A MODIFIED POWER LAW FOR DETERMINIG FLOW CHARACTERISTICS OF FLUID

BY

G. SODAH AYERNOR
Department of Food Science and Technology
University of Nigeria Nsukka

ABSTRACT
A modified power law derived with "angle of deviation flow was used to determine the, rheological properties of corn syrup (CS), honey (H), emulsion salad dressing cream (SC) and mixture of SC and H: CS. The model proved useful in calculating the flow behaviour index (n) and estimating the, critical shear rate ($\dot{\gamma}_C$). Results on n using the modified formula agreed with those obtained through the conventional power law.

NOTATION

η = Viscosity

η_a = appent viscosity

τ = shear stress

$\dot{\gamma}$ = shear rate

$\dot{\gamma}_C$= critical shear, rate

n = flow behaviour index

m = consistency coefficient

θ = angle of deviation from Newtonian flow

1. INTRODUCTION

The understanding of the flow properties of fluid foods is important for the design of equipment, processing and handling in the food industry. More important is the knowledge of the change in the flow characteristics that may occur in the formulation of mixing of fluid foods, the end products of which would demonstrate rheological properties different from those of their constituents.

Aqueous solutions such as syrups, vegetables oils, clear juices and milk, are known to obey the Newtonian flow law (Eq. 1), 2, 4.

$$\eta = \frac{\tau}{\dot{\gamma}} \qquad (1)$$

In many cases fluid foods and hydocolloids or food substances that contain large molecular components do not obey the Newtonian law (Eq. 1). Most of those substances are shear-thinning or Pseudoplastic, while occasionally shear-thickening or dilatants behaveiour may be encountered. The Non-Newtonian fluids are characterized by equations (2) and (3), 2, 5.

$$\tau = m(\dot{\gamma})^n \qquad (2)$$

$$\eta_a = m(\dot{\gamma})^{n-1} \qquad (3)$$

$$\tau - \tau_o = m(\dot{\gamma})^n \qquad (4)$$

When a yield stress (T_o) is needed to initiate flow, equation (4) then applies Many flow models have been used to study fluid and semi-solid materials; and the subject have received extensive discussion and reviews 1,2,3,6,7.

The objectives of this study were to apply a modified power law to determine the flow characteristics and critical shear rate, to examine the types of rheological changes in fluid mixtures as deviations from the flow properties of their constituents and to illustrate shear-thinning (pseudoplastic) and shear-thickening (dilatant) tendencies in the blended fluid foods as a manner of testing the modified formula.

2. EXPERIMENTAL

Material:

The fluid foods used in this study were honey (H) corn syrup (CS) and emulsion salad cream (SC) which were numerical materials (Kroger company, IL. USA). Pure (unmixed) samples of H 100% and SC 100% and the mixtures of H : CS and CS:SC ranging from 20% to 80% of two combinations (H:CS and

CS:SC) were used and their relative proportions specified, accordingly.

Rheological Measurements:

Shear-rate-shear-stress programmed Rotovisco RV-3 with automatic flow curve (Haake Instruments, Saddle Brook, New Jersey, USA) was used as described by Urbanski et al. 7. The instrument is programmable to change shear rates step- wise smoothly and it automatically adjusts for geometry of the sensor system. Measurements were made at 20^0C, maintained by controlled circulating water bath.

Viscosity: Viscosity or apparent viscosity was estimated from the automatic shear-rate versus shear-stress curve. The estimated viscosity values were plotted against the shear rates on a Log-Log graph paper and the critical shear rate noted (Fig. 1).

Flow behaviour index: The magnitude of pseudoplastic or dilatant behaviour as a departure from Newtonian' flow was evaluated using the equations

$$\tau = m\dot{\gamma}^{(1-\tan\theta)} \quad (5a)$$

or

$$\eta_a = m\dot{\gamma}^{(-\tan\theta)} \quad (5b)$$

for pseudoplastic flow, and for dialatant flow:

$$\eta_a = m\dot{\gamma}^{(\tan\theta)} \quad (6a)$$

$$\tau = m\dot{\gamma}^{(1+\tan\theta)} \quad (6b)$$

The values (l-tan0) and (1+tan0) represent the magnitude of the flow behaviour index for pseudoplastic and dilatant materials, respectively. Therefore,

$$n = (1-\theta) \quad (7)$$

for pseudoplatic flow, and

$$n = (1+\tan\theta) \quad (8)$$

for dilatant flow. Plots of (+ tanθ) and (-tanθ) against (n) were made to show the relationship between equations (5a, 5b), (6a, 6b) and equation (2)

Critical shear rate $\dot{\gamma}$: Critical shear rates for the non-newtonian fluids and their mixtures were estimated as shown in Fig. 1. The power law model (Eq. 2) was also used to verify the flow behaviour index (n) by using the log T vs $\log\dot{\gamma}$ plot. Averages of three replicates are reported.

3. RESULTS AND DISCUSSIONS

A typical flow curve demonstrated by a mixture of 80% corn syrup (CS) and 20% salad cream (SC) is shown in Fig. 2 and conforms to the methodology illustrated in Fig. 1. Similarly, flow curves (omitting theoretical Newtonian horizontal lines) are shown in Fig. 3. Corn syrup demonstrated perfect Newtonian flow characteristics (n=1). This has also been reported elsewhere 2, 4. Pure honey (n=0.83) showed Newtonian properties at low shear rates but demonstrated a deviation from Newtonian flow beyond a high critical hear rate of $300sec^{-1}$. The emulsion salad cream showed perfect linear shear-thinning or pseudoplastic flow characteristics (n = 0.37) with critical shear rate at about $50.sec^{-1}$ (Table 1). This linearity is characteristic of the model in Fig. 1.

Mixtures of corn syrup and salad cream showed curve-linear pseudoplastic decline in viscosity with increased shear rate (Fig. 3). Mixing a Newtonian fluid (corn syrup) and a perfect pseudoplastic material (emulsion salad cream) produced flow patterns in favour of pseudoplasticity in terms of the gradient of the decline in apparent viscosity with shear rate (Fig. 3) and the values of the critical shear rate (Table 1). The magnitudes of apparent viscosities of the CS:SC mixtures at the specified critical shear rates are reflective of the viscosities of the pure substances in which case the higher apparent viscosity of SC influenced the viscosities of the mixtures at the critical shear rates. However, SC was shear:- thinning while CS was Newtonian, and this obviously explains why higher proportions of SC produced lower apparent viscosities at higher shear rates (Table 1 and Fig. 3).

