STUDIES IN THE RELATIONSHIP BETWEEN MOLECULAR STRUCTURE AND CHROMATOGRAPHIC BEHAVIOUR*

X. THE CHROMATOGRAPHIC BEHAVIOUR OF ALKYLPHENOLS, SOME ARYLPHENOLS AND SOME ALKOXYPHENOLS ON THIN LAYERS OF CELLULOSE IMPREGNATED WITH POLYAMIDE

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INTRODUCTION

In a previous paper[1], we have briefly reviewed the use of polyamide surfaces in the chromatography of phenols. We chromatographed a number of 2-alkyl phenols on cellulose–polyamide surfaces using both a non-aqueous eluent system (cyclohexane–acetic acid), and an aqueous one (aqueous acetic acid). The results obtained were compared with those obtained for the same phenols chromatographed:

(i) on alumina surfaces with a non-aqueous eluent system [cyclohexane][2];

(ii) by reversed-phase thin-layer partition chromatography on cellulose impregnated with ethyl oleate as the stationary phase and aqueous ethanol as the mobile phase[3].

From these comparisons, it was possible to evaluate the mechanism of the chromatographic process and to account for the alleged duality of behaviour of polyamide surfaces[4–6].

It was stated that the mechanism was a two-stage process involving:

(i) the adsorption of the phenols on to the polyamide surface by hydrogen bond formation between the phenolic group and the CONH groups of the surface[7–13].

(ii) the desorption of the phenols by solvation of the molecule with the mobile phase. In non-aqueous eluent systems, the solvation site was the hydrophobic part of the molecule, while in aqueous eluent systems, solvation of the phenolic group itself occurred.

It was shown that the change in the site of solvation offered a more rational explanation of the reversal of R_F value order with increasing chain length of the substituent group than did the previously suggested[4–7] change in the nature of the polyamide surface from a polar one to an apolar one.

For the small number of 2-alkyl phenols chromatographed, fairly regular changes in R_F values occurred with an increase in the chain length of the substituent group[1]. Because similar changes in R_F values have been reported for phenols substituted

* For Parts I, II, V, VI and IX of this series, see refs. 17, 18, 2, 3 and 1, respectively.

in the 4-position when chromatographed on paper impregnated with polyamide[12], and on thin layers of polyamide[14,15], it was decided to make a more thorough investigation of the validity of the MARTIN[16] additivity principle for alkyl phenols chromatographed on polyamide surfaces. We have chromatographed a relatively large series of alkylphenols, some arylphenols and some alkoxyphenols on the cellulose–polyamide surface previously described[1].

EXPERIMENTAL

The thin layers of cellulose impregnated with polyamide were prepared as previously described[1].

A solution of polyamide in formic acid (11 ml), cellulose (13.5 g) and formic acid (74 ml) was slurried together and used to coat five glass plates (20 × 20 cm) with an applied thickness of 0.3 mm using a Shandon* thin-layer applicator.

The layers were air-dried for 24 h at a constant temperature of 25 ± 0.5°. They were activated for 15 min at 80°, after which they were cooled in an evacuated desiccator.

Eluent systems

The following eluents were used:

(1) cyclohexane–acetic acid (93:7, v/v);

(2) aqueous acetic acid (10 %).

The components of the eluent systems were purified before preparing the eluents, by the methods previously described[1].

Application of the phenols

The phenols (1 μl of 0.25 % w/v solutions) were applied to the layers by our multiple spotting technique[18], and chromatographed by an ascending technique, at a constant temperature of 25 ± 0.5°, in our double saturation chamber[18]. The solvent front travelled 14.5 ± 0.5 cm in 2 h.

Detection of the phenols

They were detected, as yellow spots on a purple background, by spraying the layers with an alkaline solution of potassium permanganate.

RESULTS

The R_F values obtained, together with the R_M values derived from them are quoted in Table I. The R_F values are the mean of at least four values obtained from layers carrying phenol as an internal standard. The values for phenol on each plate did not differ by more than ± 0.01 R_F unit from the predetermined mean value for phenol in each eluent system. The values for the individual phenols were also within ± 0.01 R_F units of the mean values quoted.

In the ensuing discussion and in all subsequent tables, the eluent system, cyclohexane–acetic acid (93:7, v/v) is referred to as System 1, and the eluent system, aqueous acetic acid (10 % v/v) is referred to as System 2.

* Available from Shandon Scientific Co. Ltd., 65 Pound Lane, London, N.W. 10.

