Hydration behavior of D-glucose in aqueous reline solutions:

A volumetric, acoustic and viscometric approach

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Abstract

The hydration behavior of D-glucose in aqueous solutions containing a Natural Deep Eutectic Solvent (ChCl:urea 1:2) was studied in the temperature range: T= (293.15-303.15) K. For that, several volumetric, acoustic and viscometric properties were measured and calculated. The presence of reline in the aqueous solution of D-glucose affects its taste. This effect was evaluated from the values obtained of the apparent molar volume in our mixtures. The Hepler parameter and the viscosity B-coefficient showed that D-glucose in reline aqueous mixtures is a structure-making agent. Both the apparent molar properties and the transfer properties suggested a strong solute-solvent interaction with predominance of the hydrophilic - hydrophylic contribution. Lastly, the calculated viscous flow activation parameters demonstrated high stability of the hydration structure.

Keywords: Natural Deep Eutectic Solvent; D-glucose; Hydration behavior; Thermophysical properties; Taste quality.

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1. Introduction

A deep eutectic solvent (DES) is a specific composition mixture of two or more solid components at room temperature. In the mixing process, a pronounced decrease in

22   the solid-liquid transition temperature (deep eutectic) occurs due to the association of

23   the components, principally by hydrogen-bond. The characteristics of the final

24   compound are quite different from those of its components. Natural deep eutectic

25   solvents (NADES) are the deep eutectic solvents formed by primary metabolites. The

26   H-bond acceptor most common is the (2-hydroxyethyl)trimethylammonium chloride or

27   choline chloride (ChCl), which is included in family of B-vitamins and it is present in

28   many metabolic processes. Several NADES can be formed between ChCl and different

29   H-bond donors such as urea, sugars, organic acids, aminoacids, etc. The NADES term

30   was introduced in 2011 by Choi et al [1]. In this paper, authors developed a theory

31   about the role of these compounds in the cells as third cellular solvent along with water

32   and lipids. So, biosynthesis and storage of metabolites and macromolecules unstable or

33   poorly soluble in the other solvents could be carried out in NADES. Authors related this

34   fact with the survival of organisms under drought conditions where the sugars induction

35   is a key factor. In recent years, following the principles of green chemistry, NADES are

36   used as ecological solvents in different applications: Molecular purification [2],

37   production of new materials (zeolites, graphene, etc.) [3,4], electrochemical applications

38   [5], etc. Highlight their implementation in biotechnological industry in which these

39   compounds and aqueous mixtures thereof are used in biocatalysis and as a transmission

40   vehicle of drug [6-9].

41   Glucose is the most abundant monosaccharide in nature where it is involved in

42   several vital processes. It is a product in photosynthesis, primary energy source in cells,

43   and constituent of both reserve and structural polymers such as starch, glycogen,

44   cellulose and chitin. In addition, several products of great applicability are obtained

45   from glucose transformation. Thus, D-gluconic acid, used in biotechnology industry and

46   green solvents such as lactates and furans, are derived from oxidation or isomerization

47   glucose reactions. The D-glucose is a common additive in drugs and in the food

48   industry is used like sweetener with a stable taste. However, its sweetness level depends

49   on the medium in which it is; the presence of other substances can cause the appearance

50   of synergistic effects which must be studied. Since many of these processes occur in

51   aqueous media, it is important to study the glucose - water interactions in presence of

52   third compounds.

53   Determining thermodynamic and transport properties of aqueous solutions provides

54   information about the hydration process in the mixture. There are different methods to

55   calculate the moles of water bound per mole of solute (hydration number), n_h,

56   depending on the physical property measured to observe the effect of solute-solvent

57   interactions. Acoustic methods are preferred due to simplicity in the experimental

58   determination of sound velocity and density at atmospheric pressure. However,

59   assumptions to be performed provide generally high values for n_h although they are

60   coherent in a same homologous series. Other methods use properties such as viscosity,

61   isothermal compressibility, colligative properties, etc. An interesting review about the

62   hydration number of nonelectrolytes was published by Burakowski and Glinski [10].

