Dyes and Pigments 11 (1989) 191–200

Interaction between Water-Soluble Polymers and Azo Dyes Containing Fluorine Atoms. I. Monoazo Sulphonated Dyes Containing a Trifluoromethyl Group

Kunihiro Hamada,* Seiji Take‡ & Toshiro Iijima§

Department of Polymer Science, Tokyo Institute of Technology, Ookayama, Meguro-ku, Tokyo 152, Japan

(Received 24 August 1988; accepted 30 September 1988)

ABSTRACT

The interaction between sulphonated monoazo dyes containing a trifluoromethyl group and polyvinylpyrrolidone was investigated by means of visible absorption spectrum measurements. To elucidate the effects of fluorine atoms, the corresponding dyes containing a methyl group were also investigated. Dyes having one trifluoromethyl and one sulphonate group exhibited multiple binding equilibria in phosphate buffer and formed aggregates on the polymer chains. However, in pure water a single equilibrium was observed, as in the case of the other dyes. The first binding constant K_1 was determined at 288, 293, 298 and 303 K, and the thermodynamic parameters ΔH *and* ΔS *were obtained. The results suggest that the interaction is greatly affected by the fluorine atoms and sulphonate groups of the dye molecules, as well as by the phosphate ions in solution.*

1 INTRODUCTION

It is well known that dyes containing fluorine atoms such as C.I. Acid Red 266, an acid dye for nylon dyeing, have excellent lightfastness. This property is due to the electronegativity of the fluorine atom, a characterstic which has also been used in designing fine chemicals,[1] as, for example, 5-trifluoromethyluracil, an anti-tumor drug. Nishida *et al.* investigated the

* Present address: Faculty of Textile Science and Technology, Shinshu University, Ueda-shi, Nagano 386, Japan.

‡ Present address: Dai Nippon Printing Co. Ltd, Kashiwa-shi, Chiba 277, Japan.

§ Present address: Jissen Women's University, Hino-shi, Tokyo 191, Japan.

Dyes and Pigments 0143-7208/89/$03·50

interaction between this compound and sodium poly(α, L-glutamate) in aqueous solution[2] and found that the binding of this compound was strengthened through hydrophobic interaction giving larger entropic contributions than those of 5-fluorouracil[3] and 1-(2-tetrahydrofuryl)-5-fluorouracil.[4]

As the chemical shift of ^{19}F-NMR is very sensitive to changes in the microenvironment, small molecules containing ^{19}F atoms have been used as probes in investigations of the mechanisms of interaction between such molecules and macromolecules such as Chymotryspin,[5,6] Human Serum Albumin,[7] DNA,[8,9] Calmodulin,[10,11] and poly(*N*-substituted acrylamides).[12] Recently ^{19}F-NMR has been used to investigate the interaction of drugs containing fluorine atoms with cyclodextrins.[13,14]

In this connection, we synthesized some dyes containing fluorine atoms as probes to obtain information from both ^{19}F-NMR and visible absorption spectroscopy.[15,16] It was found that the dyes containing fluorine atoms had a marked tendency to aggregate in aqueous solution. Thus the dye containing one trifluoromethyl and one sulphonate group showed gelation above 1×10^{-2} mol dm^{-3}.