Interesting flow behaviours were encountered when corn syrup (Newtonian) was blended with pure honey (pseudoplastic, n = 0.83). The honey showed an apparent viscosity of 6,233 centipoises at $\dot{\gamma}_C$ = 300. sec^{-1}, while the true (Newtonian) viscosity of the corn syrup was 267 centipoises. Table 1 shows the critical shear rates and the corresponding apparent viscosities of the mixtures. These mixtures apparently demonstrated dilatant flow properties where apparent viscosities increased with shear rate: for example, H60: CS40 mixture showed an apparent viscosity of 750 centipoises at $\dot{\gamma}_C$ = 450.sec^{-1} but 1,050 centipoises at 1,000.sec^{-1}. The dilatant mixtures H60:SC40, H30:CS70 and H20:CS80 of flow behaviour indices 1.31,1.18, and 1.10, respectively, demonstrated Newtonian tendencies at lower shear rates but started showing appreciable dilatant deviations above the critical shear rates of 450;300 and 275.sec^{-1}, respectively (Fig. 4). These results are apparent of dilatant or shear-thickening flow which is not very common in the food industry; but the results here show that the increase in viscosity was relative to shearing.

It must be noted that none of the fluids and their mixtures tested showed a yielded tress (T_O)Eq. 4). The consistency coefficient: of the 'pure' fluids and their mixtures determined as the intercept of the log T vs 1og V plot is shown in Table 2.

Flow Behaviour Index and Deviations

The magnitude of the flow behaviour indices: (n) and (1+tanθ) determined from the log T. vs $\log\dot{\gamma}$ plot (Figs. 5 and 6) and the angle of deviation plot (as illustrated in Fig. 1) are shown in Table 2. Examination of the numerical figures of (n) and (1 ± tanθ) at approximation to the tenth fraction, clearly shows that the magnitudes of the flow behavior indices are closely identical. This correlation is confirmed by the relationship between (n) and (tanθ) in Figs. 7 and 8. It therefore follows that the angle of deviation (as illustrated in Figs. 1 and 2) is a graphical demonstration of deviation (tanθ) when proportions of pseudoplastic honey of n = 0.83, $\dot{\gamma} = 300.sec^{-1}$ was added to a Newtonian corn syrup. The same Fig. 9 also shows pseudoplastic deviations when proportions of a pseudoplastic salad cream of n = 0. $\dot{\gamma}_C = 50.sec^{-1}$ was added to Newtonian corn syrup. The flow trend of CS:SC mixtures is predictable especially when SC demonstrated very high pseudoplastic characteristics. On the other hand, the di1atant turn of CS:H mixtures is a phenomenon. It may be explained that although corn syrup and honey appear to be psychorheolbgically simlar, the mixtures of the relatively homogenous corn syrup and the compositionally heterogeneous honey are shear-thickening because of inter-component orientations during shearing.

Viscosity at high shear rates

Because of the possible onset of turbulence at very high shear rates, especially in narrow gap viscometer, viscosities observed at such rates tend to lose validity. The rheological behaviour of most of the materials tested were clearly noticeable at low shear rates with critical shear rates below 100.sec^{-1} (Table 1). Corn syrup was clearly Newtonian even at very high shear rates, e.g. 1000. sec^{-1} (Table 1). For practical applications in the food industry, those materials such as the honey and its mixtures with corn syrup (H:SC) can be considered Newtonian because their flow deviation occurred at very high shear rates.

4. CONCLUSION

This study had shown that the angle of deviation from Newtonian flow derived from the log viscosity versus log shear rate plot can be used to illustrate such deviations and to estimate the flow behaviour index in the power law, more validly, at lower shear rates. It was also shown that mixtures of pseudoplastic emulsion salad cream and Newtonian corn syrup showed pseudoplastic flow behaviour; and mixture of slightly pseudoplastic honey and purely Newtonian corn syrup showed apparent dilatant flow properties, though at high shear rates.

Table 1: Critical Shear rate and Viscosities at critical and at 1000.sec^{-1} shear rates of corn syrup (CS) honey (H) and the mixtures of cs:se and H:CS

Test Material % Mixture	Critical Shear rate sec^{-1}	Viscosity at Critical shear rate	Viscosity at 1000. Sec^{-1}
		Centipoise	
CS100	-	267.7	267.7
H100	300	6,233.3	255.0
SC100	50	750.0	125.0
CS80 : SC20	70	285.1	275.0
CS70 : SC30	60	294.5	255.0
CS60 : SC40	47	392.8	125.0
CS50 : SC50	45	428.6	158.0
CS40 : SC60	30	430.4	130.0
H60 : CS40	450	750.0	1,050.0
H30 : CS70	300	464.3	S-20.0
H2O : CS80	275	410.0	460.0

TABLE 2: Flow characteristics of corn syrup (CS), honey (H), salad cream (SC) and the mixtures of CS: SC and H:CS

Test Material Mixture	%Consistency dyne. Sec. cm^{-2} (k)	Flow Power (n)	Behaviour index $(1 \pm tan0)^0$.	Type of Flow
CS100	26.77	1.000	1.00	Newtonian
Hl00	13.80	0.830	0.819	pseudoplastic
SC100	81.50	0.834	0.368	pseudoplastic
CS80 : SC20	5.84	0.860	0.857	pseudoplastic
CS70 : SC30	5.99	0.808	0.825	pseudoplastic
CS60 : SC40	15.00	0.-684	0.699	pseudoplastic
CS50 : SC50	17.31	0.632	0.637	pseudoplastic
CS40 : SC60	18.11	0.607	0.628	pseudoplastlc
H60 : SC40	2.58	1.300	1.320	dilatant
H30 : CS70	2.35	1.179	1.185	dilatant
H2O : CS80	1.81	1.102	1.109	dilatant

- $(1 + \tan\theta)$ for dilatant and $(1 - \tan\theta)$ for pseudoplastic.

