DETERMINATION OF THE CONSISTENCY OF NON-NEWTONIAN FLUIDS USING A BROOKFIELD HBT VISCOMETER

By E. J. DURGUEIL

*Tongaat-Hulett Sugar Limited, La Lucia, Natal**

Abstract

The principle of the method of measurement of rheological properties using a Brookfield viscometer is outlined. Equations for the conversion of torque reading using Brookfield spindles to consistency and for the determination of the flow behaviour index of non-Newtonian fluids are developed. An empirical correlation for the determination of the consistency of low grade massecuite and molasses is developed which gives calculated consistencies in good agreement with the experimental data.

Introduction

A fluid is a substance which undergoes continuous deformation when subjected to a shear stress. The resistance offered by a real fluid to such deformation is called its consistency, K. For gases and for Newtonian liquids, the consistency is constant if static pressure and temperature are fixed and for such materials, the consistency is called the viscosity. However, for many liquids used in chemical processes, the flow curve (a plot of shear stress vs shearing rate) is not linear through the origin and they are known as non-Newtonian fluids. If the flow curve has a slope decreasing with increasing rate of shear, the fluid is called pseudoplastic. The rheology of pseudoplastics can be described by a number of models, the most commonly used being the Ostwald-de Waele or power law model:

$$\tau = K\left(\frac{d\delta}{dt}\right)^n \text{ for } n < 1 \qquad (1)$$

The flow behaviour index, n, is a measure of the degree of departure from Newtonian behaviour. The further n departs from unity, the more pronounced are the non-Newtonian properties.

Literature review

There are a number of different viscometric techniques for measuring the flow behaviour of fluids and many different types of commercial instruments are available. A review of the various techniques applied in the sugar industry is given by Ness[1], Mathlouthi and Kasprzky[2].

Any rotational viscometer like the Brookfield HBT viscometer assumes the fluid to be Newtonian. If the fluid is non-Newtonian, the viscosity is shear rate dependent and it is necessary to relate the shear rate and stress to the torque and rotational speed. Calibration of the Brookfield HBT viscometer by the manufacturer was apparently conducted using a Newtonian fluid and it is from here that the anomalies arise (Behne[3]).

In the literature, the use of the words consistency and viscosity is confusing. Consistency is an intrinsic characteristic of the fluid independent of the shearing strain applied during the measurement period whereas viscosity is a measurement of the resistance to flow of the fluid under specific conditions of shear.

Viscosity determination using the Brookfield HBT viscometer has little meaning unless the shear rate is specified. Various authors (Bhattacharyya et al[4], Garcia[5], Rouillard[6]) have tried to determine the shear rate by considering the Brookfield spindle as a cylindrical bob rotating in an infinite medium (infinite cup theory - Kreiger and Maron[7]). The theory does not apply to a disc spindle and if different spindles are used, the values of the viscosity obtained are different.

The Brookfield HBT viscometer

Description

The Brookfield HBT viscometer measures consistency by measuring the force required to rotate a spindle in the material under test. The force or drag is indicated by a pointer which is attached to the spindle shaft. The speed of rotation and the dial reading are directly proportional to the rate of shear and shearing stress respectively; thus a speed of rotation versus dial reading plot is comparable with a flow curve. Conversion factors supplied with the instrument enable dial readings to be converted to common viscosity units. The viscometer was calibrated for Newtonian fluid and any fluid will be considered to be Newtonian if measurement is made only at one speed. It is necessary to relate the shear rate and stress to the torque and rotational speed if the fluid is non-Newtonian.

The spindles which can be used with the Brookfield HBT viscometer are of different geometrical form and size. The spindles generally used for low consistency fluids have the form of a cylinder (cylindrical spindle T1) or the form of a disc (disc spindles T2, T3 and T4). The spindles used for solids suspensions and also for high consistency fluids have the form of a T and are called T bar A, B and C. To allow the T bar spindle to cut continuously into a fresh sample, the spindle can be submitted to an upward and downward movement while under rotation, creating an helicoidal path. This overcomes the separating effect of the particles in suspension where progressive disentanglement occurs under the influence of shearing forces, the particles tending to orient themselves and move in the direction of the shear.

Method of measurements

A Brookfield HBT viscometer model was used for the determination of the consistency of C-products, ie C-massecuite, C-nutsch and C-molasses samples.

The sample in a container of diameter 110 mm was placed into a water bath to allow the temperature to stabilise. The consistency was then measured using different spindles and different rotational speeds. The spindle was allowed to rotate in the sample for 10 minutes before the reading was taken to avoid variations in the measurement due to thixotropic effects (Taylor[8]). The molasses consistency was measured

* Present address: Mondi Paper Company, Merebank, Durban

using the disc and cylindrical spindles. The massecuite measurement was done using the T bar spindles submitted to an helicoidal path and rotating at a speed lower than 10 rpm. The nutsch consistency was measured using the T bar and disc spindles to establish if measurement and conversion of readings were the same for the various spindles. The scale deflection was kept in the 10 to 80% range. The temperature of the sample was measured with a digital temperature probe at 0,1°C. The measurement of the consistency was then repeated at a higher temperature in the 40 to 70°C range.

