Solubilities of *o*- and *p*-Chlorobenzoic Acids and *o*- and *p*-Nitroanilines in *N*,*N*-Dimethylformamide + Water

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The solubilities of *o*-chlorobenzoic acid, *p*-chlorobenzoic acid, *o*-nitroaniline, and *p*-nitroaniline in dimethylformamide (DMF) + water at different compositions are reported at 303 K. At this temperature, p-chlorobenzoic acid is more soluble than o-chlorobenzoic acid in DMF + water with the difference in solubilities increasing with the DMF content. For the nitroanilines, however, *o*-nitroaniline is more soluble than *p*-nitroaniline in DMF + water.

Introduction

Hydrotropes are organic salts which can increase solubility of otherwise water insoluble organic compounds in the aqueous phase. Thoma and Kasper (1988) have reported the use of organic amides and dimethyl sulfoxide as hydrotropes for increasing the solubility of pharmaceutical drugs in aqueous solutions. As a part of our ongoing effort to identify systems showing hydrotropism and to determine whether dimethylformamide (DMF) behaves as a hydrotrope or not, mixed solvents with varying compositions were tried in the present study for solubilization of individual isomers of chlorobenzoic acid and nitroaniline. These are industrially important as starting materials or intermediates, in the dye and pharmaceutical industries. These isomers show a substantial difference in their solubilities in different organic solvents because of an *ortho* effect (Jagirdar, 1984).

Murthy *et al.* (1981) suggested a possibility of complex formation between water and the amide of the type DMF·3H_2O and DMF·2H_2O, on the basis of the thermal expansion coefficient data of DMF + water mixtures. The region between $0.25 < x_{DMF} < 0.35$ was characterized by strong intercomponent association and has been ascribed to hydrogen-bonding characteristics of the amide. Guarino *et al.* (1985) also had suggested that DMF can bind two water molecules so that a two- or three-dimensional hydrogen-bonded network can be formed. We therefore expected that DMF may form complexes with other molecules, such as nitroanilines, which are capable of forming intra- and intermolecular hydrogen bonds. On the other hand the hydrogen-bonded structure of the DMF + water mixtures may modify the solubility behavior of these solutes.

Experimental section

N,*N*-Dimethylformamide, *o*-chlorobenzoic acid, and *p*-chlorobenzoic acid were from S.d. Fine Chemicals Ltd., Bombay, with a manufacturer's stated purity of 99%, which was verified by high-performance liquid chromatography. Nitroanilines were obtained from Loba Chemie, Bombay, with a purity of 99%+. The nitroanilines were crystallized once from alcohol before use. For each solubility test about 4 g of the solid was placed in a fully baffled glass reactor and mixed solvent of a known composition was added. For DMF + water mixtures of high DMF content more of the solid was added, where necessary. The resulting suspension was stirred for 2 h, which was found to be adequate for equilibrium. The reactor assembly was kept in a thermostatic bath with the temperature maintained at 303 K with an accuracy of ±0.5 K. The calibration for nitroanilines in the UV range was done for solutions of individual isomers in water that gave molar extinction coefficients 22 245 and 8497.4 for *o*-nitroaniline and *p*-nitroaniline, respectively, at the wavelengths of 224.6 nm for *o*-nitroaniline and 227.4 nm for *p*-nitroaniline. For the solubility determination of a nitroaniline, a sample was withdrawn and diluted sufficiently with water so that UV absorbance was obtained between 0.2 and 0.8. Chlorobenzoic acid was determined titrimetrically with a standard NaOH solution using phenolphthalein indicator. Each experiment was conducted in duplicate, and only consistent values have been reported. The relative error in the solubility values from the repeated runs was less than 0.1%.

Results and Discussion

The solubility of each isomer (*A*) increases with increasing volume fraction of DMF (Φ_B) in the mixed solvent. However, changes in the solubility for *o*- and *p*-isomers are not the same. The solubility of chlorobenzoic acids and nitroanilines in the solvent mixture is shown in Figures 1 and 2, respectively.