REFERENCES

1. Ayernor, G.S. and Steinberg, M.P. 1977. Hydration and rheology of soy-fortified pre-gelled corn flours. Food Sci. 42:65.

2. Krumel, K. L. and Sardar, N. 1975. Flow Properties of gums usef to the food industry. Food Techno. 36.

3. Rao, M. A. Palomino, L. N.O., and .Bernhardt, L.W. 1974. Flow properties of tropical fruit purees. J. Food Sci. 39: 160.

4. Rao, M. A. and Anantheswaran, R. C. 1982. Rheology of fluids in food processing. Food Technol. February: 116.

5. Scott-Blair, G. W. 1970. On power equations relating stress to shear rate in rheology. J. of Tex. Studies 1:431.

6. Sherman, P. 1970. "Industrial Rheglogy". Chapter 3, Academic Press, New York.

7. Urbanski, G. E., Wei, L. S., Nelson, A. I., and Steinberg, M.P. 1983. Rheology models for pseudoplastic soy 5fstems based on water binding. J. Food sci. 48:1436.

8. Walters, K. 1975. Rheometry, Chapman and Hall, London.

ACKNOWLEDGEMENT

The provision of funds by the Department of Food science, University of Illunois, Urbana, USA, for the purchase of equipment and the opportunity to do this work in the Department is acknowledged.

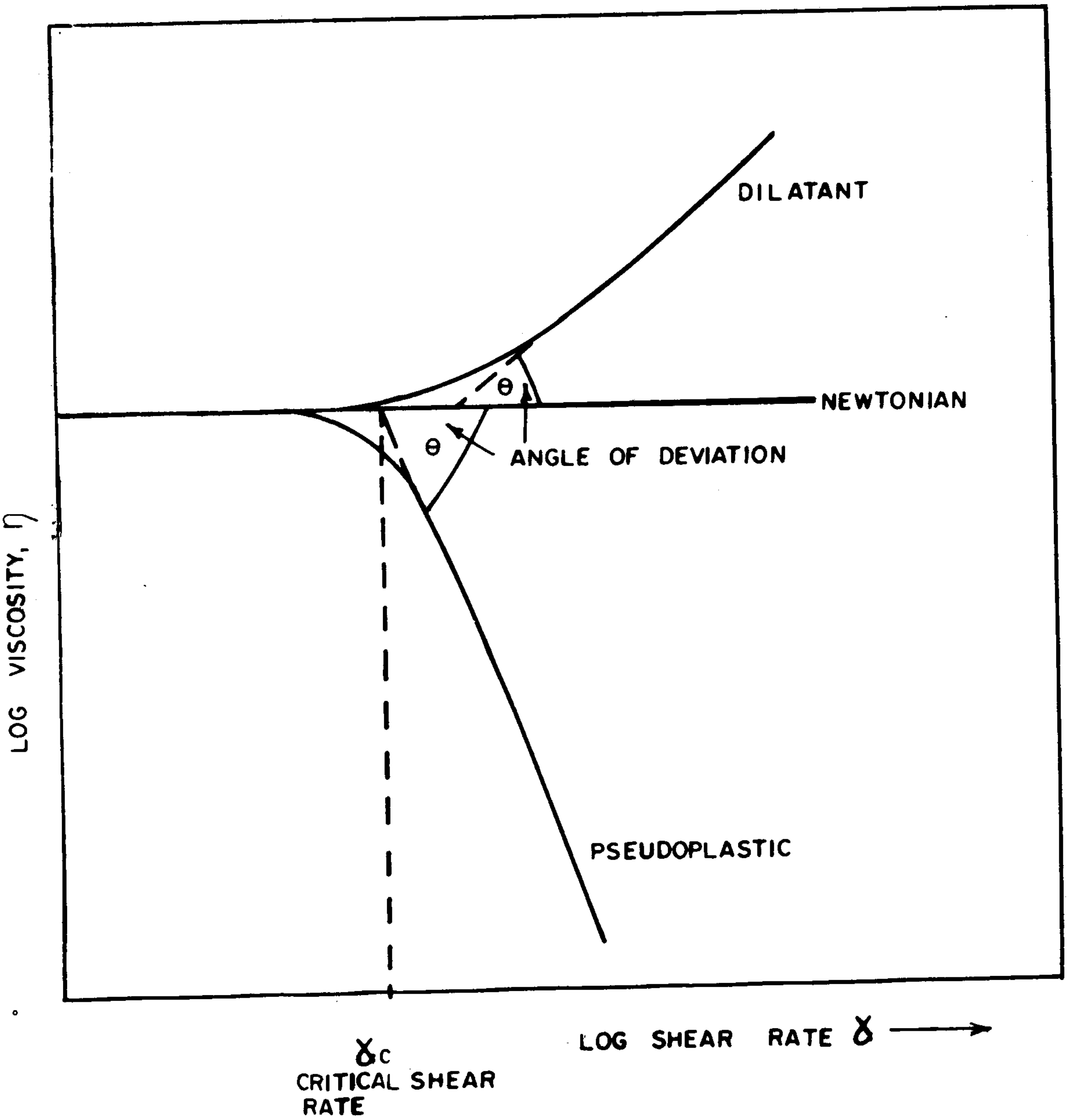

Fig. 1. Identification of angle of deviation from Newtonian Flow in Pseudoplastic and dilatants materials.