Equations for the determination of consistency

The shear stress is obtained from the torque and the dimensions of the spindle. The torque, τ, product of the scale deflection and the maximum torque available on the Brookfield HBT viscometer is evaluated by multiplying the tangential component of the shear stress by the differential area $drd\theta$ and then by the lever arm r and integrating the product over the surface of the completely wetted spindle:

$$\zeta = -\int_0^{2\pi}\int_0^{R} \tau_{\theta r}\, r dr d\theta \qquad (2)$$

The shear rate is obtained from the tangential component of the "rate of deformation tensor", Δ, for the Ostwald-de Waele model[9] as:

$$\frac{(d\delta)^n}{(dt)} = -\int_0^{R}\left[\frac{\partial}{\partial r}\left|\sqrt{\frac{1}{2}(\Delta:\Delta)}\right|^{(n-1)}\frac{\delta(\Delta)}{\partial r}\right] dr \qquad (3)$$

The consistency of the fluid is determined by applying the equation of a power law fluid:

$$K = \frac{\tau}{\left(\frac{d\delta}{dt}\right)^n} \qquad (4)$$

The equations for the determination of the consistency for the various spindles have been derived from equations (2) to (4) and are shown in Table 1.

Results

Determination of the flow behaviour index

It is possible to determine the flow behaviour index, n, of a sample showing pseudoplastic characteristics from various measurements of the consistency at different speeds with the same spindle and at the same temperature:

$$K = \frac{Sd_1}{B}\left(\frac{A}{N_1}\right)^n = \frac{Sd_2}{B}\left(\frac{A}{N_2}\right)^n$$

with A and B the constants determined in Table 1, and Sd the scale deflection at a speed N.

After mathematical simplification, the flow behaviour index is given by:

$$n = \ln\left(\frac{Sd_1}{Sd_2}\right) \times \frac{1}{\ln\left(\frac{N_1}{N_2}\right)} \qquad (5)$$

This calculation is equivalent to the determination of the flow behaviour index from the flow curve, n being the slope of the plot on log-log graph of the speed versus torque measured.

The range of value of n is shown in Table 2 for final sugar products. Massecuites exhibit a smaller degree of pseudoplasticity than molasses. The crystals in the massecuite represent a discontinuity in the solid matrix and reduce the elasticity by creating a breaking tie. In the same way, water seems to reduce the plasticity of the solid matrix by separating the lines of preferential shear and the value of n for the nutsch has been found generally smaller than for the molasses.

Table 2

Different values of n

Author	Range of n	Mean Value of n	Product
Done[9]	0,85 + 0,04		Massecuite
Adkins[19]	0,6/0,9		Massecuite
Kot et al[20]	0,8/1		Massecuite
Bhattacharyya et al[4]	0,8/0,9		Molasses
Awang and White[21]	0,92 + 0,07		Massecuite
Broadfoot et al[22]	0,81/0,88		Molasses
Rouillard and Koenig[23]	0,8/0,93 with low at 0,68		C-massecuite
This work	0,67/0,81	0,77	C-massecuite
	0,56/0,81	0,73	C-molasses
	0,60/0,66	0,63	C-nutsch

Determination of the consistency

For Newtonian fluids, the viscosity is calculated by multiplying the torque reading by the conversion factor given by the manufacturer of the Brookfield HBT viscometer. The conversion factor depends on the spindle used and the rotational speed.

Table 1

Equations for the determination of the consistency

Spindle	Shear stress	Shear rate	Consistency	
			Literal form	Simplified form
Cylindrical T1	$\frac{-\tau}{2\pi R^2\left(\frac{2}{3}R + L\right)}$	$-\left(\frac{\pi N}{10}\right)$	$\frac{\tau}{2\pi R^2\left(\frac{2}{3}R + L\right)}\left(\frac{10}{\pi N}\right)^n$	$\frac{Sd}{B}\left(\frac{A}{N}\right)^n$
Disc spindle T2, T3, T4	$\frac{-\tau}{2\pi R^2\left(\frac{2}{3}R + L\right)}$	$-\left(\frac{\pi N}{15}\right)$	$\frac{\tau}{2\pi R^2\left(\frac{2}{3}R + L\right)}\left(\frac{15}{\pi N}\right)^n$	$\frac{Sd}{B}\left(\frac{A}{N}\right)^n$
T bar spindle TA, TB, TC	$\frac{-\tau}{3R^2L}$	$-\left(\frac{\pi N}{10}\right)$	$\frac{\tau}{3R^2L}\left(\frac{10}{\pi N}\right)^n$	$\frac{Sd}{B}\left(\frac{A}{N}\right)^n$

The value of the consistency can be determined using the conversion factor of the manufacturer and simplified equation of Table 1 as:

$$K = Sd \times C = \frac{Sd}{B} \times \left(\frac{A}{N}\right)^n$$

with C being the conversion factor at a speed N. The simplified equation for the consistency can be used for Newtonian fluids (n = 1) and after mathematical manipulation and using the conversion table from the manufacturer, the value of B can be determined for the various spindles (Table 3).