TABLE I

Key	Phenol	System 1		System 2	
		R_F	R_M	R_F	R_M
(a) Methylated phenols					
1	Phenol	0.160	+0.720	0.620	−0.213
2	2-Methyl-	0.280	+0.410	0.380	+0.213
3	3-Methyl-	0.200	+0.602	0.440	+0.105
4	4-Methyl-	0.210	+0.580	0.430	+0.123
5	2,3-Dimethyl-	0.345	+0.279	0.350	+0.269
6	2,4-Dimethyl-	0.360	+0.250	0.340	+0.288
7	2,5-Dimethyl-	0.350	+0.269	0.350	+0.269
8	2,6-Dimethyl-	0.570	−0.123	0.230	+0.525
9	3,4-Dimethyl-	0.260	+0.454	0.380	+0.213
10	3,5-Dimethyl-	0.270	+0.432	0.380	+0.213
11	2,3,4-Trimethyl-	0.375	+0.223	0.270	+0.432
12	2,3,5-Trimethyl-	0.385	+0.203	0.260	+0.454
13	2,3,6-Trimethyl-	0.700	−0.368	0.000	—
14	2,4,5-Trimethyl-	0.420	+0.140	0.250	+0.477
15	2,4,6-Trimethyl-	0.700	−0.368	0.000	—
16	3,4,5-Trimethyl-	0.305	+0.358	0.300	+0.368
17	2,3,4,5-Tetramethyl-	0.430	+0.123	0.200	+0.602
18	2,3,4,6-Tetramethyl-	0.790	−0.575	0.000	—
19	2,3,5,6-Tetramethyl-	0.790	−0.575	0.000	—
(b) Straight chain monoalkyl-substituted phenols substituted in the 3- and/or 4-positions					
1	Phenol	0.160	+0.720	0.620	−0.213
3	3-Methyl-	0.200	+0.602	0.440	+0.105
4	4-Methyl-	0.210	+0.580	0.430	+0.123
20	3-Ethyl-	0.290	+0.398	0.310	+0.348
21	4-Ethyl-	0.290	+0.398	0.310	+0.348
22	4-*n*-Propyl	0.350	+0.269	0.240	+0.501
23	4-*n*-Butyl-	0.390	+0.195	0.090	+1.005
24	4-*n*-Amyl-	0.430	+0.123	0.000	—
25	4-*n*-Nonyl	0.530	+0.052	0.000	—
(c) A comparison of straight chain monoalkyl-substituted phenols with their polymethylated isomers					
1	Phenol	0.160	+0.710	0.620	−0.213
3	3-Methyl-	0.200	+0.602	0.440	+0.105
9	3,4-Dimethyl-	0.260	+0.454	0.380	+0.213
10	3,5-Dimethyl-	0.270	+0.432	0.380	+0.213
20	3-Ethyl-	0.290	+0.398	0.310	+0.348
21	4-Ethyl-	0.290	+0.398	0.310	+0.348
16	3,4,5-Trimethyl-	0.350	+0.269	0.300	+0.368
22	4-*n*-Propyl-	0.350	+0.269	0.240	+0.501
(d) The effect of chain branching in monoalkyl-substituted phenols containing no groups ortho to the phenolic group					
22	4-*n*-Propyl	0.350	+0.269	0.240	+0.501
26	4-Isopropyl-	0.370	+0.231	0.245	+0.489
23	4-*n*-Butyl-	0.390	+0.195	0.090	+1.005
27	4-*sec.*-Butyl-	0.390	+0.195	0.140	+0.789
28	3-*tert.*-Butyl-	0.410	+0.158	0.195	+0.616
29	4-*tert.*-Butyl-	0.390	+0.195	0.210	+0.580
24	4-*n*-Amyl-	0.430	+0.123	0.000	—
30	4-*sec.*-Amyl-	0.410	+0.158	0.060	+1.195
31	4-*tert.*-Amyl-	0.410	+0.158	0.120	+0.865
32	4-(3-Methylbutyl)-	0.360	+0.250	0.100	+0.954
33	4-*tert.*-Octyl-	0.495	+0.008	0.000	—

(continued on p. 119)

TABLE I (*continued*)

Key	*Phenol*	*System 1*		*System 2*	
		R_F	R_M	R_F	R_M
(*e*) *4-Mono-substituted phenols containing other structural features*					
1	Phenol	0.160	+0.720	0.620	0.213
22	4-*n*-Propyl	0.350	+0.269	0.240	+0.501
34	4-Allyl-	0.275	+0.421	0.374	+0.223
23	4-*n*-Butyl-	0.390	+0.195	0.090	+1.005
24	4-*n*-Amyl-	0.430	+0.123	0.000	—
35	4-Crotyl-	0.340	+0.288	0.210	+0.580
36	4-Cyclopentyl-	0.375	+0.223	0.100	+0.954
37	4-Cyclopent-2-enyl	0.335	+0.298	0.180	+0.695
38	4-Cyclohexyl-	0.390	+0.195	0.050	+1.279
39	4-Phenyl-	0.190	+0.630	0.095	+0.979
40	4-Benzyl-	0.280	+0.410	0.090	+1.005
41	4-Cumyl-	0.370	+0.231	0.035	+1.440
(*f*) *Polyalkyl-substituted phenols containing no substituent ortho to the phenolic group*					
22	4-*n*-Propyl-	0.350	+0.269	0.240	+0.501
42	3-Methyl-5-ethyl-	0.360	+0.250	0.310	+0.348
43	3-Methyl-4-isopropyl	0.385	+0.203	0.210	+0.580
44	3-Methyl-5-isopropyl	0.390	+0.195	0.215	+0.562
45	3-Methyl-5-*sec.*-butyl	0.440	+0.105	0.090	+1.005
46	3,5-Di-*tert.*-butyl-	0.590	−0.158	0.020	+1.690
(*g*) *Alkyl-substituted phenols containing one group ortho to the phenolic group*					
1	Phenol	0.160	+0.720	0.620	−0.213
2	2-Methyl	0.280	+0.410	0.380	+0.213
47	2-Ethyl	0.370	+0.231	0.260	+0.454
48	2-*n*-Propyl	0.430	+0.123	0.190	+0.630
49	2-*sec.*-Butyl-	0.500	0.000	0.120	+0.865
50	2-*tert.*-Butyl-	0.550	−0.087	0.000	—
51	2-*n*-Octyl-	0.760	−0.500	0.000	—
52	2-Allyl	0.385	+0.203	0.335	+0.298
53	2-Phenyl	0.490	+0.017	0.150	+0.750
54	2-Cyclohexyl-	0.480	+0.035	0.060	+1.195
55	2-Methyl-4-*tert.*-butyl	0.540	−0.070	0.160	+0.720
56	2-Methyl-4-octyl	0.745	−0.466	0.000	—
57	2-*tert.*-Butyl-3-methyl-	0.615	−0.203	0.070	+1.124
58	2-*tert.*-Butyl-4-methyl-	0.610	−0.195	0.080	+1.061
59	2-Octyl-4-methyl-	0.835	−0.703	0.000	—
(*h*) *Alkyl-substituted phenols containing two groups ortho to the phenolic group*					
1	Phenol	0.160	+0.720	0.620	−0.213
8	2,6-Dimethyl-	0.570	−0.123	0.230	+0.525
60	2,6-Dimethyl-4-*n*-propyl-	0.825	−0.674	0.000	—
61	2,6-Dimethyl-4-allyl-	0.730	−0.432	0.000	—
62	2,6-Di-*tert.*-butyl-	0.965	−1.444	0.000	—
63	2-Methyl-4,6-di-*tert.*-butyl	0.960	−1.377	0.000	—
64	2,6-Di-*tert.*-butyl-4-methyl-	0.960	−1.377	0.000	—
(*i*) *Alkoxyphenols*					
65	2-Methoxy	0.315	+0.338	0.510	−0.017
66	3-Methoxy-	0.090	+1.005	0.545	−0.078
67	4-Methoxy-	0.090	+1.005	0.605	−0.185
68	3,5-Dimethoxy-	0.000	—	0.360	+0.250
69	4-Ethoxy-	0.165	+0.704	0.550	−0.087

