Dielectric Relaxation and Water Activity in Aqueous Solution of D-Psicose

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Hydration behavior of a rare sugar, D-psicose, was investigated based on measurements of the dielectric relaxation and the water activity in its aqueous solutions. Dielectric relaxation spectra in the frequency domain were obtained from time domain reflectometry. The dielectric relaxation time was then determined by fitting the spectra to a Cole-Cole type equation and used to evaluate the average hydration number representing the average number of water molecules forming a complex with a sugar molecule at infinite dilution. The concentration dependence of the dielectric relaxation time in aqueous solutions of all examined sugars generated a single master curve. The average hydration number of psicose was found to be identical with that of fructose. Only slight differences were noticeable among the concentration dependences of the water activity of monosaccharides. The equilibrium constant of hydration of sugar was calculated by considering material balances in an aqueous solution of sugar and using experimentally obtained values of the average hydration number and the water activity. The equilibrium constant values increased in the order of glucose < fructose $\approx$ psicose < trehalose < sucrose < maltose. The present results suggest that both fructose and psicose interact with water in a similar manner.

Key words: dielectric relaxation, hydration, rare sugar, time domain reflectometry, water activity

1. Introduction

Rare sugars are sugars that rarely exist in nature or exist in small quantities in nature [1,2]. D-Psicose is one of the first rare sugars of which commercial production process has been established [1,2]. Due to limited availabilities of rare sugars, their physicochemical properties [3,4] as well as physiological functions have not been fully explored. The sweetness of psicose is said to be approximately 70% of that of sucrose, while its energy value corresponds to 0.3% only [5]. Evidence for promising health benefits such as anti-oxidation effects [6], reduction in the glycemic index [7], promotion of the blood insulin level [7], and anti-atherosclerosis effects [8] is emerging.

Hydration of sugar has significant implications in food preservation [9,10]. Thus, various physicochemical techniques including dielectric relaxation [11,12], differential scanning calorimetry [13], nuclear magnetic resonance [13,14], ultrasonic velocity [12,15], viscosity [3], and water activity measurements [16,17] have been applied to elucidate the interaction between sugar and water mol-

ecules in aqueous systems. It remains to be difficult, however, to systematically understand the mechanism of hydration of sugar. For example, it is possible to quantify the number of hydrated water molecules per sugar molecule (*i.e.*, the hydration number) experimentally, while experimentally evaluated values of the hydration number show great discrepancies, depending on the time scale of perturbation employed in the experimental method [9].

Matsuoka *et al.* have conducted density and ultrasonic velocity measurements to evaluate the partial molar volume and the partial molar compressibility of two disaccharides, maltose and trehalose [12]. The hydration number of trehalose evaluated from the partial molar volume and compressibility was found to be approximately 10% larger than that of maltose. Furthermore, the data of the dielectric relaxation time in aqueous solutions of trehalose and maltose generated a single master curve when it is plotted as a function of the product of the hydration number and the mole fraction of the sugar. These results indicate a practical approach for evaluating the hydration number of sugars based on the measurement of the dielectric relaxation time in aqueous solutions of sugar.

It is desirable for comparison purposes to evaluate hydration numbers of various sugars using an identical

experimental method. In this study, dielectric relaxation measurements have been adopted to evaluate the hydration number of three monosaccharides including D-psicose and three disaccharides. The equilibrium constant of hydration has been evaluated using the hydration number and water activity.

2. Theory

Gaida *et al.* have proposed a simplified model for describing hydration of sugar in an aqueous solution by assuming that one sugar molecule forms one complex with n molecules of water, where n is the hydration number [9]. This model enables us to predict various physical properties of sugar-containing food such as the boiling point, the freezing point, the osmotic pressure, and so on with known values of the hydration number n and the equilibrium constant of the hydration reaction K [9].