Table 3

Values of the new constant for the different spindles

Spindle	Constant manufacturer (at 0,5 rpm)	New constant
HBTA	3 200	502,65
HBTB	6 400	1 005,31
HBTC	12 800	2 010,62
HBT1	160	25,13
HBT2	640	67,0
HBT3	1 600	167,6
HBT4	3 200	335,1

The consistency is now determined by:

$$K = Sd \times (\text{new constant}) \times \left(\frac{A}{N}\right)^n \qquad (6)$$

Values of the consistency of C-products measured at different speed and using different spindles calculated by Equation 6 are shown in Table 4 and compared to the viscosity value obtained using the manufacturer's method. The maximum error encountered is 9%. The values of the calculated consistency are more consistent and independent of the spindles and speeds used for the measurement, thus giving an intrinsic characteristic of the fluid. The use of Equation 6 does not modify the calculation of the flow behaviour index when determined using measurements done with the same spindle.

Thixotropic effects of the molasses

The molasses showed thixotropic effects, with reading of the torque falling with increasing time of flow (Figure 1). Nevertheless, this effect is a function of the shear rate and as the rotational speed was reduced, the thixotropy was not so pronounced. Done[10] commented on thixotropic effects for the massecuite but no such effect has been found with the helipath. To avoid variations in the measurement of the consistency due to thixotropy, it is recommended that the sample be left to reach a steady temperature and allowed to rotate for at least 10 minutes after immersion of the spindle before reading the torque.

Variation of torque reading using an helipath spindle

The reading of the massecuite and nutsch viscosity using the helipath need to be averaged because the value changes during the rising and descending motion (Ness[11]). As the shear stress is dependent on the length of spindle immersed in the fluid, it is normal that the readings are affected by the depth of penetration (Figure 2). However, the way in which the value of the readings varied was contrary to that reported by Ness, the value was decreasing gradually as the spindle moved downwards and increasing on withdrawal which is in agreement with Equation 4, K being a function of 1/L where L is the immersed length of the spindle. Generally, a higher value of the readings was found somewhat after the top position due to the elasticity of the connection between the spindle and the viscometer. The readings need to be done during a complete cycle of the helipath and averaged to obtain the value of the torque.

Table 4

Comparison between Brookfield consistency * and calculated consistency **

Sample	n	Temp. °C	Reading average	Spindle	Speed rpm	Value Brookfield*	Value calculated**
Nutsch	0,660	54,6	54,75	HBT3	0,5	876	311,20
			69,62	HBT4	2,5	445,57	359,12
			63,15	HBTA	2,5	404,16	372,29
			31,98	HBTA	1	511,68	345,16
			14,42	HBTB	1	461,44	311,28
			27,91	HBTB	2,5	357,25	329,08
			45,67	HBTB	5	292,29	340,79
Massecuite	0,770	57,3	46,60	HBTB	1	1 491,20	851,09
			86,64	HBTB	2,5	1 109,03	781,43
			25,99	HBTB	0,5	1 663,20	809,44
			93	HBTA	1	1 488	849,26
Molasses	0,760	56,3	25,50	HBT2	50	16,32	2,33
			36,75	HBT2	100	11,76	1,98
			9,5	HBT2	20	15,20	1,74
			5,55	HBT3	20	22,20	2,54
			9,75	HBT3	50	15,60	2,23
			15,88	HBT3	100	12,70	2,14
			36,5	HBT1	20	14,60	1,68
			69,5	HBT1	50	11,12	1,59
			20	HBT1	10	16	1,56

* Brookfield consistency calculated by multiplying the torque reading by the manufacturer conversion factor.