(*continued on p. 120*)

TABLE I (*continued*)

Key	*Phenol*	*System 1*		*System 2*	
		R_F	R_M	R_F	R_M
70	4-Cyclopentyloxy-	0.390	+ 0.195	0.260	+ 0.454
71	4-Heptoxy-	0.485	+ 0.027	0.030	+ 1.510
72	4-Dodecyloxy-	0.555	— 0.096	0.000	—
73	4-Tetradecyloxy	0.600	— 0.176	0.000	—
74	4-Hexadecyloxy-	0.620	— 0.213	0.000	—
75	4-Phenoxy-	0.310	+ 0.348	0.120	+ 0.865
76	3,5-Carbomethoxy-	0.020	+ 1.690	0.360	+ 0.250

To assist the discussion of results, the R_F/R_M values in Table I are grouped under suitable headings. Where the R_F/R_M values of a given phenol are found under more than one heading, this is to enable comparisons to be made more easily.

DISCUSSION

For convenience, the phenols are divided into arbitrary groups similar to those considered for the adsorption chromatography of these compounds on aluminium surfaces[2], and by reversed-phase thin-layer chromatography on ethyl oleate surfaces[3].

(*a*) *Methylated phenols*

The R_F/R_M values are given in Table I (a). From these, and from Figs. 1 and 2, it can be seen that the methylated phenols can again be grouped according to the number of *ortho* groups present in the molecule. For System 1, the R_F values increase with the number of *ortho* groups, as was found to be the case for adsorption on alumina[2], while for System 2 the R_F values decrease with an increase in the number of *ortho* groups, as was found for the reversed-phase system[3].

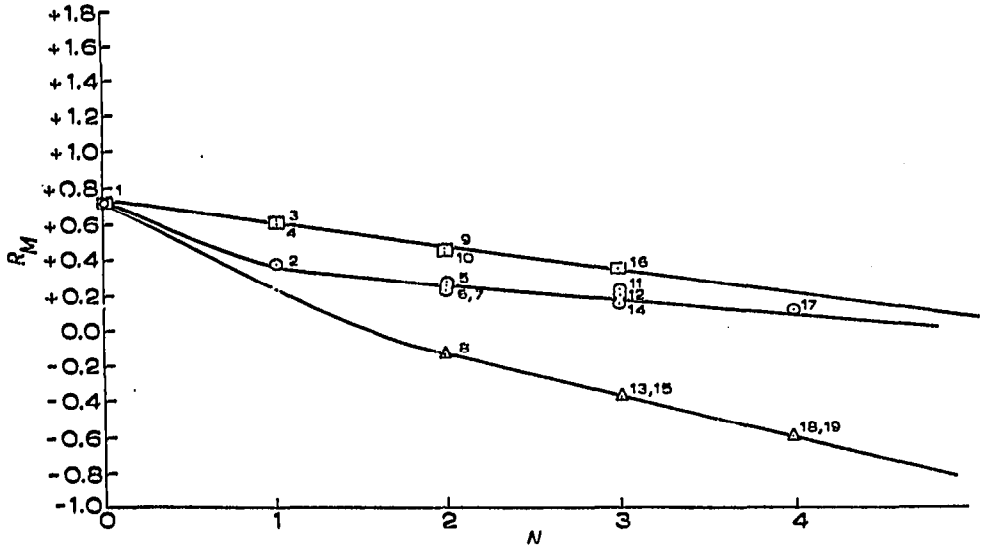

Fig. 1. R_M values (System 1) for methylated phenols *vs.* number of carbon atoms in the side chains. (□) Phenols with no groups *ortho* to the phenolic group; (⊙) phenols with one group *ortho* to the phenolic group; (△) phenols with two groups *ortho* to the phenolic group.

However, it can be seen from Figs. 1 and 2 and Table I (a) that the addition of the second *ortho* substituent to the ring has a greater effect in System 1 than in System 2. These results parallel the effect of the addition of the second *ortho* substituent to the ring in the adsorption chromatography[2] and partition chromatography respectively[3]. It is suggested that the reasons for this lie in the natures of the two

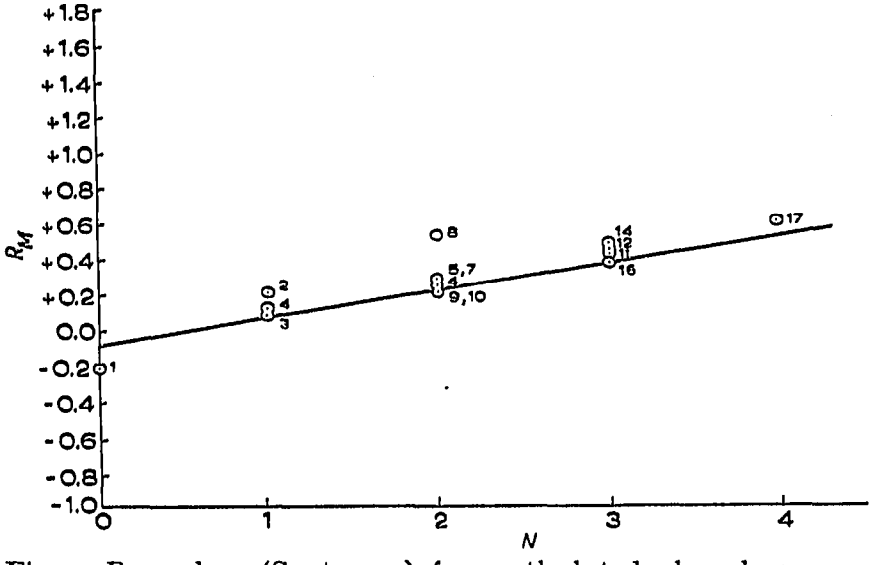

Fig. 2. R_M values (System 2) for methylated phenols *vs.* number of carbon atoms in the side chains.