From material balances of three chemical species (*i.e.*, free water, free sugar, and sugar n -hydrate), the following equations are obtained.

$$n_w^a = n_w + nn_h \quad (1)$$

$$n_s^a = n_s + n_h \quad (2)$$

where n_w^a is the apparent (total) amount of water in units of moles, n_w is the amount of free water in units of moles, n_h is the amount of sugar n -hydrate in units of moles, n_s^a is the apparent (total) amount of sugar in units of moles, and n_s is the amount of free sugar in units of moles. The mole fraction of free water x_w is given by

$$x_w = \frac{n_w}{n_w + n_s + n_h} = \frac{n_w^a - nn_h}{n_w^a + n_s^a - nn_h} \quad (3)$$

The amount of sugar n -hydrate can be then expressed by the following equation:

$$n_h = \frac{(x_w^a - x_w)(n_w^a + n_s^a)}{n(1 - x_w)} \quad (4)$$

where $x_w^a (=n_w^a/(n_w^a+n_s^a))$ is the apparent mole fraction of water. The mole fraction of sugar n -hydrate x_h is then related to the apparent mole fraction of water, the mole fraction of free water, and the hydration number by

$$x_h = \frac{n_h}{n_w + n_s + n_h} = \frac{x_w^a - x_w}{n(1 - x_w^a)} \quad (5)$$

The equilibrium constant of hydration K can be defined as

$$K = \frac{a_h}{a_s a_w^n} \quad (6)$$

where a_h , a_s , and a_w are the activities of sugar n -hydrate, free sugar, and free water, respectively. The following relationships have been derived from thermodynamic consideration [9].

$$a_h = \gamma_h x_h \quad (7)$$

$$a_s = \gamma_s x_s = \gamma_s^a x_s^a = a_s^a \quad (8)$$

$$a_w = \gamma_w x_w = \gamma_w^a x_w^a = a_w^a \quad (9)$$

where a_s^a is the apparent activity of sugar, a_w^a is the apparent water activity, γ_h , γ_s , and γ_w are true activity coefficients of sugar n -hydrate, free sugar, and free water, respectively; γ_s^a and γ_w^a are apparent activity coefficients of sugar and water, respectively; x_s is the mole fraction of free sugar, and $x_s^a (=n_s^a/(n_w^a+n_s^a))$ is the apparent mole fraction of sugar.

Results from many experimental techniques including dielectric relaxation spectroscopy are spatially averaged over a number of molecules in the sample. The average hydration number n_a that can be determined from such an experiment is defined as

$$n_a = n \frac{x_h}{x_s + x_h} = n \frac{\frac{\gamma_s}{\gamma_h} K a_w^n}{1 + \frac{\gamma_s}{\gamma_h} K a_w^n} \quad (10)$$

3. Experimental

3.1. Materials

D-Psicose (Lot No. 040506) was obtained from Kagawa Rare Sugar Cluster (Kagawa, Japan). Sucrose, potassium chloride, potassium nitrate, potassium sulfate, and sodium chloride were purchased from Nacalai Tesque Co. (Kyoto, Japan). The water content in sugar was determined by drying in an oven at ca. 110°C until a constant weight has been achieved. All the chemicals were of reagent grade quality and used without further purification.

3.2 Time domain reflectometry (TDR)

A voltage pulse of 200 mV in amplitude was applied to a sample solution through a coaxial cable and the time-dependent change in the voltage of the reflected wave was measured using an HP54121T digitizing oscilloscope consisting of an HP54120B mainframe and an HP54121A four channel test set (Hewlett-Packard, USA). The com-

plex permittivity in the frequency domain was then evaluated based on the following equations [18–21].

$$\epsilon_x^*(\omega) = \epsilon_s^*(\omega) \frac{1 + \{c f_s(\omega) / [i \omega \gamma_d \epsilon_s^*(\omega)]\} \rho(\omega) f_x(\omega)}{1 + \{[i \omega \gamma_d \epsilon_s^*(\omega)] / c f_s(\omega)\} \rho(\omega) f_s(\omega)} \quad (11)$$

$$\rho(\omega) = \frac{r_s(\omega) - r_x(\omega)}{r_s(\omega) + r_x(\omega)} \quad (12)$$