** Calculated consistency from Equation 6.

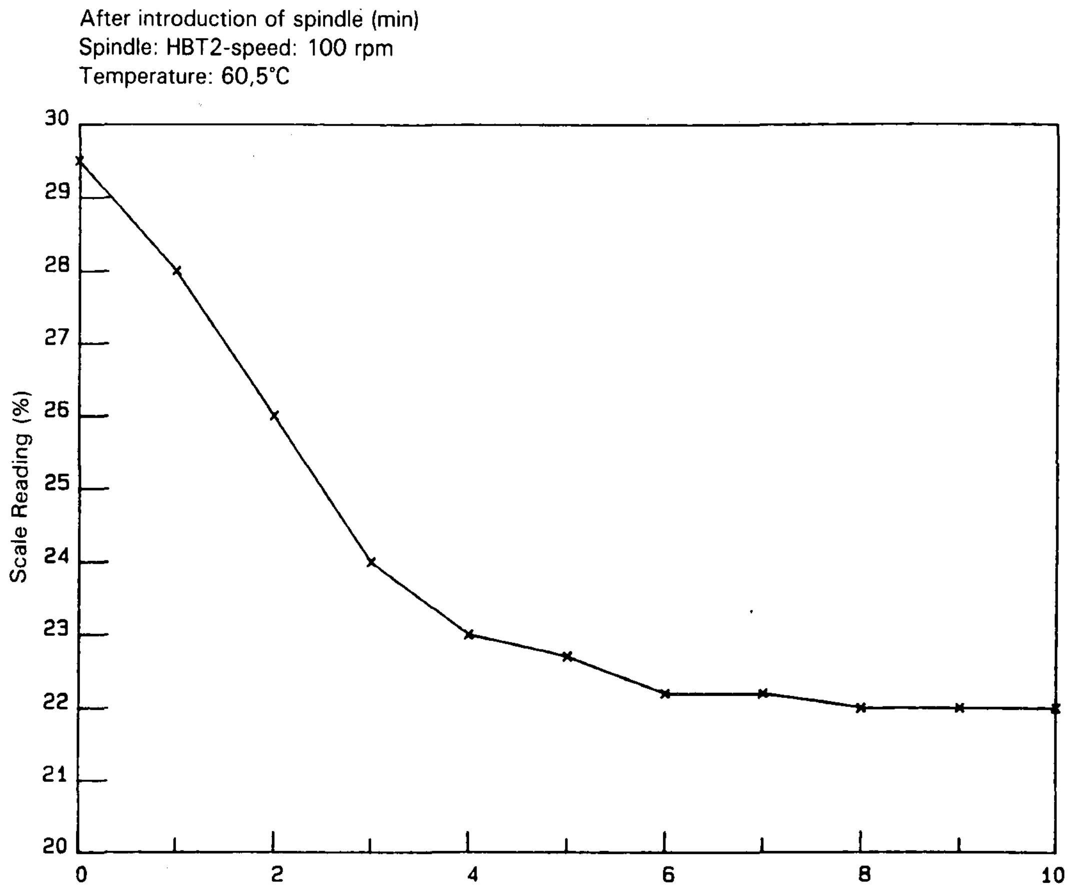

FIGURE 1 Thixotropic effect in molasses

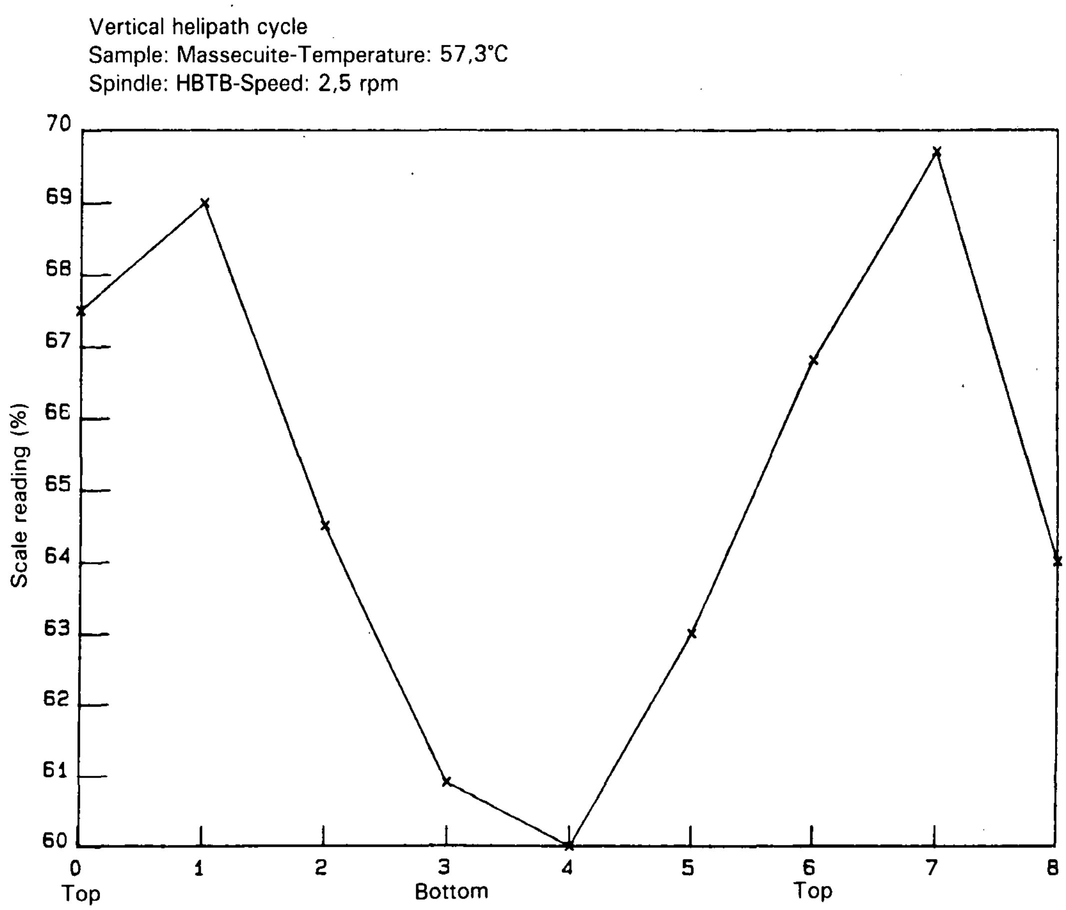

FIGURE 2 Torque variation vs helipath position

Correlation for the determination of the consistency of sugar C-products

The consistency of any C-product decreases exponentially as temperature increases (Figure 3) and increases with the total solid content of the product (Figure 4). An Arrhenius type equation was adopted for the determination of the consistency of any C-product based on the work of de Guzman[12], Andrade[13] and Eyring[14].

