Densities and Viscosities of Ternary Systems of Water + Fructose + Sodium Chloride from 20 to 40 °C

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The densities and dynamic viscosities of aqueous solutions of sodium chloride, fructose, and fructose + sodium chloride were measured at temperatures from (20 to 40) °C. The concentration range studied for both sodium chloride and fructose was (0 to 4) mol·kg^{-1}. For fructose + sodium chloride solutions, the experimental values were correlated with the concentration of sodium chloride. The maximum deviation was always less than 0.2%.

Introduction

The objective of applying an osmotic treatment, for example, to foods, is to produce products that may be stored without having to use severe heat treatment, freezing, or aseptic packaging. The improvement of nutritional, sensory, or functional properties or the storage stability of the end products is achieved by modifying the chemical composition of the food material through controlled water removal and a selective incorporation of solutes. The constraints to the formulation of new products are economic constraints and consumer acceptance. The products must be salable and producible at an economic cost. Osmotic treatments may offer these economic advantages.[1]

The range of applications of this processing technique is wide: fruit, vegetables, meat, and fish can be osmotically treated preceding conventional processing.[2−6] Binary and ternary aqueous solutions of sugars, inorganic salts, alcohols, and polyols can be used as osmotic agents. The use of mixed blends makes it possible to take benefit from the respective advantages of each solute. Therefore, the understanding of osmotic treatments needs to take into account the physical properties of the aqueous solutions.

Densities and viscosities of concentrated water + sugar + sodium chloride have been little studied to date.[7,8] The objective of this work was to measure the density and dynamic viscosity of the ternary system water + fructose + sodium chloride in the temperature range (20 to 40) °C. A molal concentration range of (0 to 4) mol·kg^{-1} of solutes was studied.

Experimental Section

Aqueous solutions of fructose, sodium chloride, and fructose + sodium chloride were prepared by mass with distilled water, obtained from the MILLI-Q 185 PLUS system with a resistivity of 18.2 MΩ·cm. The solutes were Merck reagents of nominal purity > 99% for fructose and 99.5% for sodium chloride. All solutions were prepared from water and reagents by mass using a Scaltec SBA31 analytical balance with a readability of ±0.1 mg. The physical properties were measured at temperatures ranging from (20 to 40) °C at 10 °C intervals.

The density was measured with an Anton Paar DMA 4500 densimeter with a precision of $\pm 1 \times 10^{-4}$ g·cm^{-3}. The temperature of the densimeter was controlled to ±0.01 °C. Each density value was the average of at least three measurements, and the maximum deviations from the average were always less than 0.01%.

The kinematic viscosity was determined from the transit time of the liquid meniscus through a capillary measured with a precision of ±0.1 s in a Schott-Geräte AVS 350 automatic Ubbelohde viscosimeter. The viscosimeter was immersed in a bath, and the precision of the temperature control in all these measurements was ±0.05 °C. Each measurement was repeated at least 10 times with a maximum deviation of less than 0.4%. The dynamic viscosity was calculated by multiplying the kinematic viscosity by the corresponding density.

Table 1. Densities and Viscosities of the Solutions of Fructose and Sodium Chloride