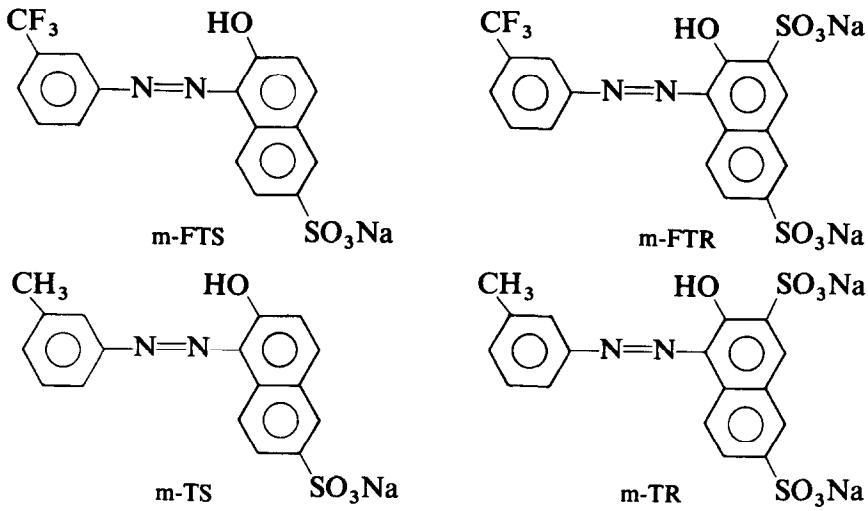
Poly(vinylpyrrolidone), PVP, has been extensively used in investigations of the binding with small molecules such as simple aromatic compounds,[17-25] surfactants,[26,27] dyes,[28-39] and fluorescent probes.[40-42] Takagishi *et al.* determined the thermodynamic parameters for the interaction of Methyl Orange and its homologues with PVP by means of equilibrium dialysis and discussed the role of the hydrophobic interaction.[30-35] They also reported the effects of cosolutes,[32,33] while Sardharwalla & Lawton recently used calorimetric techniques to elucidate those effects.[38] Reeves *et al.* determined the number of consecutive residues of the polymer covered by one dye molecule and the intrinsic binding constant to discuss the effects of dye structure on interaction.[39]

We have used visible absorption spectroscopy to study the binding of the dyes with poly(vinylpyrrolidone), PVP, with a view to ascertaining the effect of the fluorine atom on the interaction. In the present work the binding constants and thermodynamic parameters of the interaction were determined and the results used to discuss the effects of fluorine atoms, sulphonate groups and cosolute species on hydrophobic interaction.

2 EXPERIMENTAL

Four azo dyes, sodium salts of 1-(3-trifluoromethylphenylazo)-2-hydroxy-6-naphthalenesulfonic acid (m-FTS), 1-(3-trifluoromethylphenylazo)-2-hydroxy-3,6-naphthalenedisulfonic acid (m-FTR), 1-(3-methylphenylazo)-2-hydroxy-6-naphthalenesulfonic acid (m-TS), and 1-(3-methylphenylazo)-

2-hydroxy-3,6-naphthalenedisulfonic acid (m-TR) were used. The syntheses of m-FTS and m-FTR are reported in previous papers.[15,16] m-TS and m-TR were synthesized by coupling diazotized m-toluidine with Schaeffer's acid (2-naphthol-6-sulfonic acid) and R acid (2-naphthol-3,6-disulfonic acid), respectively, in an alkaline condition. The dyes were purified by repeated recrystallization from aqueous ethanol (m-TS) and aqueous acetone (m-TR). The purity was confirmed by elemental analysis and thin layer chromatography.



Polyvinylpyrrolidone ($M_w = 360\,000$) was purchased from Tokyo Kasei Kogyo Co. Ltd and used without further purification.

Sample solutions containing polymer and dye in the concentration ratios (P/D) = 50–2000 were prepared. The polymer concentration is expressed in monomer units. The dye concentration was kept constant (in pure water, m-FTS; $3{\cdot}94 \times 10^{-5}$, m-FTR; $2{\cdot}65 \times 10^{-5}$, m-TS; $2{\cdot}55 \times 10^{-5}$, m-TR; $2{\cdot}40 \times 10^{-5}$ mol dm^{-3}, in phosphate buffer, m-FTS; $3{\cdot}74 \times 10^{-5}$, m-FTR; $2{\cdot}73 \times 10^{-5}$, m-TS; $3{\cdot}22 \times 10^{-5}$, m-TR; $2{\cdot}58 \times 10^{-5}$ mol dm^{-3}). pH and the ionic strength of phosphate buffer were 7·10 and 0·011, respectively.

Visible absorption spectra were measured with a Hitachi Double-wavelength, Double-beam Spectrophotometer at 288, 293, 298, and 303 K. The temperature was controlled within $\pm 0{\cdot}1$ K.