Chlorobenzoic Acids. The solubility of *p*-chlorobenzoic acid (PCA) in water is 0.08 $g{\cdot}L^{-1}$ and that of *o*-chlorobenzoic acid (OCA) is 2.1 $g{\cdot}L^{-1}$ at 303 K. These values are in excellent agreement with 0.080 $g{\cdot}L^{-1}$ and 2.097 $g{\cdot}L^{-1}$ as reported for PCA and OCA, respectively, by Laddha and Sharma (1978). Upon addition of DMF, initially the solubility of *o*-chlorobenzoic acid rises gradually and is higher than the solubility of *p*-chlorobenzoic acid. However, when Φ_B exceeds 0.4, *p*-chlorobenzoic acid shows a sharp increase in the solubility. On the further increase in Φ_B, the difference between the solubility of the two acids increases significantly. The increase in the solubility of *p*-chlorobenzoic acid is exponential with Φ_B while that of *o*-chlorobenzoic acid shows a sigmoidal variation.

Nitroanilines. The solubility of *o*-nitroaniline (ONA) in water (1.0 $g{\cdot}L^{-1}$) is slightly higher than that of *p*-nitroaniline (0.8 $g{\cdot}L^{-1}$) at 303 K. With an increase in the Φ_B of the solvent mixture, initially the solubility of *p*-nitroaniline (PNA) is higher than that of *o*-nitroaniline. The solubilities of *p*-nitroaniline and *o*-nitroaniline, are 44.5 $g{\cdot}L^{-1}$ and 40.1 $g{\cdot}L^{-1}$ at $\Phi_B = 0.33$. However, as in the case of chlorobenzoic acids, at $\Phi_B = 0.4$, the solubility of ONA rises sharply and exceeds that of PNA. The solubilities of *o*-nitroaniline and *p*-nitroaniline in a mixed solvent at $\Phi_B = 0.4$ are 79 $g{\cdot}L^{-1}$ and 60.1 $g{\cdot}L^{-1}$ and at $\Phi_B = 0.74$, are 820 $g{\cdot}L^{-1}$ and 459 $g{\cdot}L^{-1}$, respectively.

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Table 1. Solubility of Chlorobenzoic Acids and Nitroanilines in DMF (B) + Water (C) at 303 K

o-chlorobenzoic acid		*p*-chlorobenzoic acid		*o*-nitroaniline		*p*-nitroaniline	
x_B	$x_A{}^b$	x_B	x_A	x_B	x_A	x_B	x_A
0	0.000 24	0	0.000 0 09	0	0.000 13	0	0.000 11
0.012	0.000 32	0.012	0.000 12	0.007	0.000 32	0.007	0.000 46
0.025	0.000 40	0.025	0.000 23	0.012	0.000 45	0.012	0.000 72
0.040	0.000 83	0.053	0.000 48	0.024	0.000 74	0.024	0.001 18
0.053	0.001 12	0.072	0.002 14	0.030	0.000 91	0.040	0.003 36
0.072	0.001 81	0.104	0.003 93	0.040	0.001 29	0.065	0.004 58
0.104	0.005 51	0.135	0.013 97	0.053	0.001 68	0.082	0.006 25
0.123	0.006 92	0.189	0.028 33	0.082	0.002 99	0.104	0.007 75
0.160	0.015 42	0.250	0.057 01	0.104	0.004 63	0.118	0.008 99
0.189	0.024 05	0.302	0.081 09	0.118	0.007 22	0.135	0.011 20
0.222	0.036 31	0.402	0.12834	0.136	0.014 67	0.189	0.015 23
0.250	0.044 72	0.497	0.162 79	0.189	0.035 76	0.244	0.030 12
0.337	0.062 44	0.569	0.220 35	0.259	0.088 26	0.315	0.059 38
0.402	0.079 99	0.631	0.254 46	0.315	0.145 38	0.402	0.122 13
0.497	0.093 37	0.678	0.286 12	0.402	0.199 06	0.472	0.16084
0.569	0.103 38	0.816	0.350 23	0.495	0.305 33	0.560	0.236 97
0.678	0.117 79	1.0	0.470 67	0.560	0.346 98	0.677	0.314 81
0.816	0.135 09			0.677	0.402 78	0.816	0.372 08
1.0	0.160 84			0.816	0.474 06	1.0	0.412 14
				1.0	0.543 25		