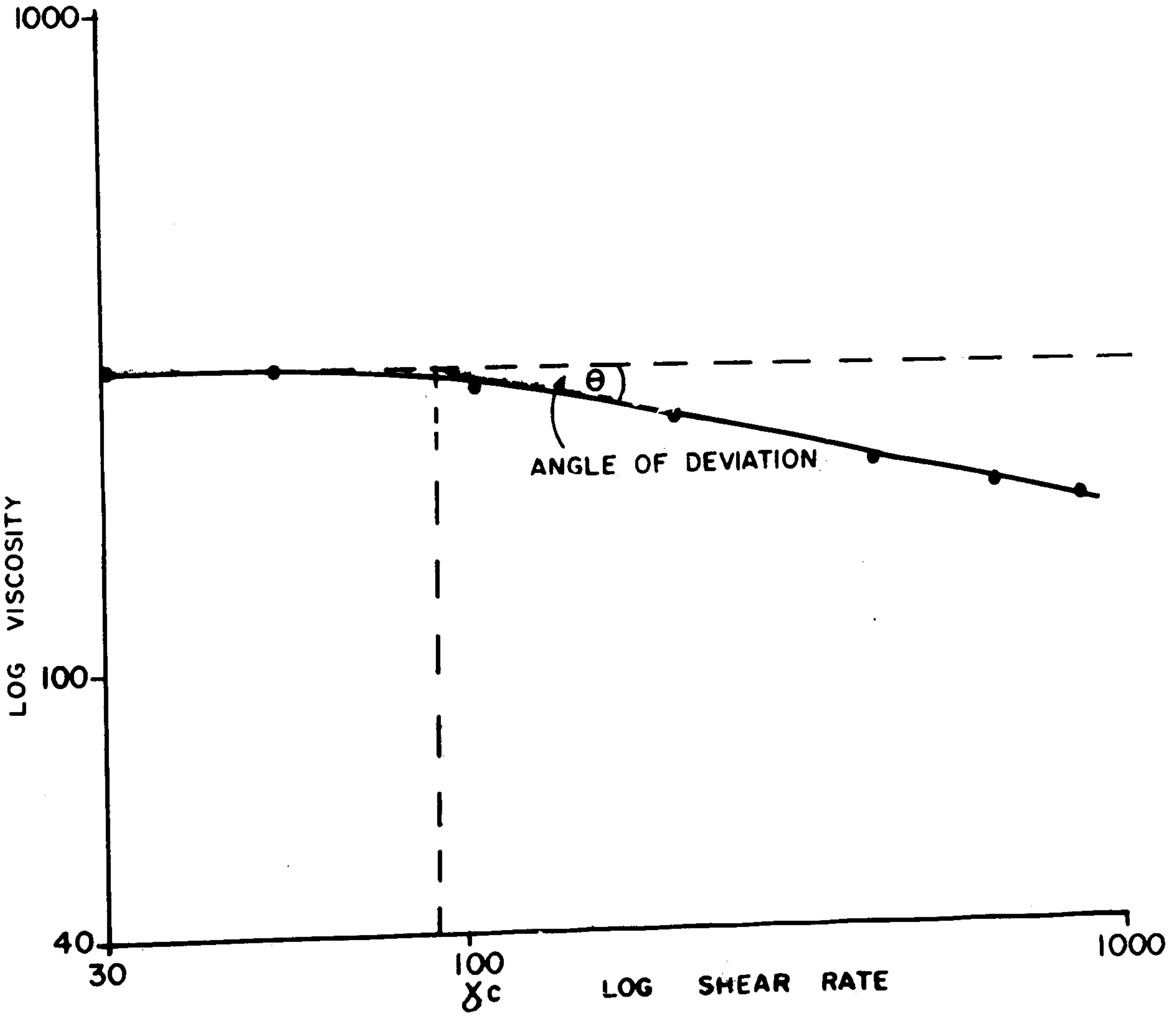

Fig 2 Flow behavior of a mixture of 80% corn syrup and 20% salad cream and angle of deviation from Newtonian flow

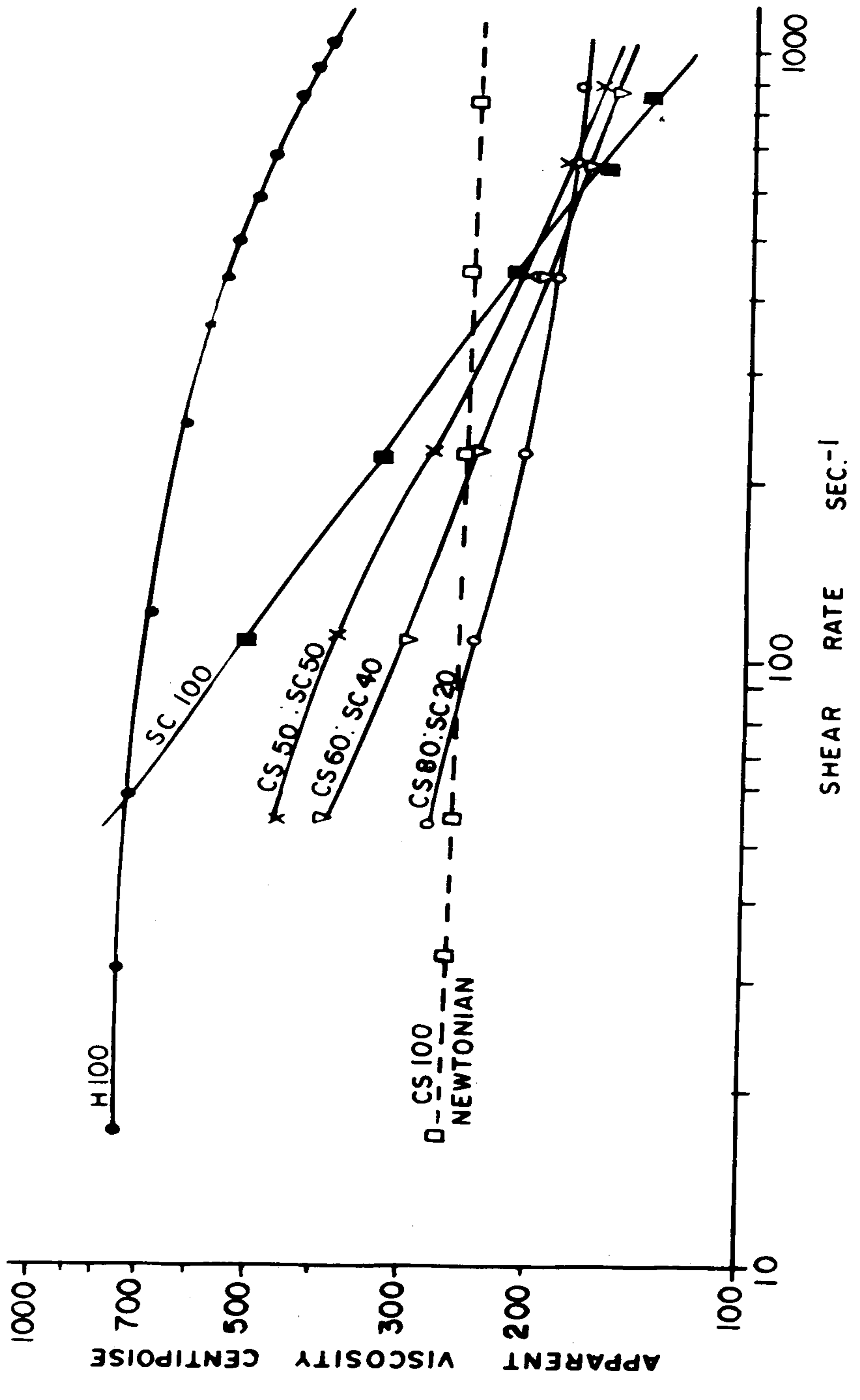

Fig. 3 Double log. plots of viscosity against shear rate for honey (H), corn syrup (cs), salad cream (sc) and mixtures of cs and sc.