3 RESULTS AND DISCUSSION

The difference spectra of m-FTS in the presence of PVP in phosphate buffer solution are shown in Fig. 1. Isosbestic points were observed at P/D = 50–500, but at P/D = 1000 the spectra did not pass through the isosbestic

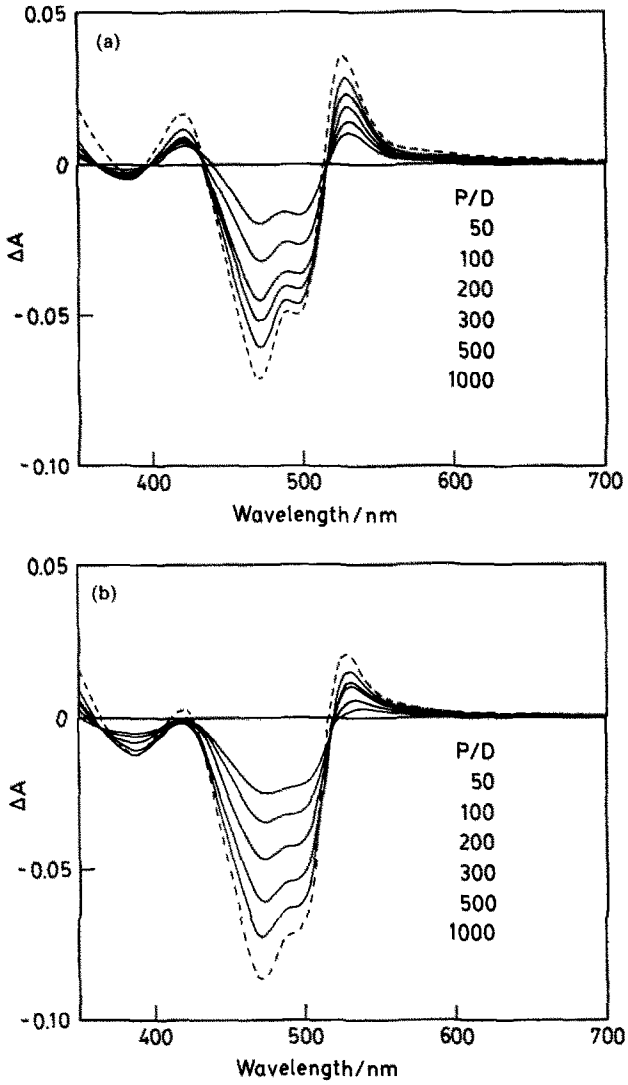


Fig. 1. Difference spectra of m-FTS ($3{\cdot}74 \times 10^{-5}$ mol dm^{-3}) in aqueous PVP phosphate buffer solution. (a) 288 K; (b) 303 K.

points, suggesting the formation of more than one equilibrium at such a high P/D value. The shapes of the spectra varied with temperature. On the other hand, all dye solutions except the m-FTS phosphate buffer solution gave distinct isosbestic points, which did not disappear with increasing temperature. Thus it appears that the m-FTS–PVP system forms more than one equilibrium in phosphate buffer, whereas the other systems form only one equilibrium.

The first binding constant, K_1, was calculated from the difference spectra,

by employing the equation used in the interaction between sodium poly(styrenesulphonate) and *p*-aminoazobenzene derivatives.[43] When the concentrations of the total dye, the total polymer, the bound dye, and the free dye are defined as C_0, C_p, C_b, and C_f, respectively, K_1 is represented by eqn (1), where the polymer concentration is based on the monomer unit:

$$K_1 = \frac{C_b}{(C_p - C_b).C_f} \tag{1}$$

Assuming a very small bound dye concentration, $C_p \gg C_b$,

$$K_1 = \frac{C_b}{C_p.C_f} \tag{2}$$

If ε_b and ε_f are the extinction coefficients of the bound and free dye, respectively, then the observed extinction coefficient, ε, is

$$\varepsilon = \frac{C_b}{C_0}\varepsilon_b + \frac{C_f}{C_0}\varepsilon_f \tag{3}$$

Since $C_0 = C_f + C_b$, eqn (3) can be rewritten as follows:

$$\frac{C_b}{C_f} = \frac{\varepsilon_f - \varepsilon}{\varepsilon - \varepsilon_b} \tag{4}$$

and by substituting eqn (4) in eqn (2), we obtain

$$\varepsilon = \frac{\varepsilon_f - \varepsilon}{C_p} \cdot \frac{1}{K_1} + \varepsilon_b \tag{5}$$

As ε_f is obtained in the absence of PVP, a plot of ε against $(\varepsilon_f - \varepsilon)/C_p$ gives K_1 and ε_b. Ando *et al.* used absorbance instead of the extinction coefficient,[43] and Maruthamuthu & Sobhana employed a modified form of eqn (5) for the binding of anionic dyes to PVP.[36]

Plots of ε against $(\varepsilon_f - \varepsilon)/C_p$ are shown in Fig. 2. In the case of m-FTS in phosphate buffer, ε_b changed with temperature (Fig. 2(a)), whilst in all other cases ε_b was constant. These observations are consistent with a variation of the nature of the m-FTS–PVP complex with temperatures.