[a] x_B is the mole fraction of DMF in the mixture on solute-free basis. [b] x_A is the mole fraction of the solute in the saturated solution.

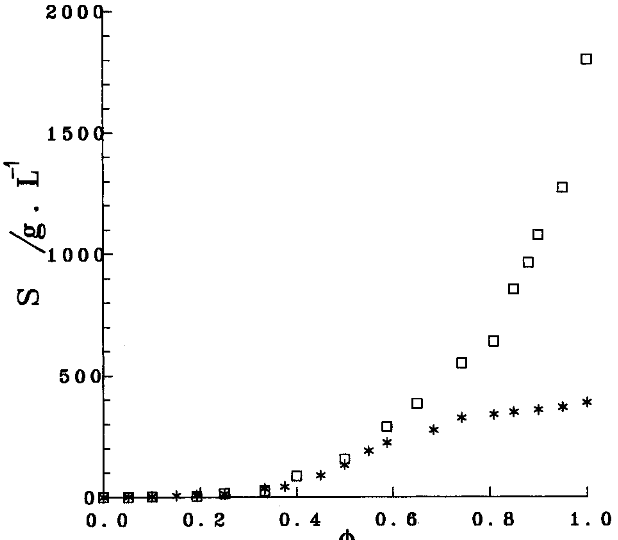

Figure 1. Solubility of chlorobenzoic acids in *N*,*N*-dimethylformamide + water at 303 K: (□) *p*-chlorobenzoic acid; (*) *o*-chlorobenzoic acid. Φ_B is expressed on the solute-free basis.

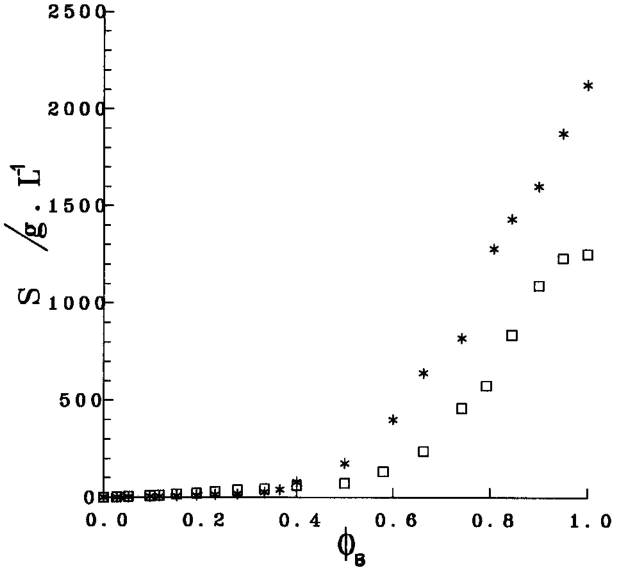

Figure 2. Solubility of nitroanilines in *N*,*N*-dimethylformamide + water at 303 K (□) *p*-nitroaniline; (*) *o*-nitroaniline. Φ_B is expressed on the solute-free basis.