63   When the solute is a taste compound, the information above allows us to measure even

64   the quality and intensity of flavor [11,12].

65   In this paper, we present density, ρ, speed of sound, u, and kinematic viscosity, v,

66   experimental values of D-glucose in aqueous solutions of reline, a NADES formed by

67   ChCl and urea in mole proportion 1:2. The studied temperature ranges from 293.15 to

68   303.15 K. From this data, we calculate several properties such as: (i) apparent molar

69   volume, $V_{2,\phi}$, apparent molar isentropic compression, $K_{S,2,\phi}$, and the corresponding

70   values at infinite dilution, V_2^0 and $K_{S,2}^0$; (ii) the dynamic viscosity, η; (iii) viscosity B-

71   coefficients; (iv) the transfer properties, $\Delta_{tr}V_2^0$, $\Delta_{tr}K_{S,2}^0$ and $\Delta_{tr}B$; (v) the activation

72   parameters of viscous flow, $\Delta\mu_1^{0\neq}$, $\Delta\mu_2^{0\neq}$, $\Delta S_2^{0\neq}$ and $\Delta H_2^{0\neq}$; and (vi) the hydration

73   number, n_h. Thus, we analyze the influence of the reline in the taste of D-glucose

74   aqueous mixtures and its ability to stabilize the structure of the solvent.

2. Materials and Methods

75

2.1. Materials

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77   Information about the chemicals used in this work is reported in Table 1. The

78   mass fraction purity and the source of the chemicals used in this work were: D-glucose

79   (> 99.5 %) supplied from Sigma; and reline 200 (> 98 %) provided from Scionix Ltd.

80   Both compounds were used without further purification. The reline water content was

81   253 ppm, determined by Karl Fischer method (automatic titrator Crison KF 1S-2B).

82   Their chemical structures are shown in Supplementary Figure S1. All the aqueous

83   solutions were prepared using Milli Pore MilliQ water with resistivity less than 18.2

84     $\mu S \cdot cm^{-1}$. The mixtures were prepared just before of the property measurements by

85   weighing using a Sartorius Semimicro balance CP225-D; the uncertainty of the mass

86   determination was 0.01 kg.

2.2. Apparatus and procedure

87

88   Density, ρ, and speed of sound, u, at atmospheric pressure were simultaneous

89   obtained from a vibrating tube densimeter and sound analyser (3 MHz) Anton Paar

90   DSA 5000 thermostated at ± 0.005 K. The equipment was calibrated using ultra-pure

91   water supplied by SH calibration service GmbH, and dry air. The combined expanded

92   uncertainties ($k \approx 2$) in the measure of density and speed of sound were $U_c(\rho) = 0.1$

93     $kg \cdot m^{-3}$ and $U_c(u) = 0.5$ $m \cdot s^{-1}$, respectively.

94   An Ubbelohde capilar viscosimeter along with an automatic measuring unit

95   Schott-Geräte AVS-440 were used to determine the kinematic viscosity, v, of the

96   mixtures. The corresponding kinetic energy corrections were applied to the

97   experimental data. The temperature was kept constant within $\pm$ 0.01 K by means of a

98   Schott-Geräte CT52 thermostat. The calibration was carried out with ultra-pure water

99   (SH calibration service GmbH) and the kinematic viscosity uncertainty was $U_c(v) = 1$

100   %.

101   Both devices were previously checked using benzene as reference fluid [13] and

102   the deviations between literature and experimental data calculated using equations (1)

103   and (2) were: $AAD(\rho)$ = 0.03 kg·m^{-3}, $AAD(u)$ = 0.33 m·s^{-1}, and $MRD(v)$ = 0.28%.

$$AAD(Y) = \frac{1}{n} \cdot \sum_{i=1}^{n} \left| Y_i - Y_{i,exp} \right| \tag{1}$$

$$MRD(Y)/\% = \frac{100}{n} \cdot \sum_{i=1}^{n} \left| \frac{Y_i - Y_{i,exp}}{Y_{i,exp}} \right| \tag{2}$$

104   where Y_i and $Y_{i,exp}$ are the literature and experimental values and n is the number of

105   points.