		Water + *c* Sodium Chloride				Water + *c* Fructose			
		ρ/(kg·m^{-3})		η/(mPa·s)		ρ/(kg·m^{-3})		η/(mPa·s)	
c/(mol·kg^{-1})	*t*/°C	exptl	lit.	exptl	lit.	exptl	lit.	exptl	lit.
0.000	20	998.2	998.2[a]	1.002	1.002[a]	998.2		1.002	
	30	995.6	995.7[a]	0.797	0.7975[a]	995.6		0.797	
	40	992.2	992.2[a]	0.653	0.6530[a]	992.2		0.653	
0.500	20	1018.6	1018.5[b]	1.041	1.047[b]	1031.4	1031.3[b]	1.244	1.242[b]
			1018.5[c]		1.034[d]				
	30	1015.7	1015.5[c]	0.835	0.834[d]	1028.3		0.979	
	40	1011.9	1011.8[c]	0.688	0.682[d]	1024.4		0.795	
1.000	20	1037.8	1037.8[b]	1.087	1.092[b]	1061.1	1060.9[b]	1.549	1.547[b]
			1037.8[c]		1.079[d]				
	30	1034.4	1034.5[c]	0.873	0.873[d]	1058.0		1.202	
	40	1030.4	1030.4[c]	0.722	0.716[d]	1053.6		0.964	
1.500	20	1056.3	1056.4[b]	1.138	1.144[b]	1087.3	1087.3[b]	1.941	1.932[b]
					1.130[d]				
	30	1052.6		0.918	0.917[d]	1083.3		1.484	
	40	1048.4		0.760	0.753[d]	1078.6		1.173	
2.000	20	1074.1	1074.1[b]	1.196	1.203[b]	1111.3	1111.2[b]	2.397	2.400[b]
			1074.2[c]		1.187[d]				
	30	1070.1	1070.2[c]	0.966	0.964[d]	1106.7		1.803	
	40	1065.7	1065.8[c]	0.802	0.793[d]	1101.7		1.408	
2.500	20	1091.4	1091.3[b]	1.264	1.272[b]	1132.7	1132.6[b]	2.978	2.972[b]
					1.251[d]				
	30	1087.2		1.021	1.015[d]	1128.0		2.218	
	40	1082.5		0.848	0.836[d]	1122.6		1.697	
3.000	20	1107.8	1107.9[b]	1.333	1.346[a]	1152.3	1152.3[b]	3.744	3.700[b]
			1108.0[c]		1.321[d]				
	30	1103.4	1103.5[c]	1.077	1.072[d]	1147.2		2.728	
	40	1098.6	1098.7[c]	0.895	0.836[d]	1141.6		2.055	
3.500	20	1123.9	1123.8[b]	1.411	1.420[b]	1170.2	1170.2[b]	4.603	4.628[b]
					1.398[d]				
	30	1119.2		1.140	1.133[d]	1165.0		3.284	
	40	1114.3		0.945	0.934[d]	1159.1		2.451	
4.000	20	1139.2	1139.4[b]	1.499	1.502[b]	1186.6	1186.5[b]	5.698	5.728[b]
			1139.4[c]		1.483[d]				
	30	1134.4	1134.6[c]	1.208	1.199[d]	1181.0		3.976	
	40	1129.3	1129.6[c]	1.000	0.989[d]	1174.9		2.923	

[a] Marsh (1987). [b] Weast (1976). [c] Pitzer et al. (1984). [d] Afzal et al. (1989).

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Table 2. Densities and Viscosities of the Solutions of Fructose + Sodium Chloride