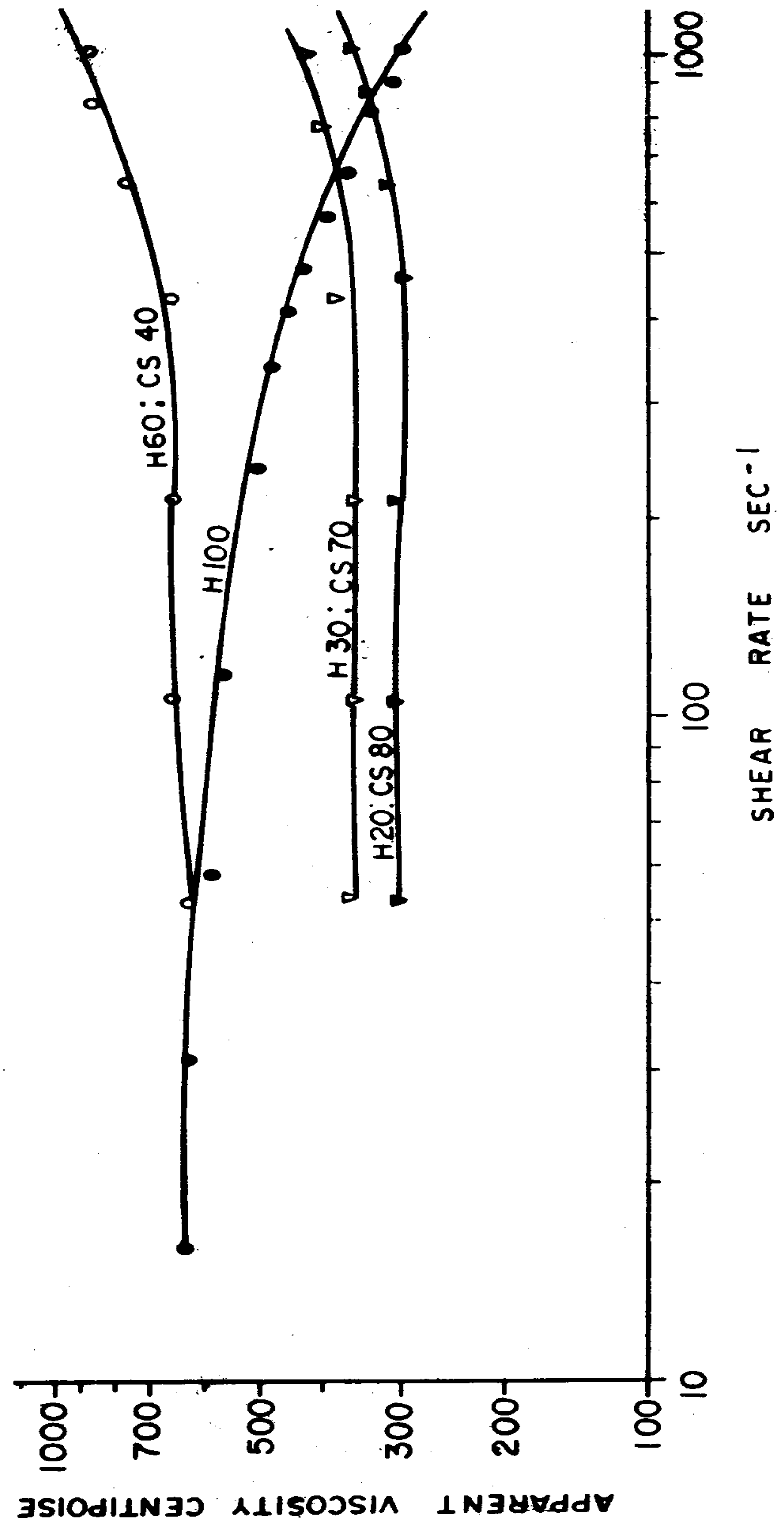

Fig. 4. Double log plots of viscosity against shear rate for honey (H) and mixtures of honey and corn syrup (cs).