The solubility trend in the case of nitroanilines is exactly opposite to that shown by the chlorobenzoic acids. In both cases, the solubility begins rising sharply only above $\Phi_B = 0.35$. This behavior probably indicates the presence of a collective molecular phenomena in the solution. Taniewska-Osinska *et al.* (1983) explained the viscosity changes of DMF + water with an increase in Φ_B in terms of hydrogen-bonded structures between water and DMF. The solubility increase for a given solute would then depend on the ability of the solute to take part in such hydrogen-bonded structures of the mixed solvent. The selectivity in solubilization may then arise because of complex formation between the solute and DMF in the solution.

Zvaigzne and Acree (1994a,b) suggested a possible mathematical representation for the isothermal solubility of hydrocarbons in a mixed solvent based on either the combined NIBS/Redlich–Kister model

$$\ln x_A^{sat} = x_B^0 \ln(x_A^{sat})_B + x_C^0 \ln(x_A^{sat})_C + x_B^0\, x_C^0 \sum S_i (x_B^0 - x_C^0) \quad (1)$$

or a modified Wilson equation

$$\ln \frac{a_A(s)}{x_A^{sat}} = 1 - \frac{x_B^0\left(1 - \ln \dfrac{a_A(s)}{(x_A^{sat})_B}\right)}{x_B^0 + x_C^0 \Lambda_{BC}} - \frac{x_C^0\left(1 - \ln \dfrac{a_A(s)}{(x_A^{sat})_C}\right)}{x_C^0 + x_B^0 \Lambda_{CB}} \quad (2)$$

where S_i and Λ are the curve fitting parameters, x_B and x_C are the mole fractions of DMF and water, calculated on the solute-free basis, $(x_A)_i$ is the saturated mole fraction solubility of the solute in the pure solvent *i*, and $a_A(s)$ is the activity of pure solid solute which can be approximated from the following equation using the molar enthalpy of fusion ($\Delta_{fus}H$) of the solute at its normal melting point (T_m).

$$\ln a_A(s) = -\frac{\Delta_{fus}H}{RT}\left(1 - \frac{T}{T_m}\right) \quad (3)$$

These models have been successfully used for a number of hydrocarbons in the mixture of organic solvents of different natures and particularly for the sparingly soluble solutes

Table 2. Fitting Parameters for the Modified Wilson Equation

solute	Λ_{B-C}/J·mol^{-1}	Λ_{C-B}/J·mol^{-1}
o-chlorobenzoic acid	0.514	33.89
p-chlorobenzoic acid	0.72	129.49
o-nitroaniline	0.498	35.09
p-nitroaniline	0.402	43.68

(Zvaigzne and Acree, 1994a,b). We tried to fit the data to both of these equations although the solute concentration is too high to ignore the solute-induced changes in the solvent structure. The experimental data could be fitted in the modified Wilson model but not in the combined NIBS/Redlich−Kister model which required a large number of fitting parameters (S_i). Considering that the NIBS/Redlich−Kister model does not consider specific interactions, it is not surprising that data could not be fitted. Even for the modified Wilson model, the relative error (in the range of 10%−39%) is much larger than the experimental uncertainties. However, the trends in the solubility with the solvent composition were correctly predicted by the modified Wilson model. Table 1 gives the solubility data of the aromatic solutes in mole fractions for the saturated solution, and Table 2 gives the fitted parameters for the modified Wilson model. The mole fraction of the solute in the DMF rich solutions is very high considering the high solubility of all the solutes. Under these conditions the solute becomes the major component in the saturated solutions and the amount of water may be insufficient to form the solvent phase.

Conclusions

The solubility of *o*-chlorobenzoic acid, *p*-chlorobenzoic acid, *o*-nitroaniline, and *p*-nitroaniline in DMF + water mixtures has been determined. *p*-Chlorobenzoic acid and *o*-nitroaniline show higher solubility than *o*-chlorobenzoic acid and *p*-nitroaniline, respectively, in DMF + water mixtures with the difference increasing with DMF content of the solvent. The solubilization of the solute may be due to complexation of the solute with DMF. The solubility data can be represented using a modified Wilson model but not by the combined NIBS/Redlich−Kister model.

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