c/(mol·kg^{-1})	t/°C	ρ/(kg·m^{-3})	η/(mPa·s)	ρ/(kg·m^{-3})	η/(mPa·s)	ρ/(kg·m^{-3})	η/(mPa·s)	ρ/(kg·m^{-3})	η/(mPa·s)
		Water + 0.5 m Fructose + c Sodium Chloride		Water + 1.0 m Fructose + c Sodium Chloride		Water + 1.5 m Fructose + c Sodium Chloride		Water + 2.0 m Fructose + c Sodium Chloride	
0.500	20	1049.9	1.295	1077.8	1.618	1102.7	2.016	1125.4	2.513
	30	1046.4	1.024	1073.9	1.259	1098.5	1.546	1121.0	1.893
	40	1042.2	0.834	1069.4	1.012	1093.7	1.227	1115.8	1.480
1.000	20	1067.4	1.355	1093.9	1.693	1117.8	2.108	1139.3	2.633
	30	1063.6	1.075	1089.8	1.324	1113.4	1.620	1134.6	1.994
	40	1059.3	0.878	1085.1	1.066	1108.4	1.288	1129.4	1.559
1.500	20	1084.4	1.418	1109.5	1.773	1132.2	2.214	1152.7	2.773
	30	1080.3	1.127	1105.2	1.388	1127.6	1.703	1147.8	2.090
	40	1075.8	0.922	1100.3	1.119	1122.5	1.354	1142.5	1.637
2.000	20	1100.8	1.491	1124.7	1.864	1146.2	2.332	1165.6	2.918
	30	1096.5	1.186	1120.1	1.459	1141.4	1.791	1160.6	2.203
	40	1091.7	0.971	1115.1	1.178	1136.2	1.426	1155.2	1.729
2.500	20	1116.6	1.573	1139.1	1.968	1159.6	2.458	1178.2	3.077
	30	1112.1	1.251	1134.4	1.540	1154.7	1.890	1173.1	2.323
	40	1107.2	1.025	1129.3	1.243	1149.4	1.504	1167.6	1.819
3.000	20	1131.7	1.662	1153.3	2.079	1172.6	2.596	1190.4	3.256
	30	1127.1	1.322	1148.4	1.624	1167.6	1.994	1185.2	2.453
	40	1122.0	1.081	1143.2	1.310	1162.2	1.583	1179.5	1.921
3.500	20	1146.5	1.762	1166.9	2.202	1185.4	2.752	1202.1	3.452
	30	1141.7	1.399	1161.9	1.718	1180.3	2.108	1196.8	2.595
	40	1136.5	1.143	1156.6	1.384	1174.7	1.672	1191.1	2.025
4.000	20	1160.8	1.871	1180.2	2.341	1197.6	2.923	1213.6	3.665
	30	1155.8	1.483	1175.0	1.821	1192.3	2.231	1208.2	2.745
	40	1150.6	1.211	1169.6	1.463	1186.8	1.768	1202.5	2.131
		Water + 2.5 m Fructose + c Sodium Chloride		Water + 3.0 m Fructose + c Sodium Chloride		Water + 3.5 m Fructose + c Sodium Chloride		Water + 4.0 m Fructose + c Sodium Chloride	
0.500	20	1146.1	3.139	1164.6	3.890	1181.7	4.818	1197.4	5.957
	30	1141.2	2.323	1159.6	2.829	1176.5	3.434	1192.0	4.159
	40	1135.7	1.790	1153.9	2.146	1170.6	2.569	1185.9	3.063
1.000	20	1158.9	3.286	1176.8	4.088	1192.9	5.053	1207.9	6.260
	30	1154.0	2.437	1171.6	2.967	1187.6	3.605	1202.4	4.372
	40	1148.5	1.882	1166.0	2.256	1181.7	2.694	1196.3	3.217
1.500	20	1171.3	3.453	1188.4	4.293	1203.8	5.329	1218.0	6.584
	30	1166.2	2.560	1183.1	3.122	1198.4	3.787	1212.4	4.598
	40	1160.7	1.979	1177.3	2.372	1192.5	2.837	1206.3	3.377
2.000	20	1183.4	3.636	1199.6	4.527	1214.3	5.606	1227.9	6.951
	30	1178.1	2.693	1194.2	3.283	1208.8	3.981	1222.3	4.833
	40	1172.5	2.079	1188.4	2.493	1202.8	2.977	1216.2	3.552
2.500	20	1195.0	3.850	1210.5	4.772	1224.6	5.923	1237.6	7.344
	30	1189.7	2.849	1205.1	3.461	1219.0	4.204	1232.0	5.103
	40	1184.0	2.197	1199.2	2.624	1213.0	3.132	1225.8	3.733
3.000	20	1206.3	4.070	1221.1	5.066	1234.5	6.273	1247.0	7.799
	30	1201.1	3.012	1215.6	3.667	1229.0	4.444	1241.3	5.400
	40	1195.3	2.311	1209.7	2.762	1223.0	3.304	1235.2	3.933
3.500	20	1217.4	4.313	1231.4	5.357	1244.3	6.652	1256.2	8.246
	30	1212.0	3.170	1226.0	3.864	1238.7	4.694	1250.5	5.694
	40	1206.2	2.434	1220.0	2.913	1232.6	3.478	1244.3	4.142
4.000	20	1228.2	4.567	1241.6	5.692	1253.8	7.075	1265.0	8.754
	30	1222.7	3.351	1236.0	4.088	1248.2	4.966	1259.4	6.022
	40	1216.8	2.567	1230.0	3.082	1242.1	3.672	1253.2	4.368

The densimeter and the viscosimeter were calibrated with distilled water. The measured density and kinematic viscosity of water at the working temperatures are included in Table 1 and are compared with values published by Marsh.[9]

Results and Discussion

The densities and viscosities of aqueous solutions of fructose and sodium chloride at (20, 30, and 40) °C are presented in Table 1. Some of these values are compared with others found in the literature.[10−12]

The experimental results show that, for each temperature studied, the values of both properties increase as the concentration in both solutions increases, the effect being greater in the case of fructose, especially for viscosity.