The K_1 values of m-FTS in water and in phosphate buffer are shown in Table 1. The values at two wavelengths in water agree within experimental error, but they differ in buffer solution. In all systems other than the m-FTS–PVP solutions, the K_1 values at various wavelengths coincided. This indicates that the interaction between m-FTS and PVP in phosphate buffer involves more than one equilibrium. As we have reported previously,[15,16] m-FTS aggregates in aqueous solution to form polyaggregates when the concentration is higher than 1×10^{-2} mol dm^{-3}. Furthermore, Methyl Orange homologues having long alkyl chains[34] and low molecular

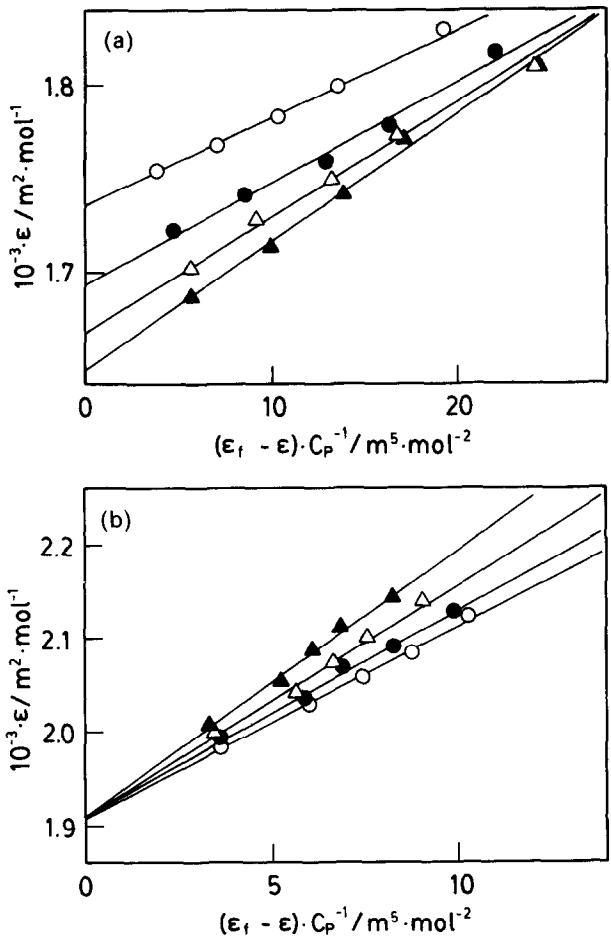


Fig. 2. ε vs $(\varepsilon_f - \varepsilon)/C_p$. ○: 288 K; ●: 293 K; △: 298 K; ▲: 303 K. (a) m-FTS, at 476 nm, in phosphate buffer; (b) m-FTR, at 483 nm, in water.

surfactants[27] were known to form aggregates by the addition of PVP. On the basis of these results, it is estimated that PVP and phosphate ions enhance the aggregation of m-FTS and therefore the interaction between m-FTS and PVP in phosphate buffer is not simple.

Table 2 shows K_1 determined at the wavelength of maximum absorption. The K_1 values decreased with an increase in the number of sulphonate groups and introduction of fluorine atoms. It is worthwhile to mention that the introduction of fluorine atoms into the dye molecule increases the solubility in water, i.e. the solubility increases in the order of m-TS < m-FTS < m-TR < m-FTR, which corresponds to the decreasing order of K_1 in water (m-TS > m-FTS > m-TR > m-FTR). This means that the binding affinity to PVP decreases with increasing water solubility. K_1 in phosphate buffer also