systems. In System 1, the approach of the phenolic group to the surface is partially hindered by the presence of methyl group in the 2-position. This results in a weakening of the hydrogen bond formed between the phenolic group and the surface, and hence the easier removal of the phenol as a consequence of solvation of the hydrophobic part of the molecule by the non-aqueous eluent. In System 2, however, a different mechanism of solvation of the molecule obtains, *i.e.* the solvation of the phenolic group. Thus once the phenolic/substrate hydrogen bond is broken removal of the phenols into the mobile phase depends upon solvation of the phenolic group. HEINEN[19], has shown that for 2,6-dimethylphenol, steric inhibition of solvation of the phenolic group by water is negligible, but by acetone it is considerable. It is thus probable, as was suggested when the same phenols were chromatographed by reversed-phase thin-layer partition chromatography[3], that in the aqueous acetic acid eluent of System 2 some steric inhibition of solvation of the phenolic group occurs but that the amount is small. These results therefore give added support to our proposed mechanism for the behaviour of phenols chromatographed on polyamide surfaces[1].

Within each group of methylated phenols, *i.e.* the phenols containing no *ortho*, 1 *ortho* and 2 *ortho* substituents, it is now necessary to consider the effect of the addition of further methyl groups to the 3-, 4- and/or 5-positions.

System 1. In each of the three groups, the presence of additional methyl groups results in a regular change in R_F/R_M values of the methyl-substituted phenols relative to the parent phenol (Figs. 1 and 2). This is in direct contrast to the behaviour of these phenols in the alumina adsorption system, where the addition of methyl groups to the 3- and/or 4-positions had negligible effect on the R_F values relative

to the parent compound, and suggests that, as is to be expected, the hydrogen bond between the phenolic hydrogen and the substrate is weaker than the phenolic oxygen/hydroxylated alumina hydrogen bond. Thus this former bond would appear to be susceptible to fine changes in molecular constitution. Three possible reasons exist for this:

(1) Here the bond is broken by competitive hydrogen bonding involving the acetic acid of the eluent.

(2) A weakening of the hydrogen bond as a consequence of electron repulsion into the ring by the methyl group(s). This will cause an increase in electron density at the hydrogen atom so weakening the phenolic hydrogen/substrate hydrogen bond.

(3) An increase in solubility of the non-polar part of the molecule in the mobile phase by the normal process of dissolution.

It is suggested that (1) and (3) will undoubtedly operate, but the operation of (2) is small, if indeed it operates at all. Evidence for this will be given when the other alkyl phenols are considered below, but it suggests a further parallel with the alumina adsorption systems where it was also observed that electronic effects were relatively unimportant.

Fig. 1 indicates the approximate validity of the MARTIN[16] relation.

System 2. Here, the addition of one or more methyl groups to the ring results in a decrease in the R_F values in all three groups, thus paralleling the behaviour of the same phenols in the reversed-phase systems. Fig. 2 shows that the MARTIN[16] relation is valid for Groups 1 and 2. A study of the relation cannot be extended to the di-*ortho* compounds because only the 2,6-dimethylphenol moves in this system, the remaining substituted 2,6-dimethylphenols remaining at the point of application.

(*b*) *Straight chain monoalkyl-substituted phenols substituted in the 3- and/or 4-positions*

Table I (b) and Fig. 3 show that in System 1, the R_F values increase with an increase in chain length and the R_M values decrease but that the changes are not regular. Fig. 3 shows that the MARTIN[16] relation is valid for an alkyl straight chain con-

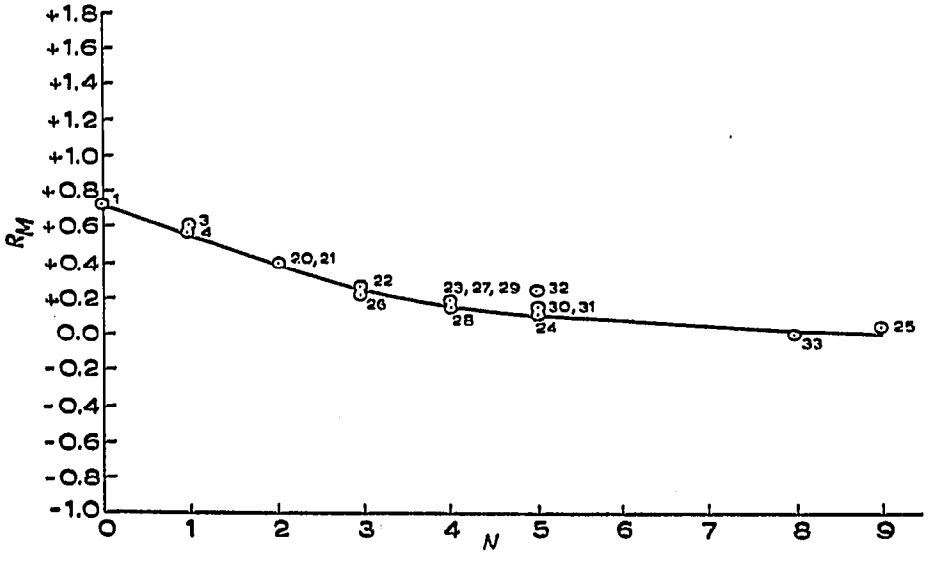

Fig. 3. R_M values (System 1) for 3- and 4-alkyl-substituted phenols *vs.* number of carbon atoms in the side chains.

