P I I: S 0 2 6 0 - 8 7 7 4 (9 7) 0 0 0 6 0 - 5

A Simple Model for Predicting the Viscosity of Sugar and Oligosaccharide Solutions

J. Chirife* & M. P. Buera†

Departamento de Industrias, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Ciudad Universitaria, (1428) Buenos Aires, Argentina

ABSTRACT

*A model originally developed to predict the viscosity of concentrated electrolyte solutions was adapted to fit viscosity data of various sugars and sugar mixtures up to very high concentrations. The model was $\mu_r = a \, exp(\mathbf{E}\mathbf{X})$, where μ_r is the relative viscosity, **a** and **E** are parameters (in most cases **a** was very close to unity). The model was used to describe the concentration dependence of viscosity of sucrose, fructose, glucose, maltose, lactose and corn syrup (having different dextrose equivalent values) solutions up to very high solids concentration.*

*The molecular weight of the sugar was a main factor in determining the value of parameter **E**, which on theoretical grounds may be somewhat related to the free energy of activation for viscous flow per mole of solute. © 1997 Elsevier Science Limited. All rights reserved*

INTRODUCTION

Goldsack and Franchetto (1977) deduced from rate process theory a successful equation which was adequate for describing the viscosity of concentrated electrolyte solutions. The simplified general equation developed by Goldsack and Franchetto (1977) for the relative viscosity (μ_r) of a single electrolyte solution is

$$\mu_r = exp(\mathbf{X}\mathbf{E})/(1 + \mathbf{X}\mathbf{V}) \tag{1}$$

where **X** is an appropriate mole fraction and **E** and **V** are the average non-dimensional free energy and volume parameters. For a 1:1 electrolyte the parameters **E** and **V** were defined as

*To whom correspondence should be addressed.
†Member of CONICET.

221

$$\mathbf{E} = (\delta G^*{}_c + \delta G^*{}_a - 2\delta G^*{}_1)/RT$$

$$\mathbf{V} = (V_c + V_a/V_1) - 2$$

where V_c = molar volume of the cation particle, V_a = molar volume of the anion particle, V_1 = molar volume of the solvent particle, $\delta G^*{}_c$ = molar free energy of activation for viscous flow of the cation particle, δG^*_a = molar free energy of activation for viscous flow of the anion particle, and $\mathbf{X} = m/(55\cdot51 + 2m)$, where m is the salt molality.

Goldsack and Franchetto (1977) fitted existing viscosity data to eqn (1) for a number of 1:1 inorganic electrolytes and their results showed that this two-parameter equation can reproduce the observed viscosities within experimental error up to very high concentrations.

Chirife *et al.* (1984) noted that eqn (1) may be also used to fit viscosity data of some non-electrolyte solutions and observed that in these cases values of parameter **V** were very small such that eqn (1) was reduced to

$$\mu_r = \exp(\mathbf{XE}) \tag{2}$$

and the mole fraction **X** was in this case calculated as, $\mathbf{X} = m/(55\cdot51 + m)$.
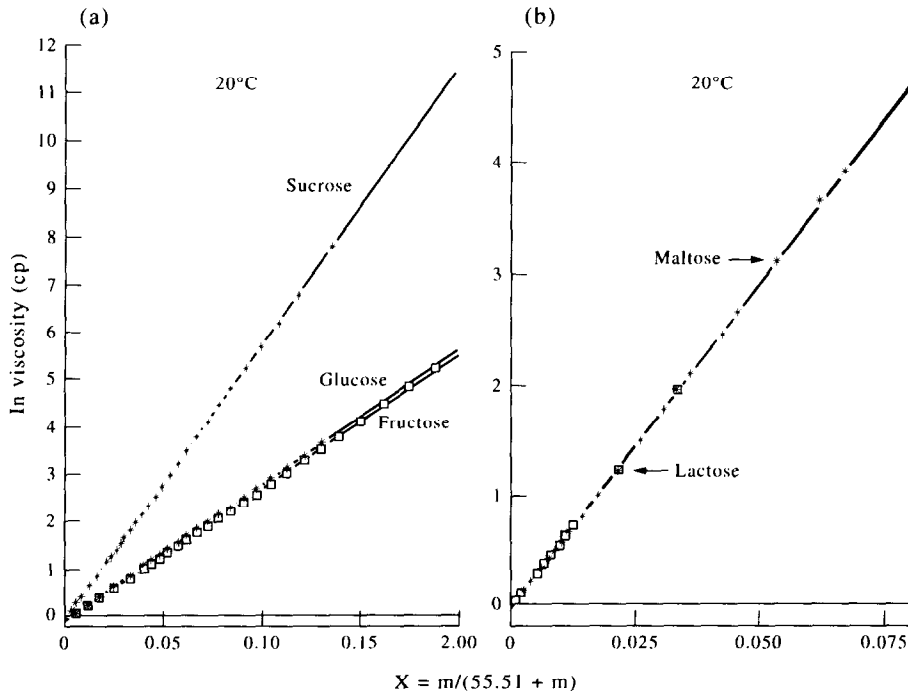

Fig. 1. Application of eqn (3) to the concentration dependence of the viscosity of sugar solutions at 20°C.