3. Results and Discussion

107   This work presents experimental data of density, ρ, speed of sound, u, and

108   kinematic viscosity, v, of D-glucose in aqueous solutions of reline. The studied

109   composition ranges of solute and co-solute were m_B = 0 to 0.15 mol·kg^{-1} in D-glucose

110   and m_A = 0.1 to 0.5 mol·kg^{-1} in reline. The measures were performed at atmospheric

111   pressure and at temperatures from 293.15 to 303.15 K. The values of the three

112   properties are listed in Supplementary Table S1.

113   There is no data in the literature for the system studied in this work: D-glucose

114   in aqueous reline solutions. We have only found experimental densities and viscosities

115   data of reline in pure water [14,15,16] but the values are not compared because the

116   concentrations do not match. Anyway, we have compared our data at 303.15 K with

117   those and we can conclude that they are consistent (Fig. S2).

118   *3.1. Volumetric properties*

119   From our ρ data, we calculated (equation 1) the apparent molar volumes, $V_{2,\phi}$,

120   which is a measure of size of the hydrated solute molecules. The values and their

121   uncertainty [17] have been calculated with the following equations:

$$V_{2,\phi} = \frac{M_B}{\rho} - \frac{(\rho - \rho_0)}{m_B \cdot \rho \cdot \rho_0} \tag{3}$$

$$u(V_{2,\phi}) = \left(M_B + \frac{1}{m_B}\right) \cdot \frac{u(\rho)}{\rho^2} \tag{4}$$

122   where M_B and m_B are the molar mass and molality of the solute (D-glucose); ρ is the

123   density of the solution; and ρ_0 is the density of the solvent (water + reline). The

124   uncertainty ranges from $2 \cdot 10^{-6}$ m$^3 \cdot$mol^{-1} at lower m_B to $0.3 \cdot 10^{-6}$ m$^3 \cdot$mol^{-1} at higher m_B.

125   Supplementary Table S1 collects $V_{2,\phi}$ values and the Figures S3 and S4

126   (Supplementary data) show the variation of ρ and $V_{2,\phi}$, respectively, with the solute

127   molality, m_B. The density increased with increasing of solute or co-solute composition

128   and, as expected, with decreasing temperature. In the studied mixtures, $V_{2,\phi}$ was

129   positive and decreased when temperature or composition (solute or reline molality)

130   increased. This relationship was more pronounced at lower amount of reline.

131   The taste perception of a substance transferred by saliva includes its proper

132   placement on the receptor site for which an optima size and shape to permit correct

packaging within the water structure are required. Moreover, the hydration sphere of the molecule changes if certain other compounds are present so the taste can be modulated. Since 1999, it is used the apparent specific volume, $ASV = V_{2,\phi}/M_B$ (M_B is the solute molar mass), as a determining parameter of the flavor quality [11]. In aqueous solutions, low ASV values show that the solute is strongly hydrated and, therefore, solute transport to receptors is more effective. Several apparent specific volumes intervals including the different scents have been established [12]. For sweet molecules, the ASV values range from 0.52 to 0.71 cm^3. g^{-1} and the central value, 0.618 cm^3.g^{-1}, is considered as the ideal sweetness. This value is similar to that the D-glucose in pure water at 293.15 K. For the system studied, the apparent specific volumes obtained were higher than the glucose ones in pure water and the maximum value found was for the mixture most dilute at the highest temperature: 0.643 cm^3·g^{-1}. Then, the addition of small amounts of reline to dilute aqueous solutions of D-glucose decreases its sweetness by providing a slightly bitter flavor.