taining up to five carbon atoms, but for a chain length of between five and nine carbon atoms the increase in R_F values is small and is not in agreement with that suggested by the equations based on the MARTIN postulates. It is obvious that in this case, a real deviation from the MARTIN[16] relation occurs. In reviewing the many works

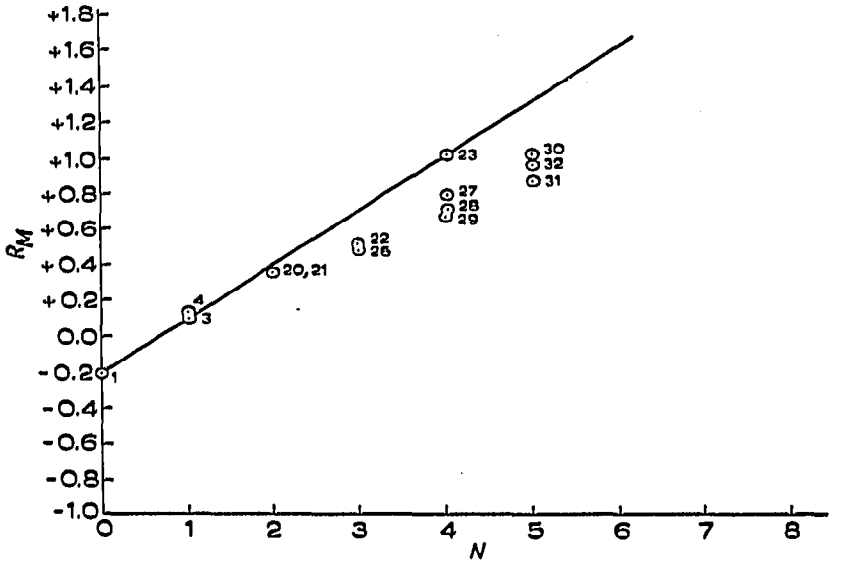

Fig. 4. R_M values (System 2) for 3- and 4-alkyl-substituted phenols *vs.* number of carbon atoms in the side chains.

in which failure of the MARTIN relation is reported, GREEN and MARCINKIEWICZ[20] were of the opinion that the reason for the failure of the relation was lack of attention to the standardisation of extra-molecular factors by the several authors. They also reported that the MARTIN[16] relation is better obeyed when polar eluents are used, even under non-ideal conditions. In this present work, every extra-molecular factor which is known to affect chromatographic behaviour has been standardised, and moreover the eluent, cyclohexane–acetic acid, is polar. The results therefore represent a real failure of the MARTIN equation when the side chain length has reached a limiting number of carbon atoms. The results differ from those obtained from adsorption chromatography on alumina[2], in that, here, the lower members of the homologous series do show an increase in R_F values. We suggest that since the polyamide is less polar than the alumina surface, the polyamide/phenol hydrogen bond is weaker than the alumina/phenol hydrogen bond and hence the fine constitutive effect of the addition of the methylene group to the phenol becomes apparent in the polyamide system.

For System 2, the MARTIN[16] relation appears to be valid for some straight chain hydrocarbons (Fig. 4). However, a strict evaluation of the relation is prevented by the low R_F values obtained for the higher members of the homologous series.

(c) A comparison of the 3- and/or 4- straight chain monoalkylphenols with their polymethylated isomers

It has already been stated that the electronic effects of the methyl groups, and other alkyl groups on the chromatographic behaviour will be small. Table I (c) shows that this is so. In both systems, the electron donation by the methyl group(s) should decrease the acidity of the phenolic hydrogen and so reduce its tendency to hydrogen

bond with (a) the polyamide surface, and (b) with the eluent. Thus it would be expected that the polymethylated phenols should have a higher R_F value than its monoalkyl isomer, in System 1, where the polyamide/phenolic hydrogen bond and solvation of the hydrophobic part of the molecules by the molule phase are of primary importance in controlling the system, and lower R_F values in System 2, where solvation of the phenolic group is the controlling factor. The results indicate that in System 1 there is little or no difference between the values for the isomers, while in System 2, the order is the reverse of that expected. Thus it must be concluded that the electronic effect on chromatographic behaviour of the alkylphenols is small. For System 2, the order is similar to that observed in the reversed phase systems described previously[3]. This may be taken as confirmatory evidence for the mechanism of chromatography proposed for this system[1].

(*d*) *The effect of chain branching in monoalkyl substituted phenols containing no groups ortho to the phenolic group*

The results for the effect of chain branching (Table I (d)) show that, for System 1, branching has little effect on the R_F values (compare our results for adsorption chromatography on alumina)[2]. For System 2, the effects are of the same order as for the reversed phase chromatographic system reported previously[3]. This again confirms that the mechanism proposed for System 2 is solvation of the phenolic group and not a change in the nature of the polyamide surface[4].

(*e*) *4-Mono-substituted phenols containing other structural features*

We have previously shown that the presence of a double bond in a side chain substituent of phenols substituted in the 4-position reduces the R_F values of that phenol relative to its saturated analogue in thin-layer adsorption chromatography[2], while in a reversed-phase thin-layer partition system the R_F values of the unsaturated compounds are higher than those of the comparable saturated compound[3].

In the polyamide system reported here, evidence is again found for the increase in the polarity of the phenol molecule caused by the presence of a double bond in the substituent group.

In System 1, the behaviour is comparable to that observed for adsorption chromatography, *i.e.* the R_F value of the unsaturated compound is reduced relative to its saturated analogue. It is possible that the reduction in the R_F value may be attributed to two causes:

(i) The presence of the double bond increasing the polarity of the phenol and so increasing the strength of the phenolic group/polyamide hydrogen bond.

