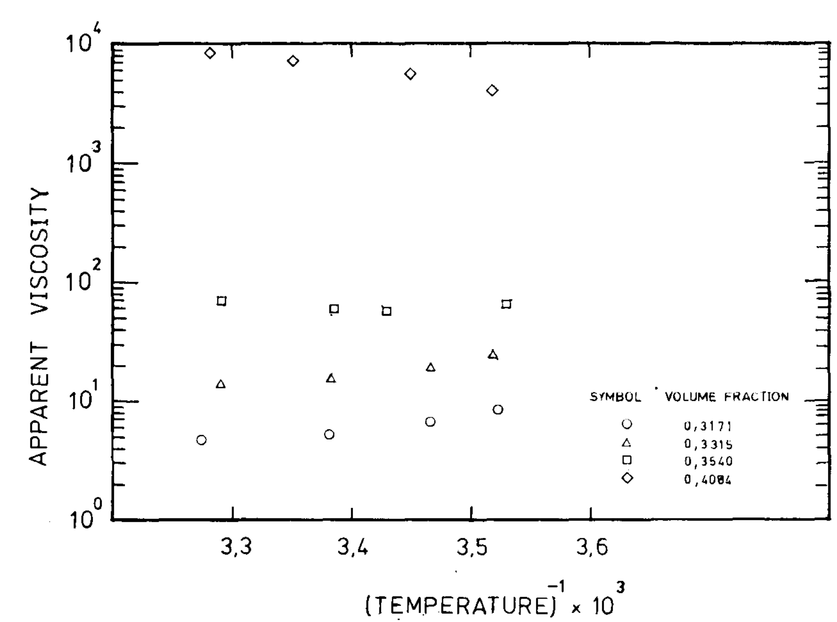

Fig. 5—The effect of temperature on apparent viscosity at a common shear stress

The increase in viscosity found in the change from an acid to an alkaline pulp is encountered in normal mine operations[25]. Curves of all three pulps can be seen in Figs. 6 to 8.

Presence of Bentonite

As a further test of the applicability of the method in the determination of the rheological properties of a pulp, a short investigation was conducted on the effect of bentonite in a pulp. Commercially pure bentonite was suspended in water and then added to prepared samples of neutral pulp. Tests were run with bentonite concentrations of approximately 0,5 per cent, 1,0 per cent, and 1,5per cent (w/w).

The results are illustrated in Fig. 9, which shows that the addition of only 0,5 per cent bentonite to a pulp caused a large increase in its apparent viscosity. Further additions of bentonite resulted in additional increases in the viscosity, but the relative increase decreased with increasing bentonite concentration.

CONCLUSIONS

This research project has shown that it is feasible to investigate the rheological properties of a mine pulp with a conventional viscometer. However, it was necessary to modify the viscometer in order to avoid settling during the viscometric measurements, and it was found that a normal laboratory magnetic stirrer could be used to keep the pulp in suspension.

The experimental procedure outlined permits the determination of the rheological properties of a mine pulp and was developed with a view to its application, with commercially available equipment, in routine determinations.

A full investigation of the effect of temperature on the rheological properties was not possible, and it is suggested that further work should be done, utilizing a wider range of temperature.

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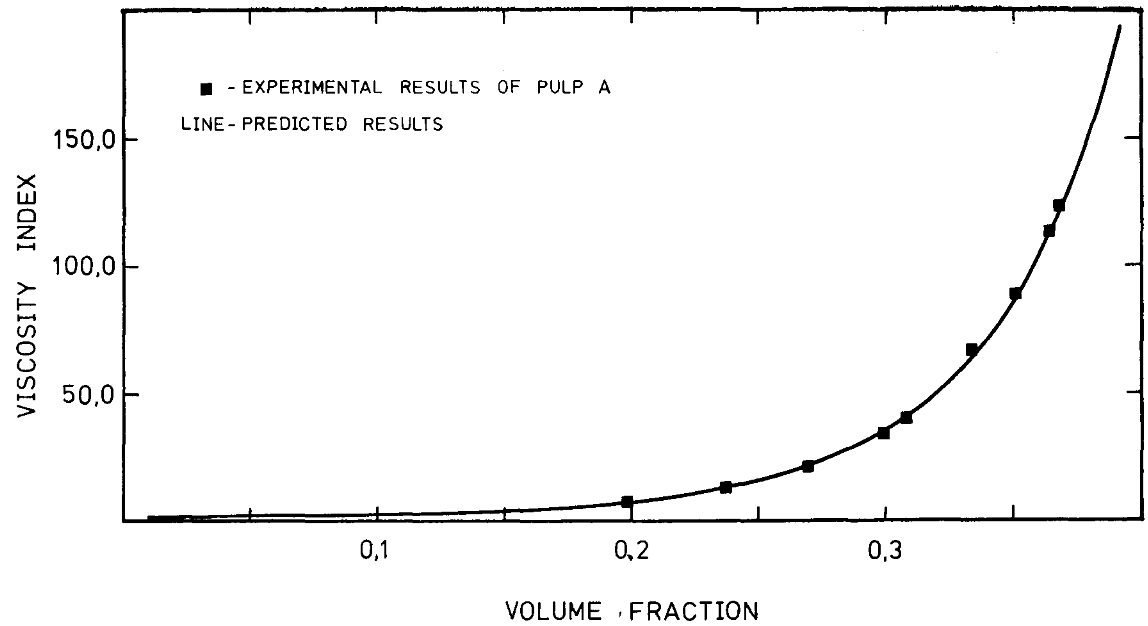