Furthermore, for a certain concentration, a reduction in the densities and viscosities of the solutions under investigation is observed when temperature increases. In the case of density, the decline is practically constant for both systems in the concentration range studied. With respect to viscosity, the behavior of the systems is different, since the variation is nearly constant in the case of sodium chloride yet for fructose it increases notably as the solutions become more concentrated.

Table 2 includes the densities and viscosities of the aqueous solutions of fructose + sodium chloride at (20, 30, and 40) °C. For each solution studied, a decrease in the values of both properties is observed when temperature is increased.

For each temperature, both properties are enhanced when the concentration of the solutions in the entire concentration range being considered augments. When densities and viscosities in different ternary systems, having a specific sodium chloride content, are compared with values of binary systems, having the same fructose content as that in the ternary, it is observed that the effect of the salt is practically the same for the different fructose concentrations. Similarly, when comparing densities and viscosities of the different ternary systems that have the same fructose content with respect to corresponding values of the binary systems with the same sodium chloride concentration as that of the ternary, it is observed that the effect of the sugar is practically the same for the different sodium chloride concentrations. Nonetheless, the effect produced by fructose is greater, especially in the case of viscosity; therefore, of the different ternary systems having a specific total molality, the one with the greatest density and viscosity is that exhibiting the highest fructose concentration.

The densities of the fructose + sodium chloride solutions, ρ, were expressed as a function of the concentration of sodium chloride by an empirical equation of the form[13]

$$\rho/(\mathrm{kg\cdot m^{-3}}) = \rho_d/(\mathrm{kg\cdot m^{-3}}) + \sum_{i=2}^{4} A_i(c/(\mathrm{mol\cdot kg^{-1}}))^{i/2} \quad (1)$$

where ρ_d is the density of the solutions in the absence of sodium chloride, c is the molal concentration of sodium chloride, and A_i are the adjustable coefficients whose values

Table 3. Parameters of Eqs 1 and 2 for the Sodium Chloride Concentration Dependence of the Densities and Viscosities of the Aqueous Solutions of Fructose + Sodium Chloride

c/(mol·kg^{-1})	t/°C	ρ (eq 1) A_2	A_3	A_4	η (eq 2) 10^3A	10^3B	10^3D	10^3E
0.500	20	38.57	−1.892	−0.612	1.076	95.26	13.037	0.276
	30	37.39	−1.321	−0.718	4.169	81.55	9.177	0.180
	40	37.11	−1.624	−0.580	0.438	76.64	5.141	0.205
1.000	20	32.96	0.536	−1.093	8.094	118.91	15.601	0.393
	30	31.95	1.013	−1.184	1.296	111.28	7.531	0.399
	40	31.73	0.860	−1.114	0.702	93.02	6.408	0.180
1.500	20	32.01	−0.911	−0.654	−32.15	186.31	13.726	0.634
	30	31.49	−0.803	−0.656	−13.032	136.94	12.738	0.172
	40	31.35	−1.017	−0.569	−11.271	118.59	7.190	0.212
2.000	20	28.79	−0.039	−0.787	5.698	212.3	20.13	0.670
	30	29.55	−1.179	−0.453	9.959	161.09	15.101	0.283
	40	29.35	−1.251	−0.415	8.499	125.82	14.420	−0.216
2.500	20	28.06	−1.571	−0.261	108.73	137.82	61.69	−1.309
	30	27.56	−1.326	−0.308	26.85	156.95	33.96	−0.724
	40	27.46	−1.310	−0.322	22.86	145.17	15.817	−0.084
3.000	20	25.84	−1.056	−0.356	−66.15	376.2	28.11	0.986
	30	26.13	−1.570	−0.197	−54.06	268.2	24.24	0.054
	40	26.15	−1.732	−0.146	−46.71	247.3	−0.620	1.100
3.500	20	23.75	−0.652	−0.387	−23.97	443.8	33.52	1.623
	30	23.95	−1.117	−0.228	9.321	272.7	35.85	−0.008
	40	24.05	−1.259	−0.197	−4.691	234.70	15.109	0.386
4.000	20	22.09	−0.423	−0.407	5.291	479.57	72.60	−0.274
	30	22.97	−1.948	−0.091	1.562	349.91	40.73	−0.062
	40	23.00	−1.530	−0.089	−8.113	284.47	16.114	0.517