The form of the equation can be written as:

$$K = \frac{\exp\left(D + \frac{H}{CpT}\right)}{(1 - TS)^x} \qquad (7)$$

where H is the activation energy necessary to give to the material for changing its state, Cp the heat capacity of the slurry, sum of the specific heats of the pure components (Thomas[15], Orr and Dalle Valle[16]), TS the total solids of the material, x an exponent and D a parameter depending on the solid concentration (Einstein[17, 18], Thomas [15]).

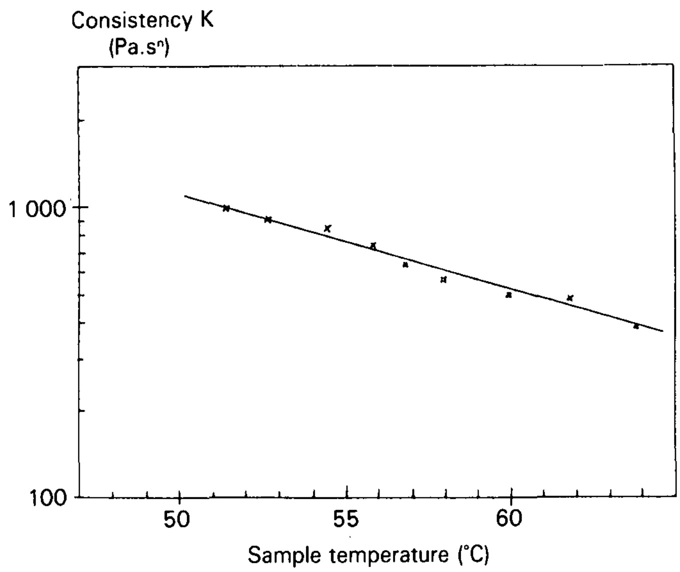

FIGURE 3 Relation between consistency and temperature

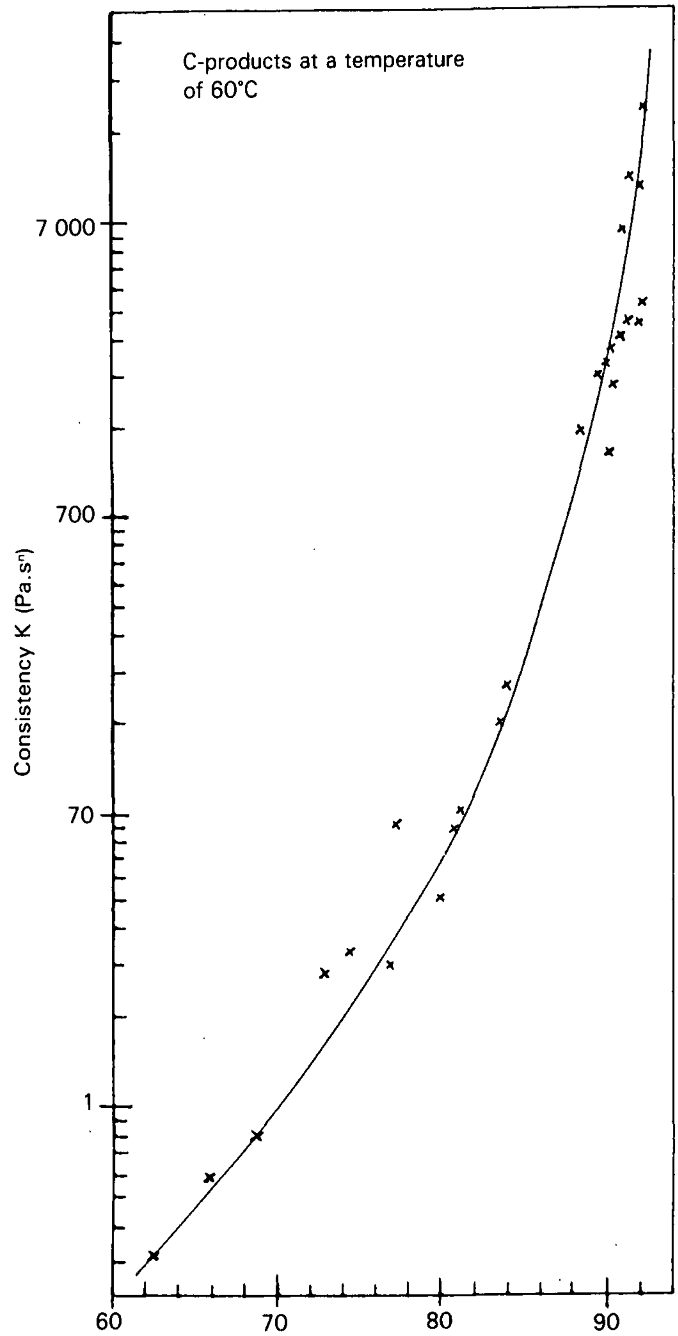

FIGURE 4 Consistency versus total solids

The coefficients of the correlation linking consistency of any C-product to the total solids content, crystal content, pol and temperature have been determined by statistical analysis done on 43 samples of molasses, nutsch and massecuite taken during the 1985/86 season at Maidstone mill.