$$f_x(\omega) = Z_x(\omega) \cot Z_x(\omega) \quad (13)$$

$$Z_x(\omega) = \frac{\omega d}{c} \sqrt{\epsilon_x^*(\omega)} \quad (14)$$

$$f_s(\omega) = Z_s(\omega) \cot Z_s(\omega) \quad (15)$$

$$Z_s(\omega) = \frac{\omega d}{c} \sqrt{\epsilon_s^*(\omega)} \quad (16)$$

where $\epsilon_x^*(\omega) (= \epsilon' - i\epsilon'')$ is the complex permittivity of the sample, ω is the angular frequency, $\epsilon_s^*(\omega)$ is the complex permittivity of the reference sample with known permittivity, c is the speed of propagation of the pulse *in vacuo*, d is the geometric cell length, i is an imaginary unit, γ_d is the effective cell length, and r_s and r_x are Fourier transforms of the reflected wave from the reference and that from the sample, respectively. Measurements were performed at 25°C using air as the reference. The effective cell length γ_d was determined so that the dielectric constant of water at the low frequency limit agrees with the known value in the literature [22]. Sample solutions containing 20% (w/w), 30% (w/w), 40% (w/w), or 50% (w/w) of D-psicose were prepared by stirring mixtures of D-psicose and water in sealed containers overnight using a magnetic stirrer. Aqueous solutions of sucrose containing 20% (w/w), 30% (w/w), 40% (w/w), or 50% (w/w) of sucrose were also prepared for TDR experiments by stirring mixtures of sucrose and water in sealed containers overnight using a

magnetic stirrer since no reported data in the literature were found to be suitable for the present analysis explained below.

The dielectric relaxation of a sugar solution is known to be well-described by the following Cole–Cole type relaxation [11,12].

$$\epsilon_x^*(\omega) = \epsilon_\infty + \frac{\Delta\epsilon}{1 + (i\omega\tau)^\beta} \quad (17)$$

where ϵ_∞ is the dielectric constant at the high frequency limit, $\Delta\epsilon$ is the relaxation strength, τ is the dielectric relaxation time, and β ($0 < \beta < 1$) is a constant reflecting the distribution of the relaxation time. The dielectric relaxation time in an aqueous solution of sugar was evaluated by fitting complex permittivity data to Equation (17) using a least-squares method.

3.3 Water activity

Sample solutions containing 20% (w/w), 30% (w/w), 40% (w/w), or 50% (w/w) of D-psicose were prepared by stirring mixtures of D-psicose and water in sealed containers overnight using a magnetic stirrer. The apparent water activity a_w^a of a sample solution was determined based on the measurement of the relative humidity in the air equilibrated with the solution using a TH2/RTD-33/BS thermoconstanter (Novasina, Zurich, Switzerland). Calibration was conducted prior to measurements using saturated salt solutions of potassium chloride, potassium nitrate, potassium sulfate, and sodium chloride with known water activity values [23]. Measurements were performed at 25°C.

4. Results and discussion

4.1 Average hydration number

Dielectric relaxation spectra obtained for aqueous

Fig. 1 Dielectric relaxation spectra of aqueous solutions of D-psicose. ○, 20% w/w; △, 30% w/w; +, 40% w/w; ×, 50% w/w. Solid curves are fitted using Equation (17).

Fig. 2 Dielectric relaxation spectra of aqueous solutions of sucrose. ○, 20% w/w; △, 30% w/w; +, 40% w/w; ×, 50% w/w. Solid curves are fitted using Equation (17).

solutions of D-psicose and sucrose are shown in Figs. 1 and 2, respectively. It can be seen in both the figures that the dielectric constant at the low frequency limit decreases with increasing sugar concentration and that the spectrum shifts toward lower frequency with increasing sugar concentration. Due to the limited width of the accessible frequency range, it was difficult to determine the dielectric constant at the high frequency limit ϵ_∞ by fitting data to Eq. (17). Therefore, values of ϵ_∞ of D-psicose and sucrose were estimated by assuming a linear relationship between ϵ_∞ and the weight fraction of each sugar and using literature values of ϵ_∞ for pure water [24] and a 50% (w/w) maltose or trehalose solution [12]. The complex permittivity data were then fitted to the Cole-Cole equation (*i.e.*, Equation (17)). The dielectric relaxation time τ of water evaluated based on the present method was 8.9 ps, consistent with literature values [22,24]. Furthermore, changes in evaluated values of τ by changing ϵ_∞ between 3.7 (*i.e.*, the literature value for a 50% maltose or trehalose solution [12]) and 5.5 (*i.e.*, the literature value for water [24]) for fitting the dielectric relaxation data of both D-psicose and sucrose to Eq. (17) were confirmed to be less than 0.1 ps.