TABLE 1
K_1 and ε_b Values in m-FTS–PVP Systems

		298 K	*293 K*	*298 K*	*303 K*
In water					
K_1[a]	472 nm	92 ± 11	84 ± 8	76 ± 9	73 ± 17
	495 nm	102 ± 13	93 ± 10	81 ± 10	78 ± 18
ε_b[b]	472 nm	1 460 ± 20	1 450 ± 20	1 450 ± 20	1 440 ± 40
	495 nm	1 380 ± 30	1 370 ± 10	1 360 ± 20	1 350 ± 30
In phosphate buffer					
K_1[a]	476 nm	215 ± 6	183 ± 10	162 ± 11	147 ± 8
	497 nm	251 ± 11	218 ± 11	200 ± 10	102 ± 15
ε_b[b]	476 nm	1 736 ± 2	1 693 ± 4	1 667 ± 6	1 649 ± 6
	497 nm	1 522 ± 2	1 488 ± 4	1 472 ± 4	1 450 ± 8

[a] $dm^3\,mol^{-1}$.
[b] $m^2\,mol^{-1}$.

decreased in the order of m-TS > m-TR > m-FTR. One can thus conclude that solubility of dyes in water is a key factor in the determination of K_1.

Thermodynamic parameters were determined from the temperature dependence of K_1, which is related to the enthalpy change ΔH and entropy change ΔS as shown in eqn (6):

$$\ln K_1 = -\frac{\Delta H}{R}\cdot\frac{1}{T} + \frac{\Delta S}{T} \tag{6}$$

where T is the absolute temperature and R is the gas constant. ΔH and ΔS were determined from the plot of $\ln K_1$ against $1/T$ (van't Hoff plot) and the

TABLE 2
K_1, ε_b and ε_f Values Determined by eqn (2)

	K_1 ($dm^3\,mol^{-1}$)				ε_b ($m^2\,mol^{-1}$)	ε_f ($m^2\,mol^{-1}$)
	288 K	*293 K*	*298 K*	*303 K*		
In water						
m-FTS (472 nm)	92 ± 11	84 ± 8	76 ± 9	73 ± 17	1 450	1 794
m-FTR (483 nm)	48 ± 2	46 ± 2	40 ± 2	35 ± 2	1 920	2 223
m-TS (479 nm)	128 ± 3	118 ± 4	101 ± 4	97 ± 4	1 640	2 094
m-TR (485 nm)	67 ± 3	63 ± 1	57 ± 2	50 ± 2	2 060	2 592
In phosphate buffer						
m-FTR (483 nm)	58 ± 3	48 ± 6	36 ± 4	30 ± 1	1 900	2 231
m-TS (478 nm)	191 ± 15	159 ± 14	128 ± 9	97 ± 6	1 550	1 984
m-TR (485 nm)	111 ± 12	87 ± 16	74 ± 3	57 ± 4	2 100	2 589

TABLE 3
Thermodynamic Parameters

	ΔH ($kJ\,mol^{-1}$)	ΔS ($J\,mol^{-1}\,K^{-1}$)
In water		
m-FTS	$-11{\cdot}6 \pm 1{\cdot}3$	-3 ± 4
m-FTR	-16 ± 2	-22 ± 8
m-TS	-14 ± 2	-9 ± 7
m-TR	$-14{\cdot}2 \pm 1{\cdot}7$	-14 ± 6
In phosphate buffer		
m-FTR	-33 ± 2	-80 ± 8
m-TS	-33 ± 2	-69 ± 8
m-TR	$-31{\cdot}4 \pm 1{\cdot}9$	-70 ± 7

values are shown in Table 3. As Reeves *et al.* pointed out,[39] apparent entropy changes reported in some papers[30-33] vary from unit to unit of K_1. It is, therefore, unimportant to discuss whether ΔS values are positive or negative; the values should be treated as relative ones. Both the ΔH and ΔS values in phosphate buffer were more negative than those in water, which suggests that the binding is more entropic in water than in buffer solution. Takagishi *et al.* attributed this difference to conformational changes of the polymer.[32] The proposal of the non-covalent cross-linking of the polymer chains by bound cosolute small molecules is suggestive.[22] When the polymer has a compact conformation, the cation loci of the polymer (PVP carries partially positive charge on the nitrogen atoms[30,44]) are hardly exposed to water, and the electrostatic interaction of the anionic dyes with the polymer is hindered, resulting in ΔH becoming less negative. Furthermore, the compact conformation is believed to form a less hydrophilic environment, which probably interacts with the hydrophobic part of the dye molecules with release of the hydrated water, thus resulting in more entropic binding. Thus the compact conformation increases the contribution of hydrophobic interactions. On the other hand, when the polymer chain is extended, the polar groups are exposed to water, and consequently the binding becomes electrostatic, i.e. enthalpic. This suggests that, in water, PVP has a compact conformation, whereas in phosphate buffer it has a highly extended conformation. Therefore, the effects of phosphate ions in buffer on the conformation of PVP may be explained as follows. If phosphate ions break the structure of water, more water is available for the hydration of PVP, resulting in extended polymer chains. Also, if phosphate ions interact with the cation loci of the polymer, the polymer chains would be extended because of the electrostatic repulsion between the charges of adsorbed