TABLE 1
Parameters *a* and E for Various Sugar Solutions at 20°C[a]

Sugar	a	E	Max. conc. (%)[b]
Glucose	0·954	27·93	60
Fructose	0·913	27·49	70
Sucrose	0·905	57·19	74
Lactose	0·979	57·49	40
Maltose	0·969	57·94	58
Sucrose:glucose:IS[c]	0·774	44·46	84
Corn syrup, D.E. 35·4	1·07	94·46	85
Corn syrup, D.E. 42·9	0·983	73·80	85
Corn syrup, D.E. 53·7	0·965	56·37	85
Corn syrup, D.E. 75·4	0·758	38·13	85

[a]26·6°C for corn syrups.
[b]Maximum solid concentration (%) for which eqn (3) was tested.
[c]Invert sugar.

It is the purpose of present work to examine the ability of eqn (2) to describe the concentration dependence of viscosity for various sugar solutions of practical interest.

RESULTS AND DISCUSSION

Viscosity–concentration data for various sugar and sugar mixtures were obtained from the literature. Data for sucrose, glucose, fructose, maltose and lactose (all at 20°C) were from Weast (1987); for corn syrups (at 26·6°C) having different dextrose equivalent (D.E.) values from Erickson *et al.* (1966); for a sucrose:glucose:invert sugar mixture (50:25:25; at 20°C) from Lipscomb (1956).

A plot of $\ln \mu_r$ vs. **X** should give a straight line if eqn (2) is obeyed; as noted in Fig. 1 excellent straight lines were observed for sucrose, glucose, fructose, maltose and lactose. Similar results were found for the other sugars examined; in all cases the correlation coefficient was above 0·999 (data not shown here). The least squares regression of present data ($\ln \mu_r$ vs. **X**) indicated that the ordinate was slightly different from zero, thus suggesting that the following equation gives a better representation of data than eqn (2):

$$\mu_r = a \exp(EX) \tag{3}$$

Table 1 shows the calculated values of parameters *a* and E for all sugars and the maximum solid concentration for which eqn (3) was tested; parameter *a* is in most cases close to unity. Figure 2 compares experimental and predicted (eqn (3)) viscosity for sucrose solutions at 20°C ; similar agreement was observed for the other sugars.

Figure 3(a) shows that a very good linear correlation (correlation coefficient was 0·998) exists between the experimentally determined values of **E** (at 20°C) and the molecular weight of various sugars. The same was observed (correlation coefficient

0·999) for corn syrups of different dextrose equivalent at 26·6°C (Fig. 3b); since corn syrups are complex multicomponent sugar mixtures their 'average' molecular weight was calculated from the formula $D.E. = 100/(M_m/180·16)$, where D.E. is dextrose equivalent, and M_m is the average molecular weight. It is to be noted that the E vs.
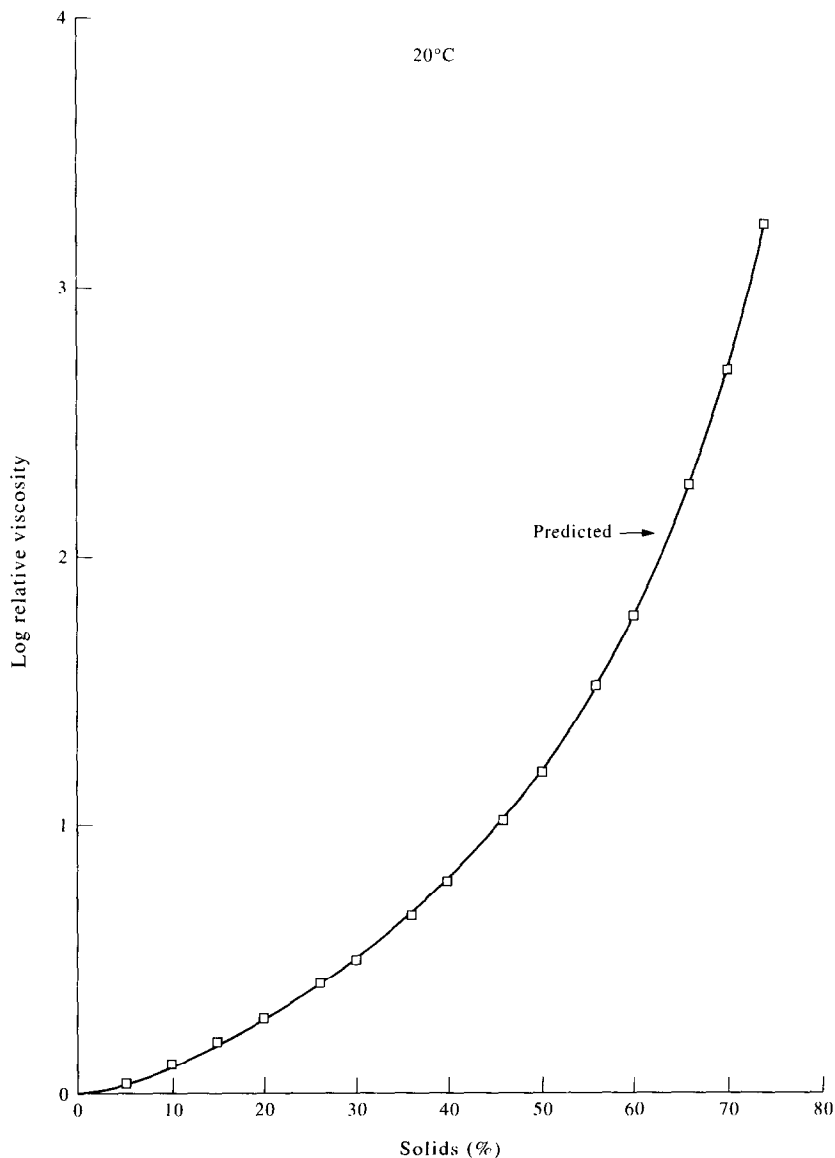