For dilute solutions containing neutral solutes, the apparent molar volume is adequately described through a linear function of the solute molality, m_B. Thus,

$$V_{2,\phi} = V_2^0 + S_V \cdot m_B \tag{5}$$

where V_2^0 is the partial molar volume at infinite dilution of D-glucose in the (reline + water) solvent which is equal to the corresponding apparent molar volume at infinite dilution. This property allows determining the efficiency of packaging by analyzing the extent of the solute-solvent interactions. S_V is the experimental slope which is related with the solute-solute ones. Table 2 reports V_2^0 and S_V values and the corresponding standard deviations calculated as following:

$$\sigma(Y) = \left(\frac{\sum_{i=1}^{n}(Y_i - Y_{i,exp})^2}{n-p}\right)^{1/2} \qquad (6)$$

where Y_i and $Y_{i,exp}$ are the correlated and experimental values, n is the number of points, and p is the parameters number.

In all studied mixtures, V_2^0 values were positives, which indicate strong solute-solvent interactions, and they were higher by increasing the temperature. However, this increase was lower at higher reline concentrations (Fig. 1). For the mixture with $m_A = 0.5$ mol kg^{-1}, V_2^0 was almost constant at the temperature range studied. In dilute solutions, the hydrogen bonds between glucose and reline were facilitated at higher temperatures due to increase in the molecular motion but this effect was becomes less important at higher reline concentrations. The negative values obtained for S_V suggested an overlap of the D-glucose and reline hydration spheres [18]. Moreover, no clear trends with m_A; so the solute-solute interactions, probably, were influenced by several factors.

The volumetric behavior was similar to that observed in dilute aqueous mixtures of D-glucose when the co-solute was an ionic liquid [19] but opposite if was urea, one of the components of the reline [20].

In 1969, Hepler [21] suggested a relation between the variation of V_2^0 with temperature and the ability of the solute to contribute to the stability of the water – water interactions. If the Hepler coefficient, $(\partial^2 V_2^0/\partial T^2)_p$, is negative, the solute is a "structure-breaking" or "chaotropic agent", and if it is positive, the solute is a "structure-making" or "kosmotropic agent". The latter contributes to increase water-water interactions, which results in, for example, protein stabilization. In our study, this coefficient is positive. Note that D-glucose, urea and choline chloride in pure water are structure breakers with Hepler coefficients: (-18.10^{-4}, - 24.10^{-4}, and - 23.10^{-4}) 10^{-6}

177    $m^3 \cdot mol^{-1} \cdot K^{-2}$, respectively [19,22,23]. In the literature, it is known the proteins

178   destabilizing effect of urea while the reline behaves as a potent stabilizer; apparently the

179   strong interaction between the components that form it causes that the reline aqueous

180   solutions, even diluted, show this opposite behavior [24].

181   Then, taking into account volumetric data, D-glucose behaves as a structure

182   breaker in water but it is a kosmotropic agent in the dilute aqueous mixtures containing

183   reline.

184   *3.2. Acoustic properties*

185   We determined simultaneously the speed of sound, u, and the density of the

186   mixtures and from these experimental data, we calculated the isentropic compressibility

187   and subsequently, the apparent molar isentropic compression, $K_{S,2,\phi}$:

$$\kappa_S = 1/(\rho \cdot u^2) \tag{5}$$

$$\kappa_S^0 = 1/(\rho_0 \cdot u_0^2) \tag{6}$$

$$K_{S,2,\phi} = \left[\frac{\kappa_S \cdot M_B}{\rho}\right] + \left[\frac{\kappa_S \cdot \rho_0 - \kappa_S^0 \cdot \rho}{m_B \cdot \rho \cdot \rho_0}\right] \tag{7}$$

188   where M_B and m_B are the molar mass and molality of the solute (D-glucose); ρ, u and

189   κ_S are the density, the speed of sound, and the isentropic compressibility of the solution;

190   and ρ_0, u_0, and κ_S^0 are the density, the speed of sound, and the isentropic

191   compressibility of the solvent (water + reline). The uncertainties in κ_S and $K_{S,2,\phi}$ were

192   calculated using the law of propagation of errors:

$$u(\kappa_S) = 2 \cdot [u(u)]/(\rho \cdot u^3) \tag{8}$$

$$u(K_{2,\phi}) = \left(M_B + \frac{1}{m_B}\right) \cdot u(\kappa_S)/\rho \tag{9}$$

193   The estimated values were: $u(\kappa_S)$=0.30 TPa^{-1} and $u(K_{2,\phi})$=0.34$\cdot$10^{-3} TPa$^{-1} \cdot$m$^3 \cdot$mol^{-1}.