The correlation in the form of Equation 7 is written as:

$$K = \frac{\exp\left(-21{,}33 + 15{,}90\,\text{pol} - 35{,}49\,CC + \frac{6802{,}37 + 3618{,}15(TS - CC) - 13129{,}53\,CC + 3042{,}79(1 - TS) + 19356{,}86(\text{pol} - CC)(1 - TS)}{((4{,}187 - 2{,}3(\text{pol} - CC)(1 - TS))(1 - TS) + 1{,}19\,CC + 1{,}7(TS - CC))\,T}\right)}{(1 - TS)^{2{,}88}} \qquad (8)$$

with K : consistency (Pa.s^n)
TS : total solids by mass (fraction)
CC : crystal content (fraction)
pol : pol of the product (fraction)
T : temperature (°K)

The crystal content is calculated from the apparent purities and brixes of the nutsch and massecuite.

The multiple correlation coefficient of the linearised function is 0,972 with a residual error of 0,465. This means that 68% of the calculated consistency will fall between 0,63 and 1,59 times the measured consistency ($0{,}63 \times K_{measured} < K_{calculated} < 1{,}59 \times K_{measured}$). The values of calculated consistency using the above correlation versus measured consistency are plotted in Figures 5 and 6.

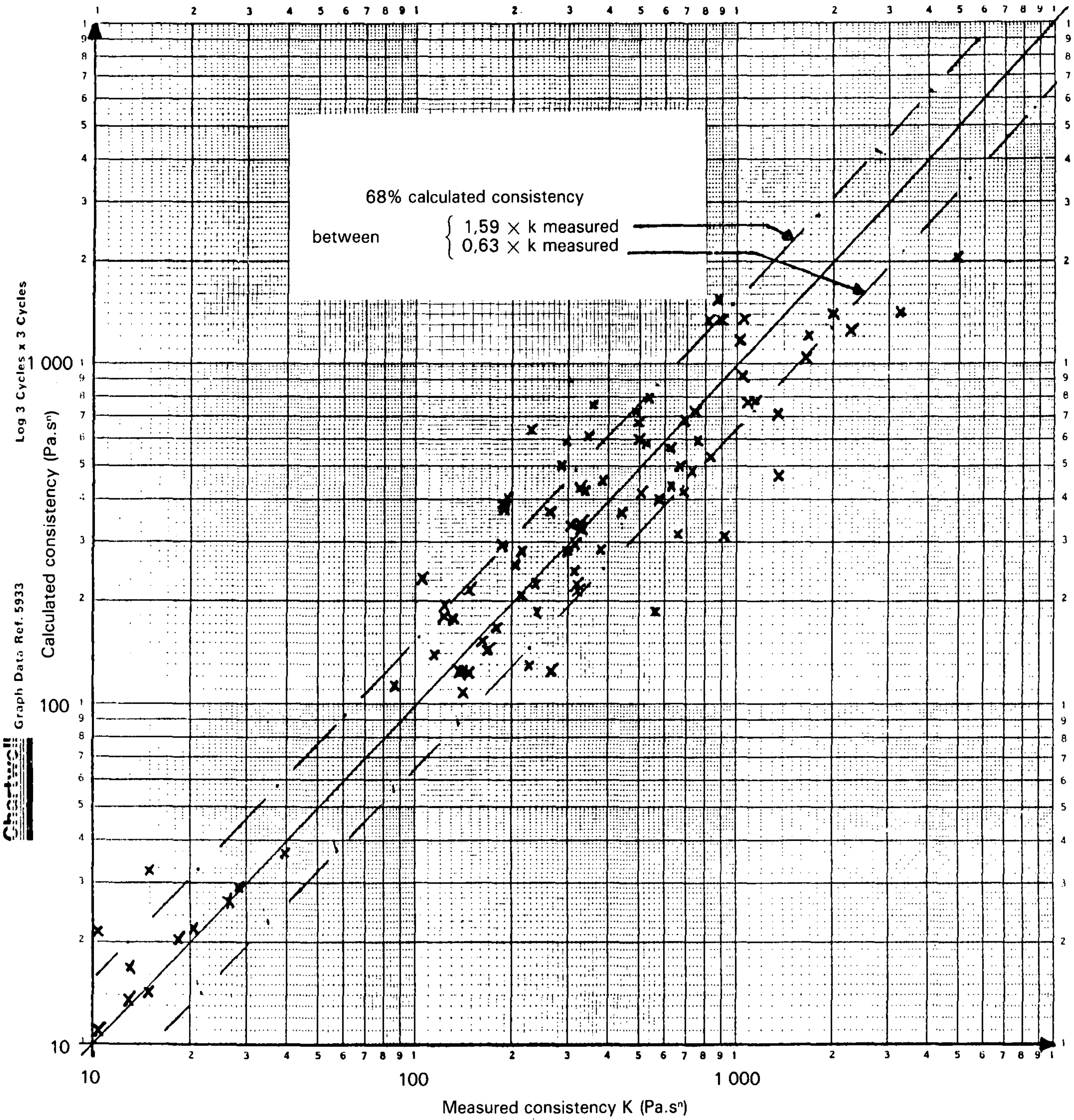

FIGURE 5 Calculated consistency versus measured consistency samples C-massecuite and C-nutsch.