(ii) The hydrogen atoms on the nitrogen atom of the amido group form a hydrogen bond with the π-electrons of the double bond.

By comparing the R_F values of 4-cyclopentylphenol with those of 4-*n*-butyl-, and 4-*n*-amylphenol, and the values of 4-cyclopent-2-enylphenol with 4-crotylphenol, it can be seen that presence of an alicyclic substituent gives R_F values approximating to those of the open straight chain compound containing one less carbon atom. It is not possible to compare this behaviour of these compounds for System 1 with the behaviour of the same compounds on alumina surfaces[2], because in the latter compounds the strength of the phenolic group/substrate hydrogen bond is little affected by these substituents. However their behaviour in System 2 is comparable

to their behaviour in the reversed phase system previously reported[3]. This is additional support for our conclusions that the change in the order of R_F values with a change in the nature of the eluent system is a result of the effect of the eluent on the solute rather than on the substrate.

The order of R_F values for the three aromatic substituted phenols in System 1 are the same as that observed for those compounds chromatographed on alumina surfaces[2], *i.e.* they show a regular increase with the increase in their molecular weight. In System 2, the R_F values of these compounds also show a similar order to those obtained for the same compounds in the reversed phase system studied by us[2], the values for *p*-phenylphenol being slightly higher than that of *p*-benzylphenol, with a large difference between the values for *p*-benzylphenol and *p*-cumylphenol. Once again the results support our proposed mechanisms for the various chromatographic systems.

(*f*) *Polylalkyl-substituted phenols containing no substituent ortho to the phenolic group*

The values for the polyalkyl-substituted phenols are collected in Table I (f). From this and from Fig. 5, it can be seen that the effects of chain branching, in System 1, is again negligible, thus confirming the observation made for the mono-alkylphenols. In this system too, it is seen that there is little or no difference between the values obtained for these compounds compared with their monoalkyl isomers.

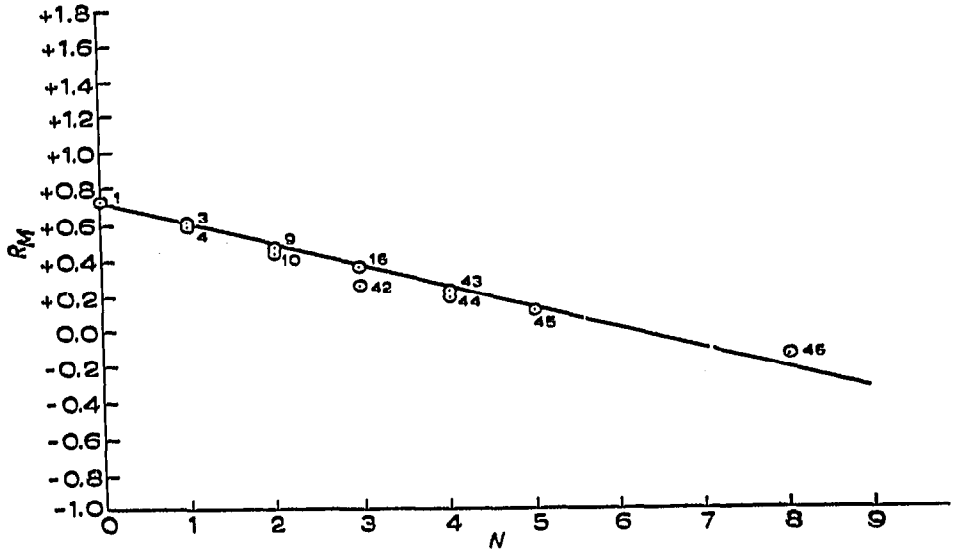

Fig. 5. R_M values (System 1) for polyalkyl-substituted phenols containing no groups *ortho* to the phenolic group *vs.* number of carbon atoms in the side chains.

This supports our contention that for these compounds, once the phenolic/substrate hydrogen bond is broken, dissolution of the molecule in the non-polar part of the mobile phase is of importance in the chromatographic process, and that this occurs by solvation of the hydrocarbon part of the molecule by the non-polar cyclohexane. The function of the acetic acid in this system is probably, as already suggested, that of a hydrogen bond breaker.

In contrast, the same compounds behave in System 2 as they did in the reversed phase systems[3], the polyalkyl phenols having higher R_F values than their

monoalkyl isomers. This therefore supports the already expressed view on the mechanism for this system[1], that the acetic acid again acts as a hydrogen bond breaker, but that once the bond is broken, solvation occurs at the phenolic group. This one point attachment of the molecule to the mobile phase means that the force needed to remove the compact polyalkyl compound is less than that needed to remove its monoalkyl straight chain isomer. Fig. 6 shows that the MARTIN[16] relation is valid.

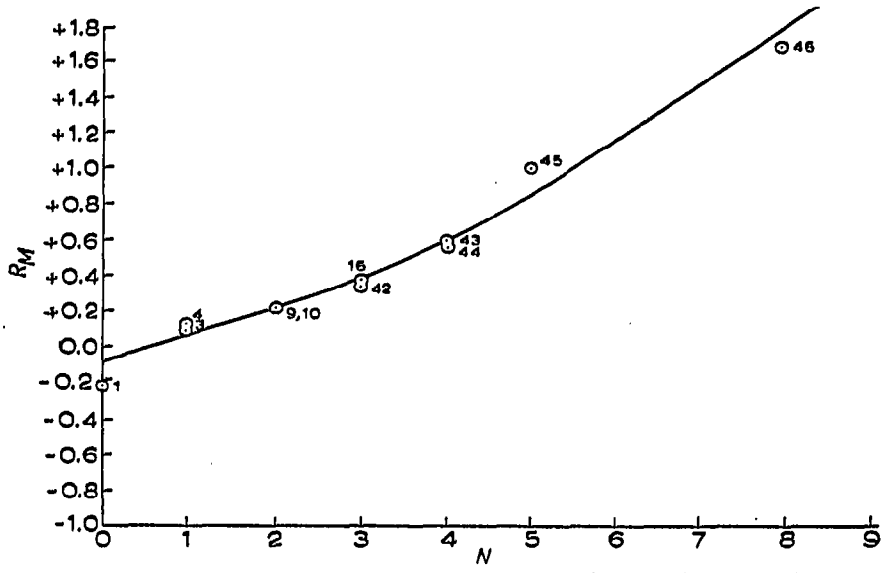

Fig. 6. R_M values (System 2) for polyalkyl-substituted phenols containing no groups *ortho* to the phenolic group *vs.* number of carbon atoms in the side chains.