194   where M and m_B are the molar mass and molality of the solute (D-glucose); ρ, u and κ_S

195   are the density, the speed of sound, and the isentropic compressibility of the solution;

196   and ρ_0, u_0, and κ_S^0 are the density, the speed of sound, and the isentropic

197   compressibility of the solvent (water + reline). The uncertainties in κ_S and $K_{S,2,\phi}$ were

198   calculated using the law of propagation of errors and the estimated data were of the

199   order of 0.30 TPa^{-1} and 0.34·10^{-3} TPa^{-1}·m^3·mol^{-1}, respectively.

200   Supplementary Table S1 lists the u experimental and κ_S and $K_{S,2,\phi}$ calculated

201   data for the mixtures studied in this work. Supplementary Figure S5 shows that the

202   speed of sound increased with increasing T, m_B or m_A. The more negative values of

203    $K_{S,2,\phi}$ suggested that the water molecules around the glucose were less compressible

204   that those found within the solution. These values were more negatives when the

205   temperature, or reline composition decreased, or when the glucose molality increased

206   (Fig. S6).

207   As $V_{2,\phi}$ (eq. 3), the apparent molar isentropic compression is a linear function of

208   the solute concentration:

$$K_{S,2,\phi} = K_{S,2}^0 + S_K \cdot m_B \qquad (10)$$

209        $K_{S,2}^0$ is the partial molar isentropic compression (that is the apparent molar

210   isentropic compression) at infinite dilution of D-glucose in the (reline + water) solvent

211   and S_K is the slope. The first parameter is related to the solute-solvent interactions and

212   the second with the solute-solute ones. Both parameters and the corresponding standard

213   deviations are given in Table 2.

214   We obtained the most negative $K_{S,2}^0$ value (-18.22·10^{-3} TPa^{-1}·m^3·mol^{-1}) for the

215   most dilute mixture at the lowest temperature. Therefore in such conditions are

216 presented the strongest solute-solvent interactions. $K_{S,2}^0$ decreased with the increasing of

217 the temperature or the reline composition. This decrease is related to the induction of

218 the dehydration process of glucose: water molecules surrounding glucose are released so

219 that those that remain are more compressible. Again, the solute-solute interactions were

220 smaller than solute-solvent ones ($|S_K| < |K_{S,2}^0|$) and no trended with the temperature or

221 composition.

3.3. Viscometric properties

223   Table S1 collects the experimental viscosities and Fig. S7 (Supplementary data)

224 reports the plots of the kinematic viscosity, v, versus D-glucose molality, m_B, at

225 different reline compositions, m_A. It is observed that the viscosity increased when m_B

226 or m_A increased, or if T decreased. From our ρ and v data, we obtained the dynamic

227 viscosities, $\eta = \rho \cdot v$, with a combined expanded uncertainty ($k \approx 2$): $U_c(\eta) = 1\%$; the

228 values are also listed in Table S1. The three properties (ρ, v, η) showed similar behavior

229 respect to m_B, m_A and T.

230   Solute-solvent interactions can also be analyzed via B-coefficient of viscosity

231 using the Jones-Dole equation [25], relating the relative viscosity, η_r, to the molarity of

232 the solution, c_B. The equation for dilute solutions of non-electrolyte solutes is:

$$\eta_r = \eta/\eta_0 = 1 + B \cdot c_B \tag{11}$$

233 being η and η_0 the solution (D-glucose + reline + water) and solvent (reline + water)

234 viscosities, respectively; and B is a coefficient related with solute-solvent interactions.