Conclusion

A method for the measurement of the consistency and flow behaviour index of pseudoplastic fluids using a HBT Brooffield viscometer is proposed. The results have not been compared to values obtained using other viscometric techniques and work should be pursued in this area.

A correlation has been developed which expresses the consistency of any C-product in terms of total solids content, crystal content, pol and temperature. Other factors which may have an influence on C-product consistency, i.e. colloids, dextran, ash ratio are not considered. The consistency values obtained by the correlation are in an interval of 0,6 to 1,6 times the measured consistency. It is the only correlation available at this time which relates the consistency to the basic analytical characteristics for all C-products, i.e. a single equation for massecuite and molasses. The accuracy of this equation has not been verified for C-products obtained from mills other than Maidstone and should be used with caution due to different analytical characteristics. It may be necessary to modify the coefficients in Equation (7) to apply it to materials from other factories.

Acknowledgements

The author would like to thank the personnel of the Tongaat-Hulett STD Laboratory for the analytical results and the CSIR for their financial assistance.

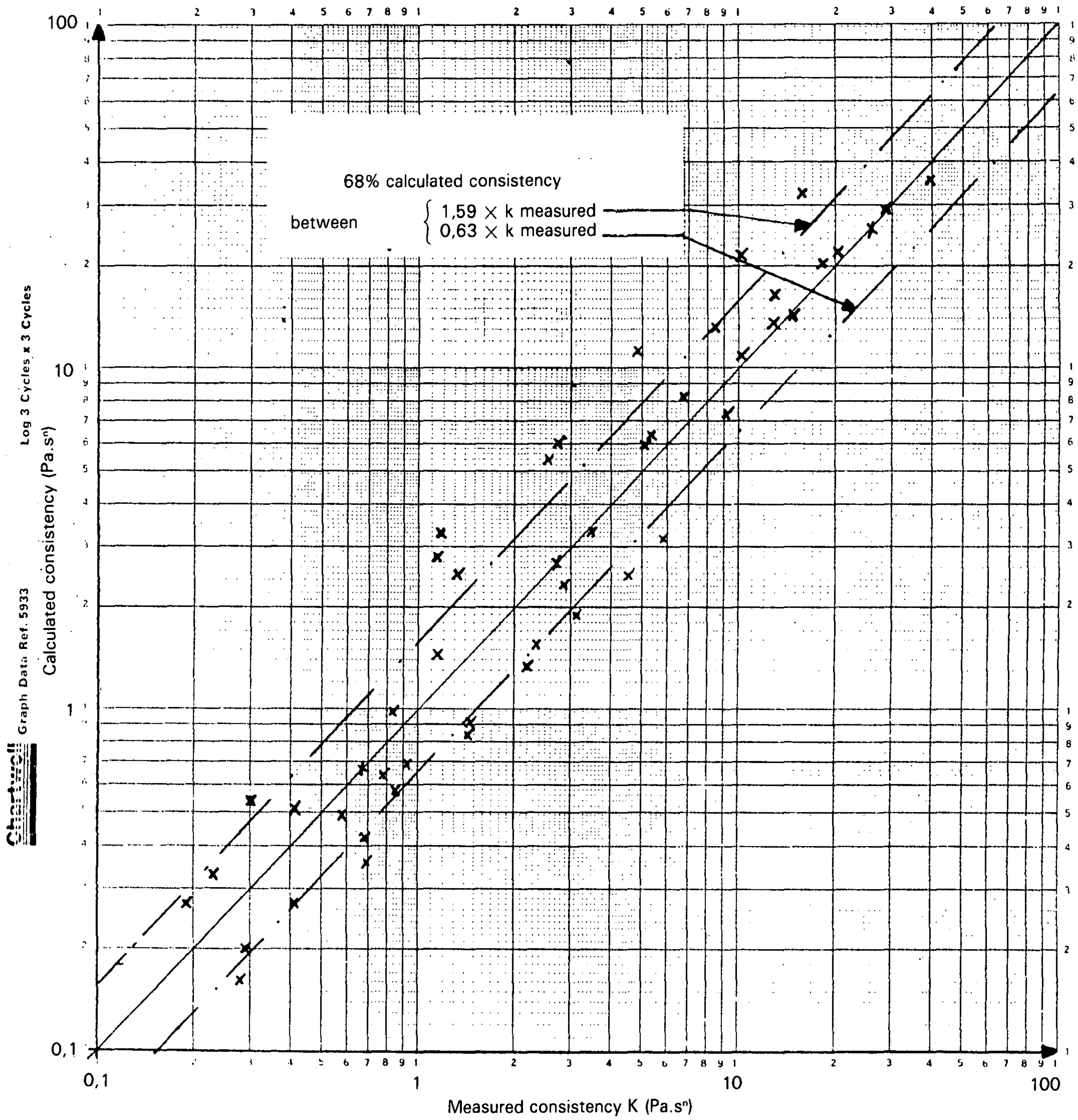

FIGURE 6 Calculated consistency versus measured consistency samples C-nutsch and C-molasses.