phosphate anions. Nakagaki & Shimabayashi reported that thiocyanate ions behave as a water structure-breaker, and interact with PVP.[45] It is possible that phosphate ions behave in a similar manner.

The difference in the thermodynamic parameters of the dyes may be interpreted by considering the conformation of PVP in each solution. The ΔS values for the dibasic dyes in water were more negative than those for the monobasic dyes: the binding of the monobasic dyes with the polymers is more entropic than that of the dibasic dyes. This suggests that the less hydrophilic dyes enter more easily into the less hydrophilic environment formed by PVP in water. On the other hand, in phosphate buffer, the difference in the thermodynamic parameters was very small, suggesting that electrostatic interactions between the charges of the dyes and the polymers are dominant because of the highly extended conformation. Effects of fluorine atoms on the thermodynamic parameters are hardly noticeable in the seven systems (Table 3). As mentioned above, the behavior of m-FTS in phosphate buffer is peculiar and m-FTS is thought to be aggregated on the extended polymer chains.

4 CONCLUSIONS

The interaction of the dyes with PVP reflects some of their properties in aqueous solution. The higher the solubility of the dyes in water, the lower is the affinity to PVP. Phosphate ions affect the conformation of PVP, as has been reported for the other cosolutes.[32,33,38] m-FTS, which aggregates easily in water, aggregates on the polymer chains when they are extended by phosphate ions. Thus the effects of fluorine atoms in the dyes on their binding with PVP and on their solution properties can be consistently discussed.

REFERENCES

1. Banks, R. E. (ed.), *Organofluorine Chemicals and Their Industrial Applications*. Ellis Horwood, Chichester, 1979.
2. Nishida, K., Ando, Y. & Yoshida, H., *Colloid Polym. Sci.*, **261** (1983) 467.
3. Nishida, K., Ando, Y. & Mochinaga, N., *Colloid Polym. Sci.*, **258** (1980) 111.
4. Nishida, K., Ando, Y. & Mochinaga, N., *Colloid Polym. Sci.*, **259** (1981) 350.
5. Gerig, J. T., Halley, B. A. & Ortiz, C. E., *J. Am. Chem. Soc.*, **99** (1977) 6219.
6. Tsunematsu, H., Nishikawa, H. & Berliner, L. J., *J. Biochem.*, **96** (1984) 349.
7. Gerig, J. T., Katz, K. E. & Reinheimer, J. D., *Biochim. Biophys. Acta*, **534** (1978) 196.
8. Mirau, P. A., Shafer, R. H. & James, T. L., *Biochemistry*, **21** (1982) 615.
9. Mirau, P. A., Shafer, R. H., James, T. L. & Bolton, P. H., *Biopolymers*, **21** (1982) 909.
10. Shimizu, T. & Hatano, M., *FEBS Lett.*, **160** (1983) 182.