235   Figure S8 shows the relative viscosity data at several solute and co-solute

236 molalities and at different temperatures. Normally, a B positive value means that the

237 solute is strongly hydrated, and therefore behaves as a kosmotrope. However, large

238 solutes, as the tetramethylammonium cation, had positive coefficients but they were

239 chaotropics agents [26]. Therefore, to establish the type of interaction solute-solvent is

240 preferred to study other parameter. According to the Eyring's theory of viscosity [27], if

241 $dB/dT < 0$ the viscous flow activation energy for the solution is greater than for the

242 solvent; i.e., the solute is a structure-making or kosmotrope. On the other hand, when

243 $dB/dT > 0$, the solute is a structure-breaking or chaotrope. The sign of dB/dT shows

244 the net balance between the structure stabilization carried out by the hydrophobic

245 groups and the disruption caused by hydrophilic ones.

246   In the studied system in this work, the B-coefficient values (Table 3) were

247 positive, changed marginally with reline composition, m_A, and decreased with T

248 increased. So, as already we obtained from volumetric properties, the D-glucose in

249 (reline + water) solvent is a kosmotropic compound. From viscosity data of this work

250 and literature [23,28,29] reported in Figure 1, we found that urea, ChCl or reline

251 solutions in pure water presented $dB/dT > 0$ and therefore they are structure breakers,

252 as saw in section 3.1. On the other hand, we observed that the D-glucose is a structure-

253 maker which is an opposite conclusion to that observed from volumetric data. So it is

254 important to study the solute-solvent interactions using different properties because they

255 present different sensibility to the solution characteristics and different error in the

256 calculation. We think that the conclusion from viscometric data is more reliable because

257 the Hepler coefficient is a derivative property of second-order which has higher error

258 than the B-coefficient.

259 *3.4. Transfer properties*

260   Transfer properties allow analyzing the type of interactions occurring between

261 solute and co-solute and the effect of both compounds on the water structure. In our

system, the possible interactions are: (i) D-glucose hydrophilic – reline hydrophilic

sites; (ii) D-glucose hydrophobic – reline hydrophilic sites; (iii) D-glucose hydrophilic –

reline hydrophobic sites; (iv) D-glucose hydrophobic – reline hydrophobic sites.

Using our experimental data of V_2^0, $K_{S,2}^0$, and B-coefficient (Tables 1 and 2), and

the literature values [28,30], we obtained the standard partial molar volume of transfer

at infinite dilution, $\Delta_{tr}V_2^0$, the standard partial molar isentropic compression of transfer

at infinite dilution, $\Delta_{tr}K_{S,2}^0$, and the B-coefficient of transfer, $\Delta_{tr}B$, of D-glucose from

water to (reline + water) mixtures (Table S2):

$$\Delta_{tr}Z = Z(\text{NADES aqueous solutions}) - Z(\text{aqueous solutions}) \qquad (12)$$

where Z is V_2^0, $K_{S,2}^0$, or B-coefficient.

Figure 2 shows the variation of $\Delta_{tr}V_2^0$ with the reline molality at several

temperatures. The obtained values were positive. Only the interactions type (i)

contributes positively to the $\Delta_{tr}V_2^0$ values; the others make it negatively [31]. Then, we

can say that in most of the conditions studied, the hydrophilic – hydrophilic interactions

are predominant. The transfer volumes increased with the temperature for the mixtures

with $m_A < 0.2$ but decreased when $m_A > 0.2$, being the slope more negative to upper

m_A. As mentioned above, increased molecular motion favors the interaction of the D-

glucose hydroxyl groups with reline in the most dilute solutions. On the other hand, a

higher value of m_A enhances the contribution of hydrophobic interactions.

The $\Delta_{tr}K_{S,2}^0$ and $\Delta_{tr}B$ values (Table S2) are positives in all T and m_A ranges,

which is related with the overlap of the hydration spheres of hydrophilic sites. The plots

$\Delta_t K_{S,2}^0$ versus T (Figure 3) show a maximum value which appears at lower temperatures

with increasing the reline molality. Also, it is noted that the influence of m_A on this

284 property is smaller with increasing T. The values of the B-coefficient of transfer

285 increase continuously with temperature and vary only slightly with reline molality.