Nomenclature

A, B	=	constants defined in Table 1
C	=	conversion factor from Brookfield manufacturer
CC	=	crystal content (fraction)
Cp	=	specific heat (J/kg. °C)
D	=	constant defined in Equation 7
H	=	activation energy (J/kg)
K	=	consistency ($Pa.s^n$)
L	=	immersed length of spindle (m)
N	=	rotational speed (rpm)
n	=	flow behaviour index

pol	=	pol (fraction)
R	=	radius of spindle (m)
Sd	=	scale deflection (fraction)
T	=	temperature (°K)
TS	=	total solids (fraction)
x	=	exponent in Equation 7
τ	=	torque (Nm)
ζ	=	shear stress (Nm^3)
$\frac{d\delta}{dt}$	=	shear rate (sec^{-1})
θ	=	angular cyclindrical co-ordinate (rad.)

REFERENCES

1. Ness, JN (1984). Viscometry in cane sugar processing. *Proc. Aust Soc Sug Cane Technol* p 271.
2. Mathlouthi, M and Kasprzky, P (1984). Viscosity of sugar solutions. *Sug Technol Review 11*, 209-257.
3. Behne, MF (1964). *Proc Queensl Soc Sug Cane Technol*, 31, p 289-296.
4. Bhattacharyya, S; Boger, DV; Halmos, AL and Tiu C (1972). Rheological properties of molasses and their use in the design of flow systems. *Proc Queensl Soc Sug Cane Technol*, 39th Conference, p 209.
5. Garcia, AD (1977). Estudio reologico para la prediccion del efecto de la temperatura y el contenido de crystales sobre la viscosidad de mieles y masas cocidas de tercera. *Cuba Azucar*, p 45.
6. Rouillard, EEA (1984). Viscosity of factory products. SMRI Technical Report No. 1375.
7. Krieger, IM and Maron, SH (1954). Direct determination of the flow curves of non-Newtonian - III - Standardised treatment of viscometric data. *J Appl Phys*, 25, p 72.
8. Taylor, LAW (1981). Laboratory determination of C-massecuite viscosity. Hulett Sugar Ltd, Report No. 35/81.
9. Bird, RB; Stewart, WE and Lightfoot, EN (1963). *Transport Phenomena. Ed.* Wiley, p 103.
10. Done, WG (1950). The determination and nature of the flow properties of molasses and massecuite. Thesis, University of Queensland.
11. Ness, JN (1982). Subject 23, *ICUMSA*, 18th Session, Dublin.
12. De Guzman, J (1913). Relacion entre la fluidez y el calor de fusion. Anales de la sociedad Espanola de Fisica y Quimica, Vol 11, p 353-362.
13. Andrade, EN da C (1930). The viscosity of liquids. *Nature*, Vol. 125, P 309-310. A theory of the viscosity of liquids. *Philosophical Magazine*, 7th Series, Vol. 17, 1934, p 497-511 and p 698-732.
14. Eyring, M (1936). Viscosity, plasticity and diffusion as examples of absolute reaction rates. *J of Chem Physics, 4*, p 283-291.
15. Thomas, DG (1965). Transport characteristics of suspension, part VIII. A note on the viscosity of Newtonian suspensions of uniform spherical particles. *J Colloid Sci*, 20, p 267.
16. Orr, C and Dalle Valle, JH (1954). Chem. Eng. Prog., Syrup Series No. 9, 50, p 29.
17. Einstein, A (1906). *Ann. der Physik, 19*, 34 and 289.
18. Einstein, A (1911). *Ann. der Physik*, p 591.
19. Adkins, BG (1951). Notes on the viscosity of molasses and massecuites. *Proc Queensl Soc Sug Cane Technol, 13*, p 51.
20. Kot, YD; Yasinshaya, TV and Sushenko, AK (1968). *Sakh Promshlennosti*, p 106-125.
21. Awang, M and White, T (1976). Effects of crystal on the viscosity of massecuites. *Proc Queensl Soc Sug Cane Technol, 43*, p 28.
22. Broadfoot, R and Steindtl, RJ (1980). Solubility - crystallisation characteristics of Queensland molasses. *Proc int Soc Sug Cane Technol, 17*, p 2557.
23. Rouillard, EEA and Koenig MFS (1980). The viscosity of molasses and massecuites. *Proc S Afr Sug Technol Ass*, p 89.