(g) *Alkyl-substituted phenols containing one group ortho to the phenolic group*

These results again serve to emphasise the differences in the essential mechanisms of solvation for the two systems. Table I (g) and Fig. 7 show that for System 1, the R_F values show a fairly regular increase with the increase in size of the *ortho*

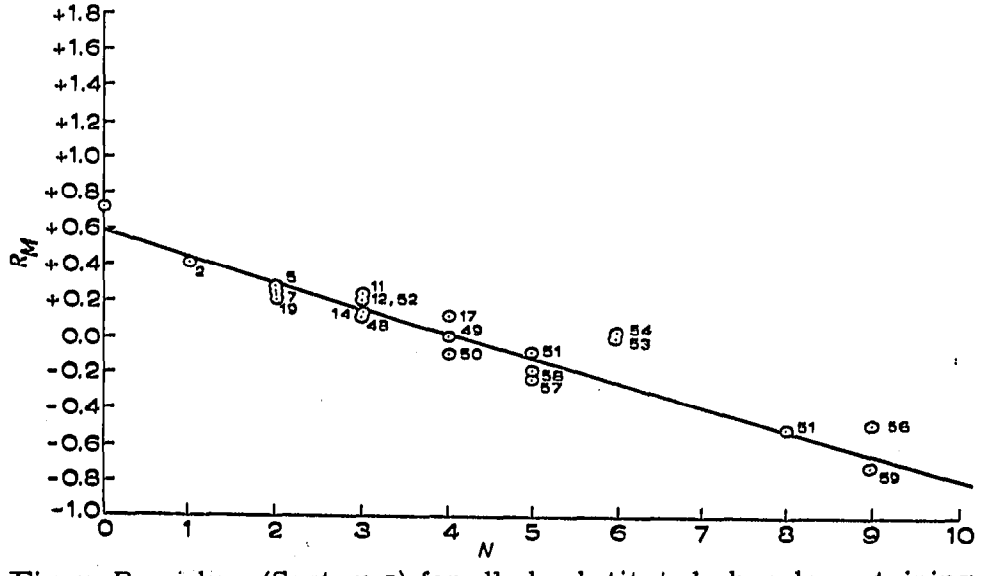

Fig. 7. R_M values (System 1) for alkyl-substituted phenols containing one group *ortho* to the phenolic group *vs.* number of carbon atoms in the side chains.

substituent, and the R_M values a corresponding decrease. In contrast to the effect of the substituent in the 3-, or 4-position (group 1 (b)) for this system, the R_F values continue to show a regular increase even up to the C_8 straight chain compound. This emphasises that the primary contribution to the behaviour is probably that of steric hindrance of approach of the phenolic group to the polyamide surface. Thus the MARTIN[16] relation is valid for these compounds, even though it breaks down for the non-*ortho* isomers. The behaviour therefore parallels that of the same compounds when absorbed on to alumina surfaces[2]. It is also seen that here, branching of the hydrocarbon chain does affect the behaviour of the phenol. This is in direct contrast to the behaviour of comparable substituents when in the 3-, or 4-positions (group 1 (b)). In contrast to the behaviour of the same substituents in group 1 (c) phenols, the polymethylated phenols have lower R_F values than their straight chain mono-alkyl isomers. This is obviously caused by the change in size of the *ortho* group and hence to the smaller steric effect of the *ortho* substituent in the polysubstituted isomers. Thus in the mono-*ortho*-substituted compounds, because the strength of the phenolic/polyamide hydrogen bond is reduced, the fine effects of variations in molecular structure are superimposed on the gross effect of the dissolution of the hydrocarbon part of the molecule in the mobile phase.

In group 1 (e) phenols, it was shown that the presence of a double bond in a compound lowers the R_F value of the compound compared with that of the saturated analogue, giving the unsaturated compound an R_F value approximating to that of the saturated compound containing one less carbon atom. It can be seen from the values for 2-ethylphenol, 2-*n*-propylphenol and 2-allylphenol that a similar behaviour also occurs in System 1. This parallels the effect of the double bond in adsorption chromatography[2]. It is probable that the hydrogen atoms of the amido-group compete with the hydrogen atom of the phenolic group for the π-electrons of the double bond. This reduces the possibility of internal hydrogen bonding[21]. This behaviour parallels that observed for 2-*n*-propylphenol and 2-allylphenol in the adsorption systems previously reported[2]. In System 2, the R_F value of 2-allylphenol is,