Figure 3 reveals approximately linear relationships between the logarithm of the dielectric relaxation time evaluated using the Cole-Cole equation and the mole fraction of sugar. Values of τ at a certain mole fraction were almost identical among monosaccharides but increased in the order of monosaccharides < sucrose <

maltose < trehalose, indicating that the total amount of hydrated water in the sugar solutions might increase in this order. The complex permittivity is related to the autocorrelation function of the dipole moment density in the material of interest and the relaxation time is the time constant in the rate of exponential decay of the orientation polarization moment [12]. Therefore, the dielectric relaxation time in a sugar solution is considered to reflect the effect of hydration of sugar on the dipole moment density, not the rotational relaxation of individual chemical species such as free water, free sugar, and sugar-water complex in the solution.

Matsuoka *et al.* have evaluated the average hydration number n_a of maltose and trehalose based on the partial molar volume and the partial molar compressibility at infinite dilution [12]. When the dielectric relaxation time τ is plotted against $n_a x_s^a$, both the data for maltose and trehalose have fallen on an identical curve, suggesting that the total amount of hydrated water in sugar solutions can be estimated as a product of the average hydration number and the mole fraction of sugar. The $\tau - n_a x_s^a$ curve constructed by Matsuoka *et al.* is used in this study as reference to evaluate the average hydration number of fructose, glucose, D-psicose, and sucrose. The data of the dielectric relaxation time of these sugars were fitted to the curve obtained for maltose and trehalose using a least-squares method (Fig. 4). Good correlations between τ and $n_a x_s^a$ were observed for all examined sugars. Evaluated values of the average hydration

Fig. 3 Dielectric relaxation time in aqueous solutions of mono- and disaccharides as a function of the mole fraction. Δ , fructose [11]; $\square$, glucose [11]; $\bullet$, psicose; $+$, maltose [12]; $\circ$, sucrose; $\times$, trehalose [12]. The solid curves are to guide the eye.

Fig. 4 Correlation between the dielectric relaxation time and the product of the mole fraction and the average hydration number. Δ , fructose; $\square$, glucose; $\bullet$, psicose; $+$, maltose [12]; $\circ$, sucrose; $\times$, trehalose [12]. The solid line is to guide the eye.

number are listed in Table 1. Considering the grate variation in the hydration number determined from varied experimental methods, it seems to be rather surprising that the average hydration number of D-psicose evaluated from the dielectric relaxation time in this study has coincided with that from viscosity measurements [3]. Additionally, this value also coincided with the average hydration number of fructose evaluated from the dielectric relaxation time. Psicose is an epimeric stereoisomer of fructose: the only difference in the chemical structure is the position of the C-3 hydroxyl group [4]. The structural similarity between psicose and fructose should play a certain role in providing an identical average hydration number although the equilibrium contents of the tautomers in an aqueous solution are known to differ greatly between D-psicose and fructose [4].

Fig. 5 Concentration dependence of the water activity of monosaccharide aqueous solutions. $\triangle$, fructose [10]; $\square$, glucose [10]; $\bullet$, psicose. Solid curves are fitted using Equation (18).

The present approach gives a single value of the average hydration number for each sugar in the examined concentration range; however, the hydration number of sugar n is expected to decrease with increasing concentration of sugar since sugar-sugar interactions become more predominant over sugar-water interactions. A decrease in the hydration number might be indicated in a $\tau - n_a x_s^a$ plot as a decrease in the slope of the curve, while no change in the slope is noticeable in Fig. 4. These results suggest two possibilities: (1) a change in the hydration number is negligible in the examined concentration range, and (2) effects of changes in the hydration number are cancelled by effects of changes in τ . An alternative approach is needed to test the validity of these hypotheses.

4.2 Equilibrium constant of hydration and hydration number

Apparent water activities a_w^a of aqueous solutions of monosaccharides are compared in Fig. 5. Values of a_w^a were almost identical at a certain concentration among the three monosaccharides examined. The data were fitted to the following empirical equation [16,17] using a least-squares method.

$$a_w^a = (1 - x_s^a) \exp(\alpha x_s^a x_s^a) \quad (18)$$

where α is a constant reflecting the concentration dependence of the water activity. Good agreements between the data and Equation (18) can be seen in Fig 5. Values of α obtained from the curve fitting analysis are summarized in Table 1. Miyawaki and co-workers [16,17] calculated the water activity in sugar solutions from the measurement of the freezing point depression and evaluated the parameter α . They have revealed that

Table 1 Hydration number, parameter α in Equation (18), and equilibrium constant of hydration for mono- and disaccharides.