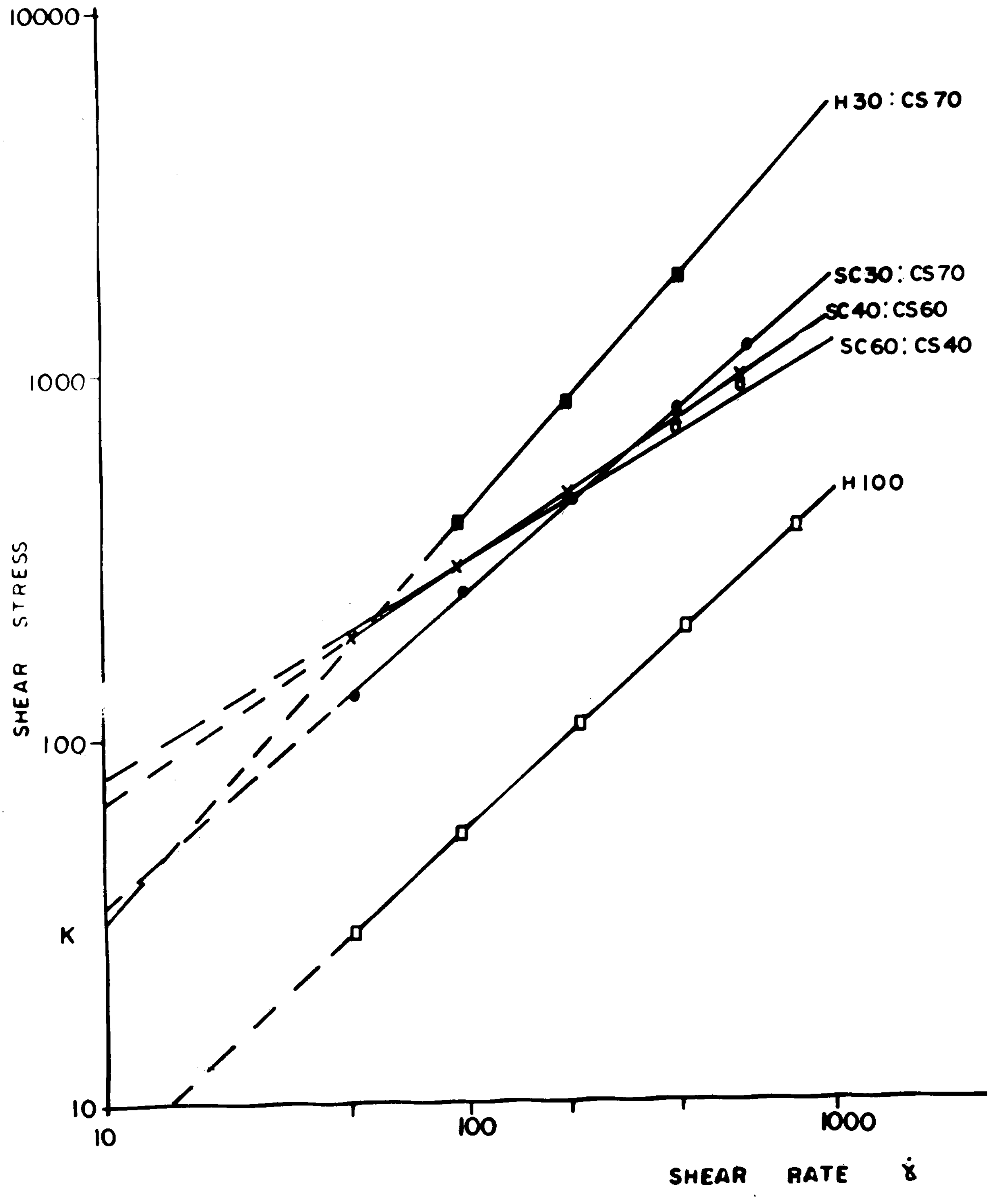

Fig. 5 Double log (shear stress vs shear rate) plots for honey (H), a mixture of honey and corn syrup (cs) and mixtures of corn syrup and salad cream (sc).

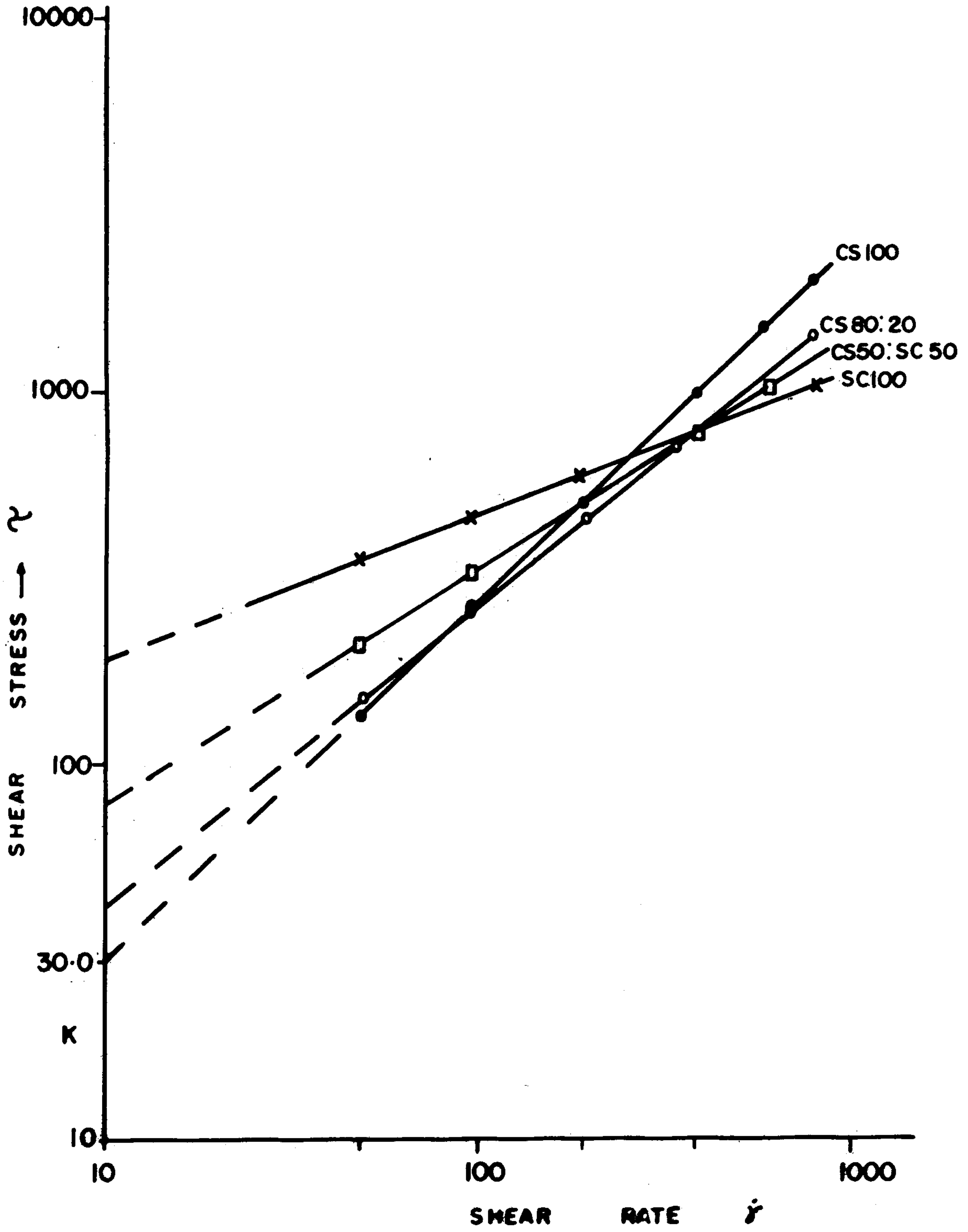

Fig. 6. Double log (shear stress vs shear rate) plots for salad cream (sc), corn syrup (cs) and mixtures of corn syrup and salad cream.