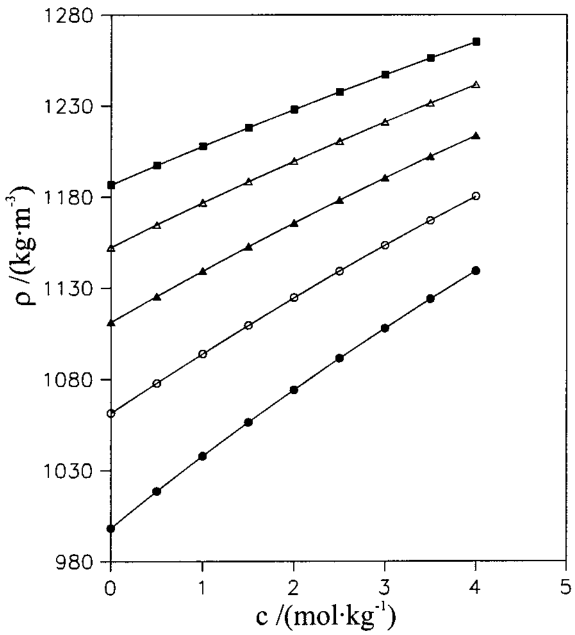

Figure 1. Densities of the aqueous solutions of fructose + sodium chloride at 20 °C plotted against the sodium chloride concentration: (●) 0 mol·kg^{-1} fructose; (○) 1.0 mol·kg^{-1} fructose; (▲) 2.0 mol·kg^{-1} fructose; (△) 3.0 mol·kg^{-1} fructose; (■) 4.0 mol·kg^{-1} fructose; (−−) calculated from eq 1.

are listed in Table 3. The relative deviation between experimental and estimated densities was not greater than ±0.1%. The comparison between the experimental and calculated densities at 20 °C is graphically shown in Figure 1.

The variation of the dynamic viscosity of the fructose + sodium chloride solutions with the concentration was expressed through an extended Jones−Dole equation:[14]

$$\eta/(\mathrm{mPa{\cdot}s}) = \eta_d/(\mathrm{mPa{\cdot}s}) + Ac^{0.5} + Bc + Dc^2 + Ec^{3.5} \quad (2)$$

where η is the viscosity of the solution, η_d is the viscosity in the absence of sodium chloride, and c is the molal concentration of sodium chloride. The values of the fitted parameters A, B, D, and E are listed in Table 3. The experimental and calculated viscosities at 40 °C are compared in Figure 2, and the maximum differences are always less than 0.2%.

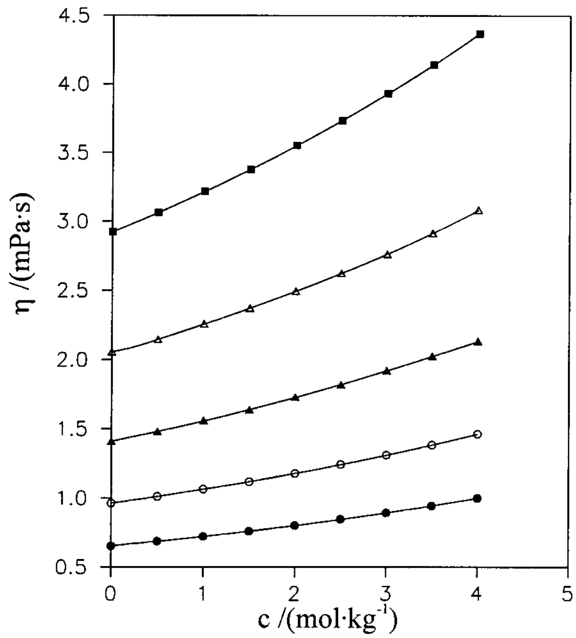

Figure 2. Viscosities of the aqueous solutions of fructose + sodium chloride at 40 °C plotted against the sodium chloride concentration: (●) 0 mol·kg^{-1} fructose; (○) 1.0 mol·kg^{-1} fructose; (▲) 2.0 mol·kg^{-1} fructose; (△) 3.0 mol·kg^{-1} fructose; (■) 4.0 mol·kg^{-1} fructose; (−−) calculated from eq 2.

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