11. Shimizu, T., Hatano, M., Muto, Y. & Nozawa, Y., *FEBS Lett.*, **166** (1984) 373.
12. Gerigand, J. T. & Loehr, D. T., *J. Phys. Chem.*, **84** (1980) 1417.
13. Brereton, I. M., Spotswood, T. M., Lincoln, S. F. & Williams, E. H., *J. Chem. Soc., Faraday Trans.*, 1, **80** (1984) 3147.
14. Pisaniello, D. L., Lincoln, S. F. & Coates, J. H., *J. Chem. Soc., Faraday Trans.*, 1, **81** (1985) 1247.
15. Hamada, K., Kubota, H., Ichimura, A., Iijima, T. & Amiya, S., *Ber. Bunsenges. Phys. Chem.*, **89** (1985) 859.
16. Hamada, K., Take, S., Iijima, T. & Amiya, S., *J. Chem. Soc., Faraday Trans.*, 1, **82** (1986) 3141.
17. Molyneux, P. & Frank, H. P., *J. Am. Chem. Soc.*, **83** (1961) 3169.
18. Molyneux, P. & Frank, H. P., *J. Am. Chem. Soc.*, **83** (1961) 3175.
19. Molyneux, P. & Frank, H. P., *J. Am. Chem. Soc.*, **86** (1964) 4753.
20. Molyneux, P. & Cornarakis-Lentzos, M., *Colloid Polym. Sci.*, **257** (1979) 855.
21. Molyneux, P. & Vekavakayanondha, S., *J. Chem. Soc., Faraday Trans.*, 1, **82** (1986) 291.
22. Molyneux, P. & Vekavakayanondha, S., *J. Chem. Soc., Faraday Trans.*, 1, **82** (1986) 635.
23. Plaizier-Vercamman, J. A. & De Nève, R. E., *J. Pharm. Sci.*, **69** (1980) 1403.
24. Plaizier-Vercamman, J. A. & De Nève, R. E., *J. Pharm. Sci.*, **70** (1981) 1253.
25. Plaizier-Vercamman, J. A. & De Nève, R. E., *J. Pharm. Sci.*, **71** (1982) 552.
26. Fishman, M. L. & Eirich, R., *J. Phys. Chem.*, **75** (1971) 3135.
27. Lissi, E. A. & Abuin, E., *J. Colloid Interface Sci.*, **105** (1985) 1.
28. Frank, H. P., Barkin, S. & Eirich, F. R., *J. Phys. Chem.*, **61** (1957) 1375.
29. Klotz, I. M. & Shikama, K., *Arch. Biochem. Biophys.*, **123** (1968) 551.
30. Takagishi, T. & Kuroki, N., *J. Polym. Sci., Polym. Chem. Ed.*, **11** (1973) 1889.
31. Takagishi, T., Nakagami, K., Imajo, K. & Kuroki, N., *J. Polym. Sci., Polym. Chem. Ed.*, **14** (1976) 923.
32. Takagishi, T., Imajo, K., Nakagami, K. & Kuroki, N., *J. Polym. Sci., Polym. Chem. Ed.*, **15** (1977) 31.
33. Takagishi, T. & Kuroki, N., *J. Polym. Sci., Polym. Chem. Ed.*, **18** (1980) 259.
34. Takagishi, T., Fujii, S. & Kuroki, N., *J. Colloid Interface Sci.*, **94** (1983) 114.
35. Takagishi, T., Yoshikawa, K., Kuroki, N., Kozuka, H. & Mitsuishi, M., *J. Polym. Sci., Polym. Chem. Ed.*, **22** (1984) 185.
36. Maruthamuthu, M. & Sobhana, M., *J. Polym. Sci., Polym. Chem. Ed.*, **17** (1979) 3159.
37. Maruthamuthu, M. & Dhandavel, R., *Makromol. Chem., Rapid Commun.*, **1** (1980) 633
38. Sardharwalla, I. & Lawton, J. B., *Polymer*, **26** (1985) 751.
39. Reeves, R. L., Harkaway, S. A. & Sochor, A., *J. Polym. Sci., Polym. Chem. Ed.*, **19** (1981) 2427.
40. Killmann, E. & Bittler, R., *J. Polym. Sci.*, C, **39** (1972) 247.
41. Takagishi, T., Naoi, Y. & Kuroki, N., *J. Polym. Sci., Polym. Chem. Ed.*, **15** (1977) 2789.
42. Takagishi, T., Naoi, Y. & Kuroki, N., *J. Polym. Sci., Polym. Chem. Ed.*, **16** (1978) 2663.
43. Ando, Y., Komiyama, J. & Iijima, T., *Nippon Kagaku Kaishi* (1978) 1537.
44. Molyneux, P. & Ahmed, G. S., *Kolloid Z. Z. Polym.*, **251** (1973) 310.
45. Nakagaki, M. & Shimabayashi, S., *Nippon Kagaku Kaishi* (1973) 207.