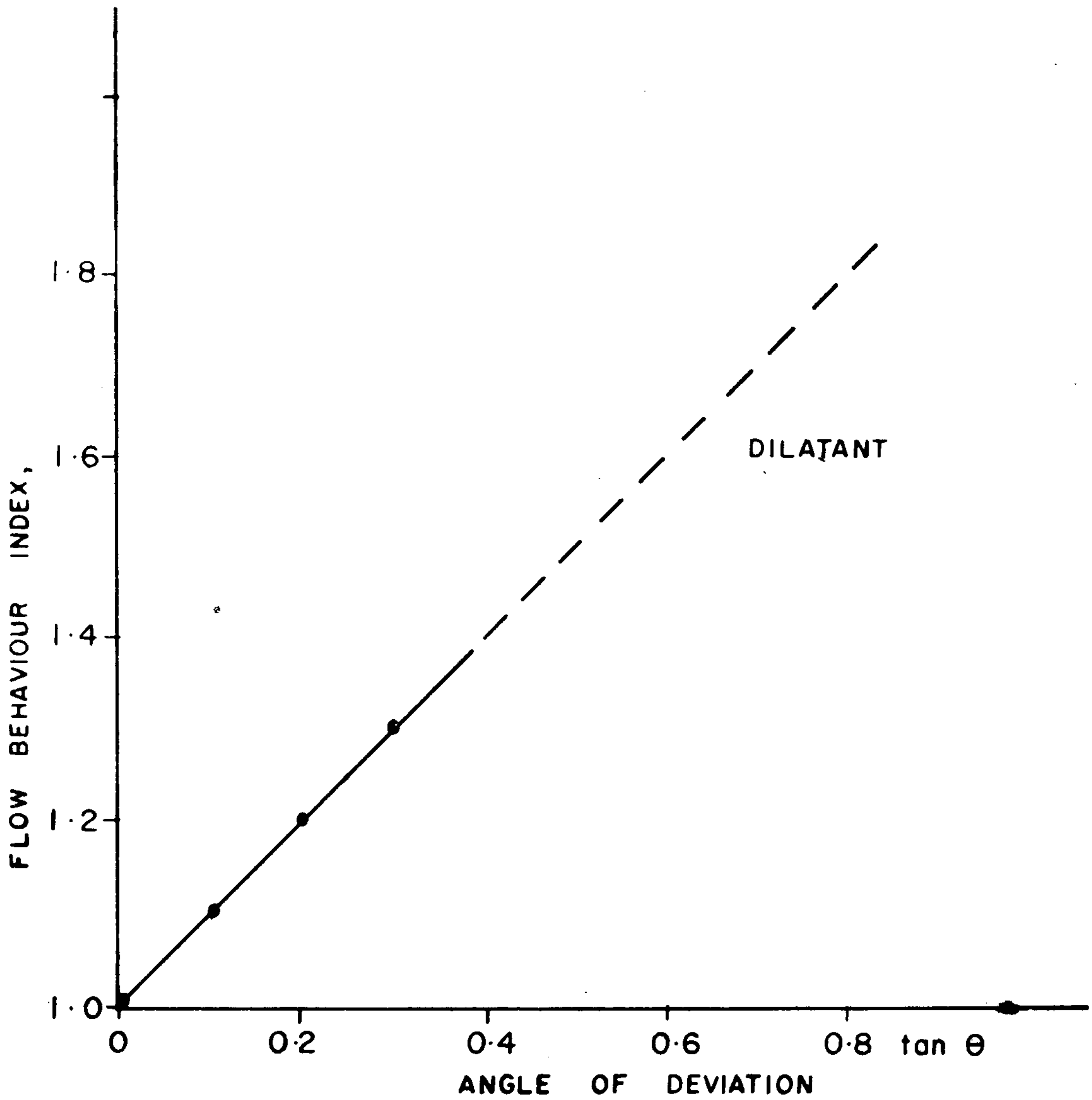

Fig. 7 A plot of flow behavior index vs angle of deviation of dilatants fluids.