Fig. 6—A comparison of experimental and predicted results

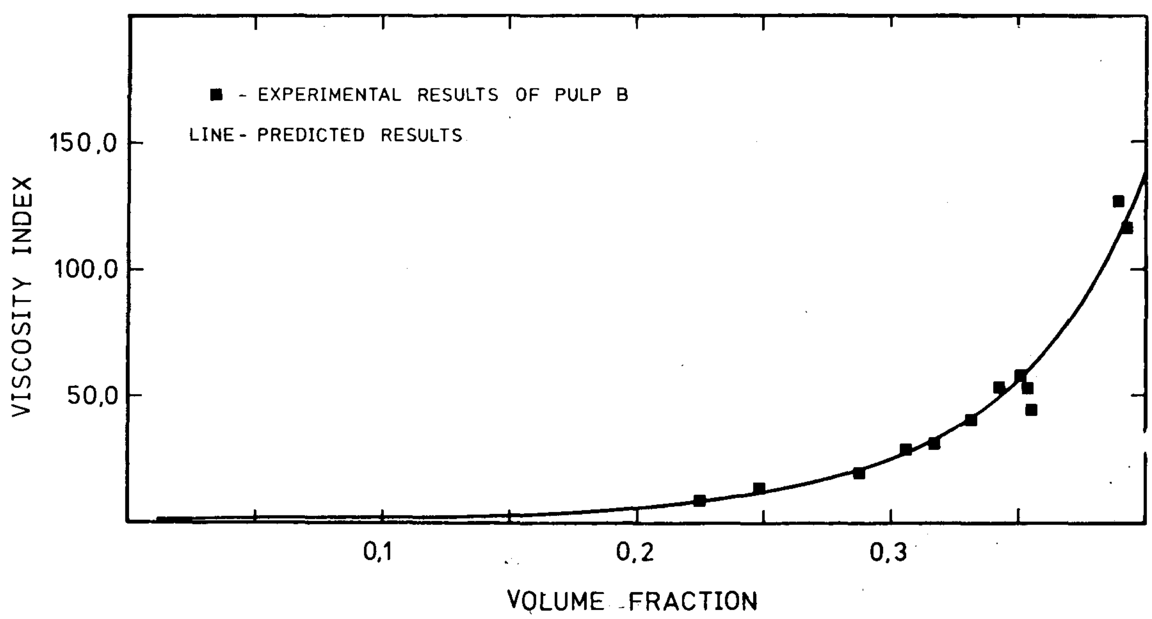

Fig. 7—A comparison of experimental and predicted results

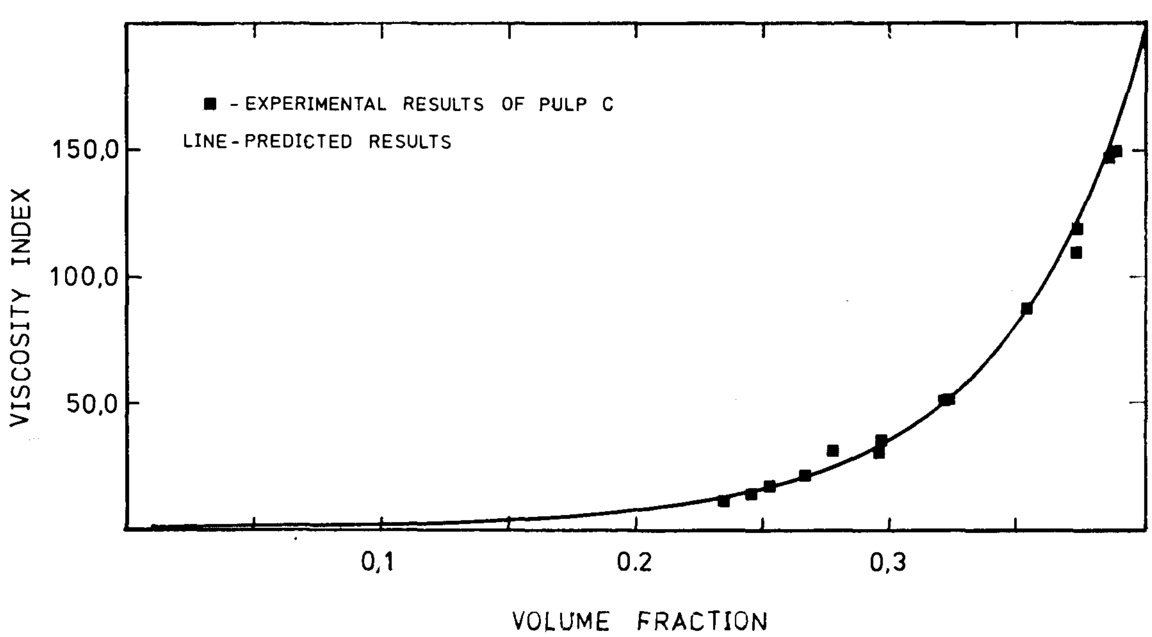

Fig. 8—A comparison of experimental and predicted results

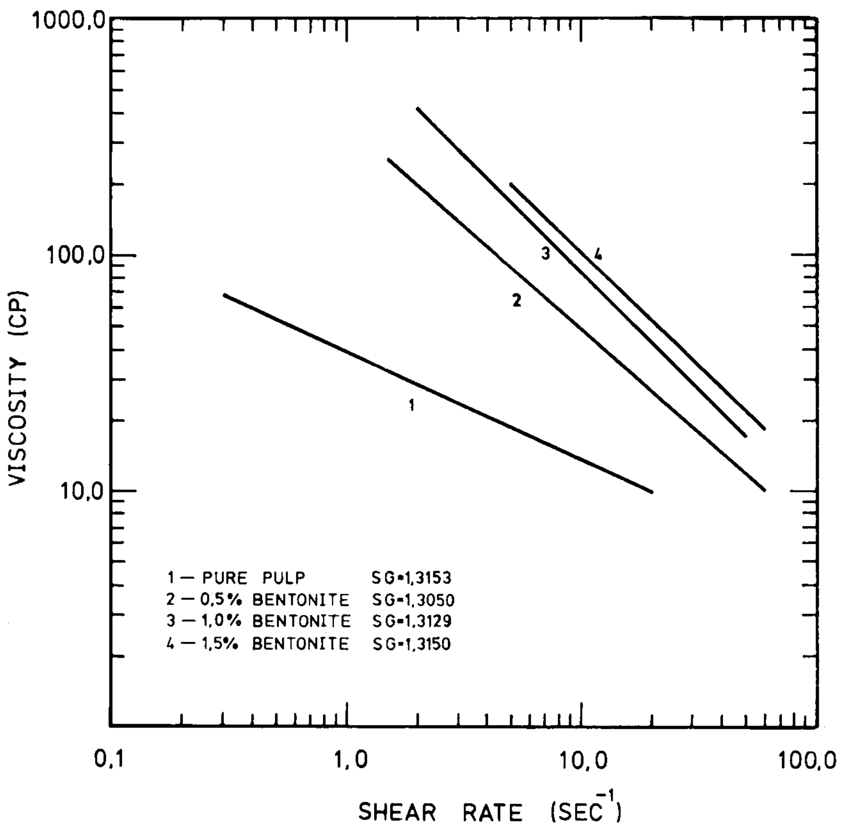

Fig. 9—The effect of bentonite addition

NOMENCLATURE

ϕ = volume fraction

η_{rel} = viscosity index defined as viscosity of suspension divided by viscosity of liquid at same temperature

τ = shear stress

$\dot{\gamma}$ = shear rate

η = apparent viscosity of non-Newtonian system

n = flow behaviour index

K = consistency index = projected value of τ at a shear rate of 1 s^{-1}

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