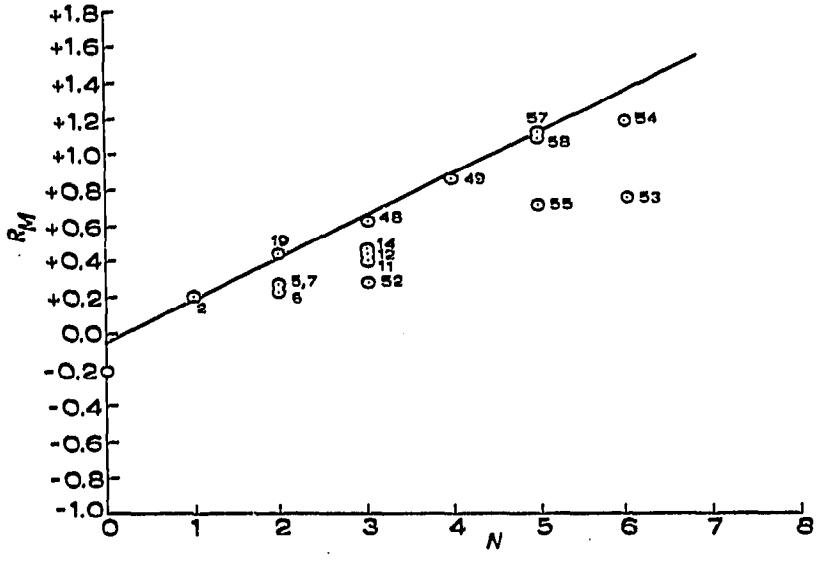

Fig. 8. R_M values (System 2) for alkyl-substituted phenols containing one group *ortho* to the phenolic group *vs.* number of carbon atoms in the side chains.

as expected, higher than that of 2-*n*-propylphenol. This also parallels the behaviour of these compounds in our reversed phase system[3]. The values for 2-phenylphenol and 2-cyclohexylphenols parallels those obtained for these compounds in adsorption chromatography[2] and reversed-phase partition chromatography respectively. Thus the overall result is to give added support for our views of the various mechanisms of chromatography. That the MARTIN[16] relation is approximately valid is shown in Fig. 8.

By comparing the R_F values of the three isomeric compounds 2-methyl-4-*tert.*-butylphenol; 2-*tert.*-butyl-3-methylphenol; and 2-*tert.*-butyl-4-methylphenol; and the isomeric pair 2-methyl-4-octylphenol and 2-octyl-4-methylphenol, the steric effect of bulky groups in the 2-position is further emphasised for both systems.

(*h*) *Alkyl substituted phenols containing two groups ortho to the phenolic group*

The results for these compounds for System 1 are similar to those obtained for the same compounds chromatographed on alumina[2]. The presence of two *ortho* groups greatly increases the R_F values relative to those of the mono *ortho* compound (group 1 (g)). For this system, the results emphasise that the presence of the *ortho* groups causes steric inhibition of the approach of the phenolic group to the polyamide surface. Some evidence of the validity of the MARTIN[16] relation is seen. The expected reduction of the R_F values by the presence of a double bond in the molecule is also seen. The comparability of these results with those obtained by chromatography of the same compounds on alumina is again taken as evidence that in System 1 removal of the phenols from the surface is a consequence of solvation of the hydrophobic part of the molecule by the non-aqueous mobile phase.

It is not possible to consider the validity of the MARTIN[16] relation for System 2 because only the 2,6-dimethylphenol migrates in this system, the other compounds remain at the point of application.

(*i*) *Alkoxyphenols*

The results for these compounds are given in Table I (i). For System 1, the results for the methoxy derivatives are the expected ones, the presence of the ether group results in a reduction in R_F values compared with phenol, but an increase compared with the corresponding dihydroxybenzenes, though evidence of the *ortho* effect is seen in the case of 2-methoxyphenol. It is probable that some hydrogen bonding between the ether oxygen and the amido-hydrogen atoms takes place. Evidence for hydrogen bonding between the ether oxygen atom and hydrogen atoms on the surface of alumina has previously been reported[2,22]. This is to some extent confirmed by the results for 3,5-dimethoxy-, and 3,5-dicarbomethoxyphenols. For the compounds in which the alkyl chain length of the substituent is increased, the results suggest that the MARTIN[16] relation may be valid for the lower members of the homologous series, but that for compounds of chain length greater than C_7, the relation breaks down. This is in agreement with the behaviour of the straight chain alkyl substituents in the 4-position (group 1 (b)).

In System 2, the results for the mono-substituted alkoxyphenols, the alicyclic compound and the phenoxyphenol are all comparable to the behaviour of these compounds in the reversed-phase systems[3]. The results for the 3,5-di-substituted compounds may be a result of the need to break the hydrogen bonds formed between the oxygen atoms of the alkoxy groups and the amido hydrogen atoms before these

compounds can be solvated by the mobile phase. The results again support the chromatographic mechanisms suggested by us for both these systems.

CONCLUSION

By comparing the behaviour of a large number of alkyl phenols when chromatographed on polyamide surfaces with the behaviour of the same phenols chromatographed on alumina surfaces, and by reversed-phase thin-layer chromatography it has been shown that the direction of R_F value change is related to the site of solvation of the phenolic molecule by the mobile phase. For non-aqueous mobile phases, the solvation site is the phenolic group. The hypothesis of the duality of behaviour of the polyamide surface is discounted.

The MARTIN relation is valid for both types of mobile phases for *ortho*-substituted phenols. For phenols with no *ortho* groups the MARTIN relation is not valid beyond a substituent chain length of five carbon atoms when a non-aqueous mobile phase is used. The relationship is, however, valid for the aqueous mobile phase.

For *ortho*-substituted compounds steric hindrance of the approach of the phenolic group to the substrate is observed for the non-aqueous system, while steric hindrance of solvation of the phenolic group occurs with the aqueous mobile phase.

Some evidence of hydrogen bonding involving the hydrogen atoms of the amido-group of the substrate is also given.

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SUMMARY

Seventy-six alkyl-, aryl-, and alkoxyphenols have been chromatographed on polyamide–cellulose with a non-aqueous mobile phase and an aqueous mobile phase. Removal of the phenol from the surface is dependent upon the solvation either of the hydrophobic part of the molecule by the non-aqueous phase or the phenolic group by the aqueous mobile phase. The behaviour of the phenols is modified by steric effects. The MARTIN additivity principle applies approximately for all phenols chromatographed with an aqueous mobile phase, and for *ortho*-phenols chromatographed with a non-aqueous mobile phase. The relationship is not valid for non-*ortho*-phenols chromatographed with a non-mobile phase.

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