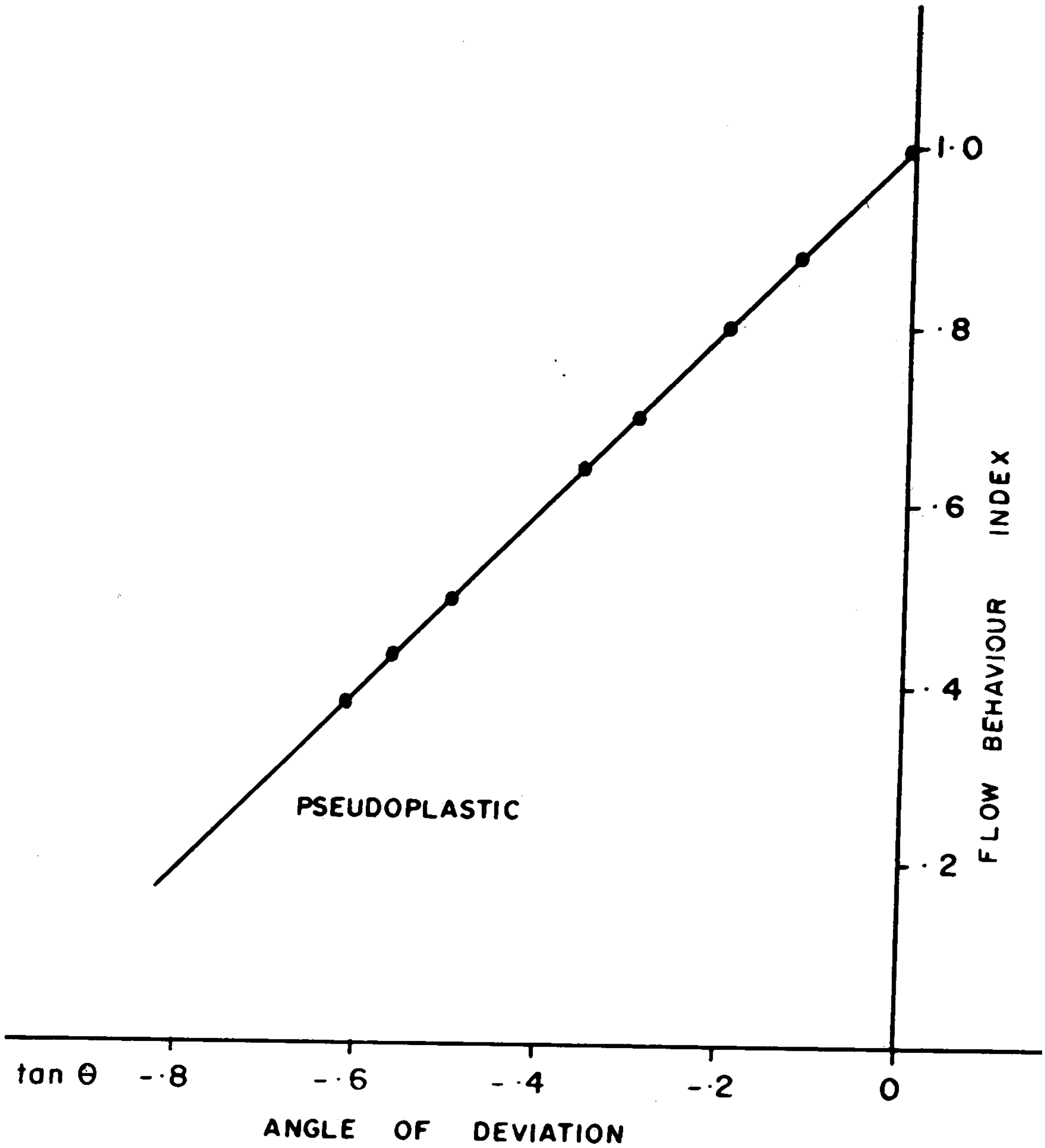

Fig. 8 A plot of flow behaviour index vs angle of deviation of pseudoplastic fluids.

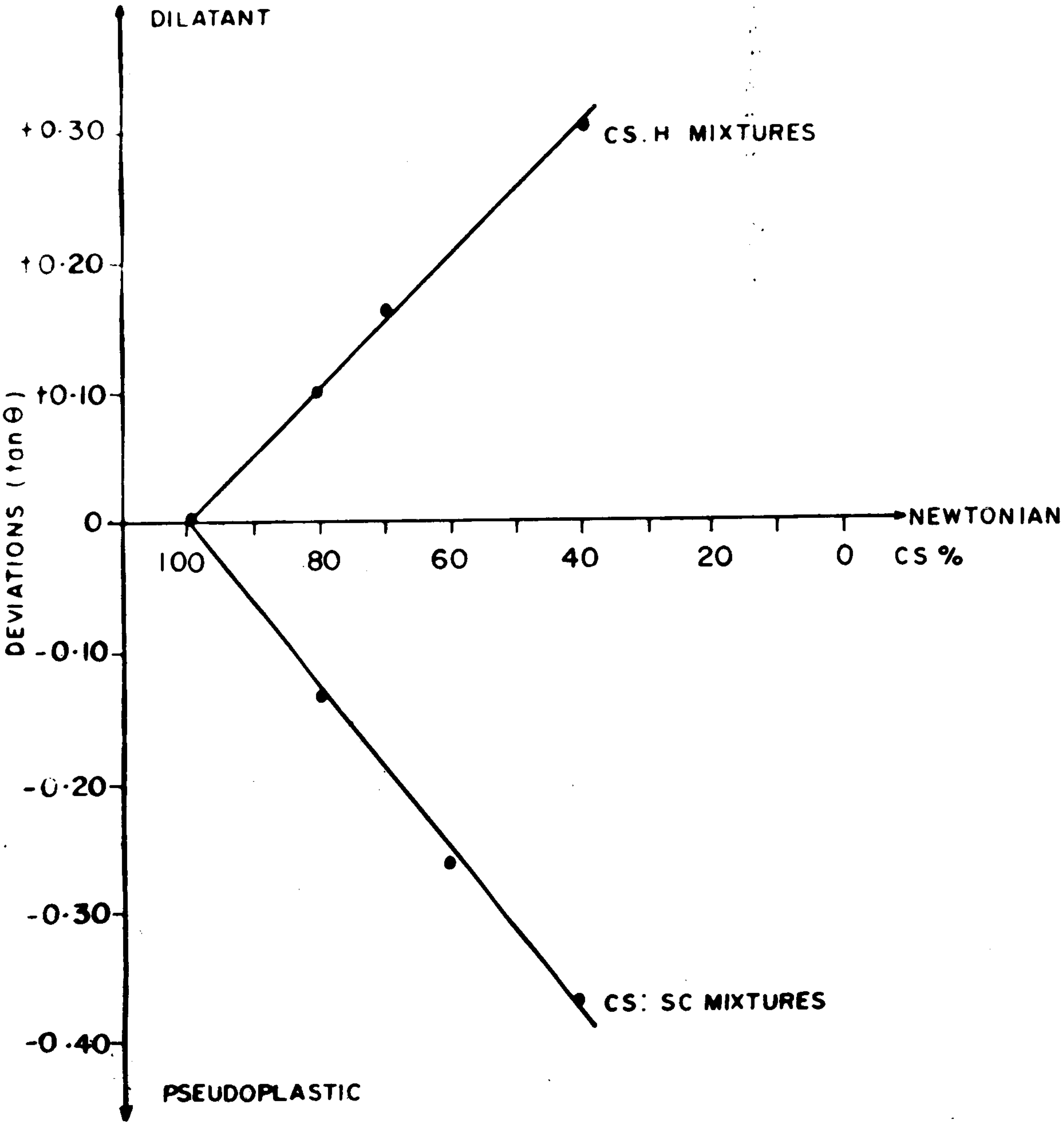

Fig. 9 Effects of mixing corn syrup (cs) with honey (H) and mixing salad cream (sc) with corn syrup on deviations from Newtonian flow.