	n_a	n	α		K	
Fructose	3.1	4.6	-3.597	-2.009 ^b	2.11 ^c	0.74 ^d
	3.0–16.5 ^a	3.39 ^a			1.74 ^a	
Glucose	3.2	5.5	-2.898	-2.734 ^b	1.43 ^e	1.29 ^f
	3.0–18.6 ^a	1.93 ^a			1.65 ^a	
Psicose	3.1	4.5	-3.616		2.19	
	3.1 ^g					
Maltose	5.9 ^h	7.6	-9.549 ^b		3.39	
	5–27.2 ^a	4.48 ^a			0.88 ^a	
Sucrose	5.0	6.6	-7.405 ^b		3.05	
	5.3–25.2 ^a	3.13 ^a			5.03 ^a	
Trehalose	6.6 ^h	9.1	-8.775 ⁱ		2.61	
	6.6–15.3 ^a	5.80 ^a			3.09 ^a	

^a [9], ^b [16], ^c calculated with $\alpha = -3.597$, ^d calculated with $\alpha = -2.009$, ^e calculated with $\alpha = -2.898$,

^f calculated with $\alpha = -2.734$, ^g [3], ^h [12], ⁱ [17]

the parameter α can be regarded as an index of the solvent-ordering since good correlations have been confirmed between α and various solvent-ordering parameters determined based on independent experiments including the measurement of the dielectric relaxation time [25]. As shown in Table 1, the measurement of the vapor pressure tended to give a value of α smaller than that evaluated from the measurement of the freezing point depression for unknown reasons.

The establishment of Equation (18) allows the evaluation of the apparent activity of sugar a_s^a using the following Gibbs–Duhem relationship.

$$x_w^a d\ln a_w^a + x_s^a d\ln a_s^a = 0 \quad (19)$$

The remaining unknown parameter in Equation (6) for calculating the equilibrium constant of hydration K is the activity of sugar n -hydrate a_h and the hydration number n . At infinite dilution, the activity coefficient of any chemical species would be approximated by unity. Equations (7), (9), and (10) then lead to Equations (20), (21), and (22), respectively.

$$a_h \approx x_h \quad (20)$$

$$x_w \approx a_w^a \quad (21)$$

$$n_a = n \frac{K a_w^n}{1 + K a_w^n} \quad (22)$$

Combining Equations (5), (20), and (21) yields

Fig. 6 Equilibrium constants of hydration of mono- and disaccharides calculated using Equation (6). $\triangle$, fructose; $\square$, glucose; $\bullet$, psicose; $+$, maltose; $\circ$, sucrose; $\times$, trehalose. The solid curves are to guide the eye.

$$a_h \approx \frac{x_w^a - a_w^a}{n(1 - x_w^a)} \quad (23)$$

Consequently, the equilibrium constant K and the hydration number n can be obtained by solving Equations (6) and (22) simultaneously. Figure 6 shows K values calculated at varied mole fractions of sugars. Values of K are fairly constant at low concentrations of sugars, while they start to decrease with increasing mole fraction around 0.001 for disaccharides and for monosaccharides around 0.01. The decreases in K are considered to reflect deviations from the ideality such as non-unity values of the activity coefficient. Thus, the K and n values obtained for a mole fraction of 0.0001 were regarded as the equilibrium constant of hydration and the hydration number, respectively, as a first approximation. Table 1 shows that both K and n values of monosaccharides are smaller than those of disaccharides, suggesting that hydration of monosaccharide is less favored than that of disaccharide. Among monosaccharides, fructose and D-psicose show similar K values when compared using values of the parameter α determined from the measurement of the vapor pressure. The larger α values of fructose and glucose determined from the measurement of the freezing point depression resulted in smaller K values.

As mentioned already, experimentally determined values of the hydration number vary greatly depending on the experimental method. Gaïda *et al.* [9] have treated the hydration number n and the equilibrium constant of hydration K of 4 monosaccharides and 3 disaccharides as two adjustable parameters in a model for describing physicochemical properties of aqueous solutions of sugar such as the water activity. They have estimated n and K in order to minimize differences between experimentally obtained values of physicochemical properties and values calculated using their model [9]. The hydration number was estimated to be less than 2 for monosaccharides except for fructose, for which $n = 3.4$, and more than 3 for disaccharides (Table 1). The hydration number of disaccharides increased in the order of sucrose < maltose < trehalose, the same order as the average hydration number reported in this study (Table 1). Compared to the best fit approach employed by Gaïda *et al.* [9], the present method gave consistently larger values of n and comparable values of K .