Fig. 2. Comparison of experimental and predicted (eqn (3)) viscosity of sucrose solutions at 20°C.
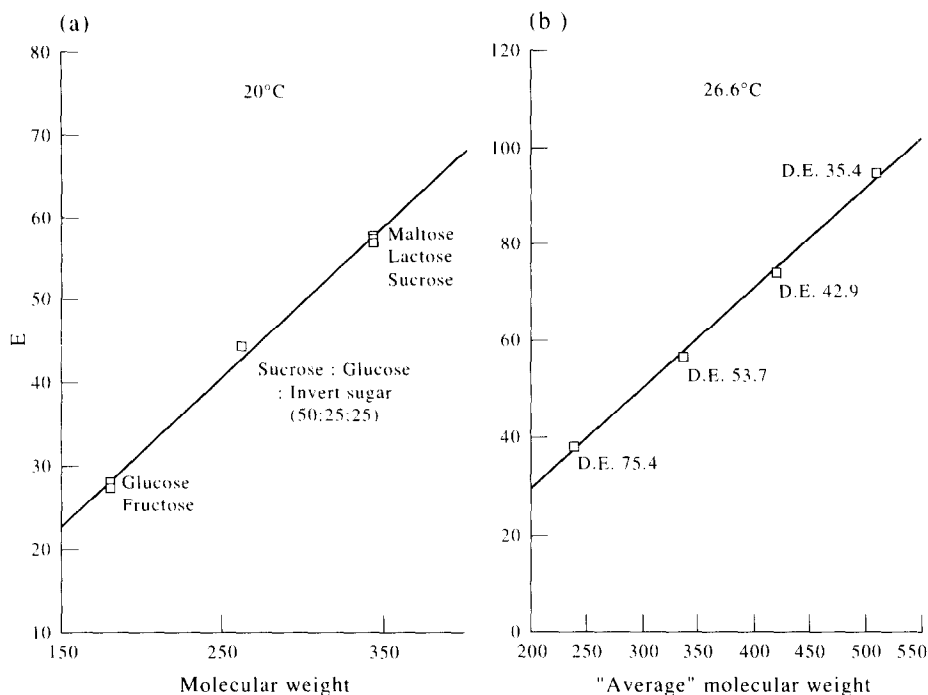
Fig. 3. Effect of the molecular weight of different sugars (a) and corn syrups (b) on the parameter **E** (eqn (3)).

molecular weight data for sugars (Fig. 3a) and corn syrups (Fig. 3b) will fit very well on the same straight line; however, they were plotted separately because viscosity data for sugars were obtained at 20°C while those for corn syrups were at 26·6°C; also the calculated 'molecular weight' of corn syrups represents only an approximate average value for their complex multicomponent mixtures.

Chirife *et al.* (1984) suggested that for non-electrolytes the parameter **E** in eqn (1) is defined as

$$\mathbf{E} = (\delta G^*_s - \delta G^*_1)/RT \tag{3}$$

where δG^*_s is the free energy of activation for viscous flow per mole of solute (non-electrolyte). Thus, it appears that the molecular weight of the sugar is a main factor in determining the value of **E**, which according to eqn (3) may be related to the free energy of activation for viscous flow per mole of solute.

ACKNOWLEDGEMENT

REFERENCES

Chirife, J. *et al.* (1984). Microbial growth at reduced water activities: some physicochemical properties of compatible solutes. *J. Appl. Bacteriol.*, **56**, 259–268.

Erickson, E. R. *et al.* (1966). Viscosity of corn syrup. *J. Chem. Eng. Data*, **11**, 485–488.

Goldsack, D. E. & Franchetto, R. (1977). The viscosity of concentrated electrolyte solutions. I. Concentration dependence at fixed temperature. *Can. J. Chem.*, **55**, 1062–1072.

Lipscomb, A. G. (1956). Die rheologie von subwaren-sirupen und gekochten bonbons. *Fette-Seifen-Anstrichmittel*, **58**, 875–879.

Weast, W. E. (ed.) (1987) *CRC Handbook of Chemistry and Physics*, 67th edn. CRC Press, Boca Raton, FL.