3.5. McMillan-Mayer coefficients

287 McMillan-Mayer theory [32] allows separating the effects due to interactions

288 between pairs of molecules and those that take place involving more than two

289 molecules. So, $\Delta_{tr}V_2^0$ and $\Delta_{tr}K_{S,2}^0$ properties can be written:

$$\Delta_{tr}Z = 2\,Z_{BA}m_A + 3\,Z_{BAA}m_A^2 + \cdots \qquad (13)$$

290 where Z is V_2^0 or $K_{S,2}^0$; B and A are D-glucose and reline, respectively; and m_A is the

291 reline molality.

292 The parameters Z_{BA} and Z_{BAA}, calculated by fitting of the transfer properties to

293 the equation 11, denote the pair and triplet interaction coefficients. For both properties,

294 Z_{BA} values are positive whereas Z_{BAA} are negative (Table S3). This fact suggests that

295 the interaction D-glucose – reline occurs by overlap of their hydration spheres. Water

296 molecules located in the hydration co-sphere have different structural organization that

297 found within the solution. Thus, if the co-sphere is more structured, releasing a water

298 molecule implies a negative change of volume whereas will be positive if the bulk is

299 more organized. The positive sign of the pair parameters indicates a predominance of

300 the interactions between two molecules.

3.6. Activation parameters of viscous flow

302 Thermodynamic parameters of the viscous flow can be obtained from the

303 viscosity B-coefficients [33]: Gibbs free energy of activation for viscous flow per mole

304 of solvent, $\Delta\mu_1^{0\neq}$; Gibbs free energy of activation per mole of solute, $\Delta\mu_2^{0\neq}$; standard

305 partial molar entropy of activation for viscous flow, $\Delta S_2^{0\neq}$; and standard partial molar

306 enthalpy of activation for viscous flow, $\Delta H_2^{0\neq}$. These parameters are given in Table S4

307 and the equations used are the following:

$$\Delta\mu_1^{0\neq} = RT \ln (\eta_1 V_1/hN_A) \tag{14}$$

$$\Delta\mu_2^{0\neq} = \Delta\mu_1^{0\neq} + \frac{RT}{V_1}(B + V_2^0 - V_1) \tag{15}$$

$$\Delta S_2^{0\neq} = - d(\Delta\mu_2^{0\neq})/dT \tag{16}$$

$$\Delta H_2^{0\neq} = \Delta\mu_2^{0\neq} + T\Delta S_2^{0\neq} \tag{17}$$

308 where η_1 and V_1 are the viscosity and the partial molar volume of the solvent (reline +

309 water), respectively; h is the Planck constant; N_A is the Avogadro number; and the other

310 symbols have usual meanings.

311     $\Delta\mu_1^{0\neq}$ calculated data were positive and decreased slightly with increasing

312 temperature but hardly varied with the co-solute concentration in T and m_A studied

313 ranges. For $\Delta\mu_2^{0\neq}$, whose values were much higher than $\Delta\mu_1^{0\neq}$, no trends were observed

314 with both variables. According to the transition state theory of relative viscosity [33],

315 $(\Delta\mu_2^{0\neq} - \Delta\mu_1^{0\neq})$ values indicate the change in the activation energy when one mole of

316 solvent is replaced by on mole of solute at infinity dilution. Then, if $\Delta\mu_2^{0\neq} > \Delta\mu_1^{0\neq}$, the

317 ground state is the favored status from the free energy point of view; i.e. solute-solvent

318 interactions are stronger than in the transition state. Furthermore, the higher $\Delta\mu_2^{0\neq}$ value

319 the higher structure-making tendency of the solute; again, our results indicate that the

320 D-glucose in (reline+water) solvent is a structure-making. Finally, it is observed that the

321 formation of the transition state is a process that involves a bond breaking and increased

322 disorder as indicated by the positives values of $\Delta S_2^{0\neq}$ and $\Delta H_2^{0\neq}$.