5. Conclusion

Time domain reflectometry has been confirmed to provide insights into hydration behavior of a rare sugar,

D-psicose. The use of the dielectric relaxation time evaluated based on the assumption of a Cole–Cole type relaxation and a literature value of the hydration number of an ordinary sugar as reference has allowed the evaluation of the average hydration number of D-psicose. The quantified average hydration number was further utilized to calculate the equilibrium constant of hydration. Both the hydration number and the equilibrium constant of D-psicose were found to be almost identical with those of an epimeric stereoisomer, fructose. The results in the present study suggest that D-psicose interacts with water in a manner similar to readily available monosaccharides such as fructose and glucose. Further investigation is required to refine the current approach: it is critical to clarify the molecular mechanism of the dielectric relaxation in aqueous solutions of sugar in order to incorporate the concentration dependence of the hydration number of sugar.

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Nomenclature

- a_h : activity of sugar n -hydrate, -
 a_s : activity of free sugar, -
 a_w : activity of free water, -
 a_s^a : apparent activity of sugar, -
 a_w^a : apparent water activity, -
 c : speed of propagation of the light in vacuo, $\text{m} \cdot \text{s}^{-1}$
 d : geometric cell length, m
 i : imaginary unit, -
 K : equilibrium constant of hydration, -
 n : hydration number, -
 n_a : average hydration number, -
 n_h : amount of sugar n -hydrate, mol
 n_s : amount of free sugar, mol
 n_w : amount of free water, mol
 n_s^a : apparent amount of sugar, mol
 n_w^a : apparent amount of water, mol
 r_s : Fourier transform of the reflected wave from a reference, -
 r_x : Fourier transform of the reflected wave from a sample, -
 x_h : mole fraction of sugar n -hydrate, -
 x_s : mole fraction of free sugar, -
 x_w : mole fraction of free water, -
 x_s^a : apparent mole fraction of sugar, -
 x_w^a : apparent mole fraction of water, -
 α : constant reflecting x_s^a dependence of a_w^a , -
 β : constant reflecting the distribution of τ , -
 $\Delta\epsilon$: relaxation strength, -
 ϵ' : real part of complex permittivity, -
 ϵ'' : imaginary part of complex permittivity, -
 ϵ_s^* : complex permittivity of a reference, -
 ϵ_x^* : complex permittivity of a sample, -
 ϵ_∞ : dielectric constant at the high frequency limit, -
 γ_d : effective cell length, m
 γ_h : true activity coefficient of sugar n -hydrate, -
 γ_s : true activity coefficient of free sugar, -
 γ_w : true activity coefficient of free water, -
 γ_s^a : apparent activity coefficient of sugar, -
 γ_w^a : apparent activity coefficient of water, -
 τ : dielectric relaxation time, s
 ω : angular frequency, $\text{rad} \cdot \text{s}^{-1}$

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◆◆◆ 和文要約 ◆◆◆

D-ブシコースの誘電緩和および水分活性

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希少糖 D-ブシコースの水和挙動を誘電緩和および水分活性により評価した。時間領域において計測した反射波をフーリエ変換することにより、周波数領域における誘電緩和スペクトルを求めた。得られた誘電緩和スペクトルを Cole-Cole 式にフィッティングすることにより、誘電緩和時間を算出した。グルコース、フルクトース、D-ブシコースおよびスクロース水溶液の誘電緩和時間およびマルトースおよびトレハロースの平均水和数の文献値を用いて、グルコース、フルクトース、D-ブシコースおよびスクロースの平均水和数を算出したところ、D-ブシコースの平均水和数はフルクトースの平均水和数と一致した。また誘電緩和時間から求め

られた D-ブシコースの平均水和数は、粘度の測定により求められた D-ブシコースの平均水和数の文献値とも一致した。

D-ブシコースの水分活性の濃度依存性はフルクトースおよびグルコースの水分活性の濃度依存性とほぼ一致した。実験的に求められた水分活性と水和数、さらには糖水溶液中における物質収支を考慮して糖の水和反応の平衡定数を求めたところ、平衡定数の値はグルコース < フルクトース ≈ D-ブシコース < トレハロース < スクロース < マルトースの順に大きくなった。D-ブシコースの水和挙動はフルクトースの水和挙動と類似することが示された。

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