323 *3.7. Hydration number*

From the viscosity and density values measured, we estimated the hydration number, n_h, of solute in the T and m_A ranges studied in this work. For this purpose, the B-coefficient is divided in two terms [34]: the first, B_{size}, is a term related to the size effect of solute on the viscosity, η, and it is calculated from the partial molar volume at infinite dilution, V_2^0, and the second, $B_{structure}$, indicates the effect of the solute on solvent-structure:

$$B = B_{size} + B_{structure} = 2.5\,V_2^0 + B_{structure} \qquad (18)$$

$$n_h = B_{structure}/2.5\,V_1 \qquad (19)$$

where V_1 is the molar volume of solvent.

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The hydration numbers obtained (Table 2) ranged from 3.03 to 4.53 and decreased to increasing the temperature due to the thermal motion. Since no trend with the reline concentration was found, we calculated average values for the hydration number, $\bar{n}_h$, and as expected, followed an equation type Arrhenius:

$$ln\,(\bar{n}_h) = ln\,(\bar{n}_{h,0}) + \frac{\Delta\bar{\mu}_1^{0\neq}}{RT} \qquad (18)$$

where $ln\,(\bar{n}_{h,0})$ is the pre-exponential factor, $\Delta\bar{\mu}_1^{0\neq}$ is the activation energy of the viscous flow, R is the gas constant and T is the absolute temperature. Figure 4 shows the high linearity obtained and the Arrhenius parameters values. Thus, the activation energy calculated, $\Delta\bar{\mu}_1^{0\neq} = 9.4$ kJ·mol^{-1} (similar to the obtained in section 3.6), was lower than those published for the aqueous mixtures of D-glucose (16.2 kJ·mol^{-1}) and choline chloride (16.9 kJ·mol^{-1}) [23,35]. This fact suggests that the hydration structure when the solvent is water + reline is more stable than in pure water.

4. Conclusions

345 In this work, we have studied the hydration behavior of D-glucose aqueous solutions in

346 presence of a Natural Deep Eutectic Solvent (reline), which is formed for Choline

347 Chloride and urea in mole proportion 1:2. For this purpose, we have measured densities,

348 speeds of sound and viscosities of {D-glucose + (reline+water)} mixtures at infinite

349 dilution in a temperature range from 293.15 to 318.15 K. From our experimental data

350 and literature values, we have calculated several volumetric, acoustic and viscometric

351 properties. Our results indicate that the reline reduces the sweetness of D-glucose

352 making its solutions bitterer. Both, the sign of Hepler coefficient and the variation of

353 viscosity *B*-coefficient with temperature show that the D-glucose in reline aqueous

354 solutions is a structure - making (or kosmotropic) agent; this behavior is opposite when

355 the solvent is pure water. From the transfer properties obtained, we can conclude that

356 the hydrophilic-hydrophilic interactions are predominant, including overlap of their

357 hydration spheres. Finally, the activation parameters of the viscous flow suggest the

358 stability of the hydration structure, as well as breaking bonds and increased disorder in

359 the formation of the transition state.

Conflict of interest

361 The authors declare that they have no conflict of interest to the best of their knowledge

Acknowledgements

Appendix A. Supplementary data

367 Supplementary data associated with this article can be found in the online version.

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464

465   **Figure 1.**

466   Viscosity *B*-coefficient values for several systems: D-glucose + (reline + water) at m_A

467   = 0.30126 (this work) (■); D-glucose + water [28] (▲); ChCl + water [23] (⬟); reline

468   + water (this work) (★); urea + water [29] (▼).

469

470   **Figure 2.**

471   Standard partial molar volumes of transfer at infinite dilution, $\Delta_t V_2^0$, of D-glucose in

472   aqueous reline solutions as a function of reline compositions, m_A, at several

473   temperatures.

474

475   **Figure 3.**

476   Standard partial molar isentropic compressions of transfer at infinite dilution, $\Delta_t K_{S,2}^0$, of

477   D-glucose in aqueous reline solutions as a function of temperature, *T*, at several reline

478   compositions, m_A.

479

480   **Figure 4.**

481   Arrhenius plot for the average hydration number, $\bar{n}_h$, of D-glucose in aqueous reline

482   solutions.

483